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ORIGINAL RESEARCH

Hazard-dependent soil factors for site-specific elastic acceleration response spectra of Italian and European seismic building codes

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Abstract
To define the seismic input in non-liquefiable soils, current seismic standards give the possibility to treat local site effects using a simplified approach. This method is generally based on the introduction of an appropriate number of soil categories with associated soil factors that allow modifying the shape of the elastic acceleration response spectrum computed at rocky (i.e. stiff) sites. Although this approach is highly debated among researchers, it is extensively used in practice due to its easiness. As a matter of fact, for standard projects, this method represents the driving approach for the definition of the seismic input. Nevertheless, recent empirical and numerical studies have risen doubts about the reliability and safety of the simplified approach in view of the tendency of the current soil factors of Italian and European building codes to underestimate the acceleration at the free surface of the soil deposit. On the other hand, for certain soil classes, the current soil factors seem to overestimate ground amplification. Furthermore, the occurrence of soil nonlinearity, whose magnitude is linked to both soil type and level of seismic intensity, highlights the fallacy of using constant soil factors for sites with a different seismic hazard. The objective of this article is to propose a methodology for the definition of hazard-dependent soil factors and simultaneously quantify the reliability of the coefficients specified in the current versions of Eurocode 8 (CEN 2005) and Italian Building Code (NTC8 2008 and revision NTC18 2018). One of the most important outcome of this study is the quantification of the relevance of soil nonlinearity through the definition of empirical relationships between soil factors and peak ground acceleration at outcropping rock sites with flat topological surface (reference condition).

Keywords Soil factors · Soil nonlinearity · Stochastic ground response analysis · Eurocode 8 · Italian building code (NTC18)

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1 Introduction

For the definition of the seismic input in standard projects, most building codes worldwide (e.g. IBC 15, Eurocode 8, Italian Building Code) allow to account for site effects using a simplified method based on the modification of the elastic acceleration response spectrum computed at rocky sites (reference condition) through the introduction of soil factors defined for different soil categories. Although detailed specifications of this approach may vary considerably from code to code, the definition of soil factors as a function of ground motion intensity expected at the outcropping bedrock site is a common feature. To a first approximation this allows to account for the nonlinear soil response of soil deposits.

It is well-known that for weak ground motion, soils behave as linear, viscoelastic materials. In this situation the amplification of near-surface ground motion is larger in soft rather than in stiff soil deposits because the phenomenon is controlled by the impedance contrast between the seismic bedrock and the overlying soil layers.

On the other hand for strong ground motions, material nonlinearity plays an important role and the above trend may be reversed because in this case, the level of ground amplification is influenced also by degradation of shear modulus and soil shear strength. Soft soils have a greater deformability and thus strong ground shaking may induce severe shear modulus degradation coupled with an increase of damping ratio due to the mobilization of rather large shear strains. An extreme case occurs when the mobilized stress reaches the soil shear strength. Beyond this value soils cannot transmit larger shear stresses and this determines a limiting threshold for ground acceleration. The fact that soil shear strength acts as an upper limit of the peak ground acceleration (PGA) that can be reached in the ground can be easily explained through the simple model proposed by Seed and Idriss (1971) used in liquefaction assessment for computing the cyclic stress ratio. In this model PGA is directly proportional to the shear stress and inversely proportional to the overburden pressure.

Moreover the shear modulus degradation, which is always associated with the increment of hysteretic damping, contributes to the modification of the frequency content of the free surface ground motion.

Several empirical and numerical data from strong motion records confirm the above statements (e.g. Mohammadioum and Pecker 1984; Idriss 1990; Suetomi and Yoshida 1998). For this reason, several seismic building codes worldwide (e.g. IBC 15, ASCE 7-10, Eurocode 8, Italian Building Code) account for soil nonlinearity by providing different spectral shapes according to the level of seismic intensity expected at the site.

Yet, a series of recent articles focused on Eurocode 8 (e.g. Pitilakis et al. 2012, 2013, 2015) showed that for certain soil classes, the soil factors prescribed by the current Eurocode 8 have a marked tendency to underestimate ground amplification. At the same time, in soft ground under strong ground shaking, these soil factors tend to overestimate the phenomenon (e.g. Peruš and Fajfar 2014).

This paper describes a novel procedure for deriving hazard-dependent soil factors for the definition of elastic acceleration response spectra at the free surface of the soil deposit from the modification of the reference spectrum at outcropping bedrock. This methodology has been applied for the definition of updated, hazard-dependent soil factors for the Italian Building Code (NTC08 2008 and revision NTC18 2018) and Eurocode 8 (CEN 2005).

2 Comparison between current Eurocode 8 and Italian Building Code

Eurocode 8 (CEN 2005) and Italian Building Code (NTC08 2008 and revision NTC18 2018) share essentially the same approach to account for stratigraphic site effects. The elastic, acceleration response spectrum associated to the ground motion at the free surface of the soil deposit can be defined based on both soil classification and the severity of expected intensity of ground shaking at the outcropping bedrock.

The analytical expressions of the elastic response spectrum associated to the horizontal component of motion are identical for the two building codes and consist in the followings four equations:

$$S_a(T) = \begin{cases} a_g \cdot S \cdot \left[1 + \frac{T}{T_B} \cdot \left(\eta \cdot F_o - 1\right)\right] & 0 \leq T \leq T_B \quad (1) \\ a_g \cdot S \cdot \eta \cdot F_o & T_B \leq T \leq T_C \quad (2) \\ a_g \cdot S \cdot \eta \cdot F_o \cdot \left[\frac{T_C}{T}\right] & T_C \leq T \leq T_D \quad (3) \\ a_g \cdot S \cdot \eta \cdot F_o \cdot \left[\frac{T_C \cdot T_D}{T^2}\right] & T_D \leq T \quad (4) \end{cases}$$

where a_g is the peak ground acceleration (PGA), η is the damping correction factor ($\eta = 1$ for viscous damping $\xi = 5\%$), the coefficient S is the *soil factor* used to account for the stratigraphic amplification, F_o is the ratio between the maximum spectral acceleration and the peak ground acceleration (a_g) at outcropping rock with flat topographic surface. T_B, T_C and T_D are the limit values of the structural period.

The coefficient S linearly scales the spectral ordinates of the elastic, acceleration response spectrum at outcropping rock with flat topological surface (i.e. reference response spectrum) whereas the variation of T_B, T_C and T_D allows to shift the spectral band (plateau) towards longer structural periods.

Essentially, the main difference between Eurocode 8 (CEN 2005) and the Italian Building Code (NTC08 2008 and revision NTC18 2018) consists in the fact that Eurocode 8 defines two types of shape for the response spectrum: type 1 for regions of high seismicity ($M_S > 5.5$) and type 2 for regions of low to moderate seismicity ($M_S \leq 5.5$). On the other hand, the spectral shape of the Italian Building Code depends on the geographical coordinates over a grid of the Italian territory having a spatial resolution of 0.05° (~5.5 km). The site specific, acceleration response spectra (horizontal component) are defined by means of three parameters related to the seismic hazard: a_g, F_o and the period indicating the beginning of the constant velocity branch of the response spectrum (T_C^*). In the Italian Building Code, these parameters are based on the results of a probabilistic hazard study carried out for the whole Italian territory by the Italian Institute of Geophysics and Volcanology (GdL MPS 2004). Like other seismic building codes and standards (e.g. IBC 15, ASCE 7-10), the Italian Building Code provides an analytical relationship between soil amplification factors and seismic hazard parameters. In this sense, the Italian Building Code is more refined if compared to EC8 where the dependence on the seismic intensity at outcropping rock has been implemented with the definition of only two spectral shapes with constant soil factors (e.g. type 1 and type 2).

The comparison between the soil amplification factors of Eurocode 8 and Italian Building Code is shown in Table 1. In the Eurocode 8, the coefficient S depends exclusively on the soil class and category of magnitude (i.e. Type 1 or Type 2). In the Italian Building Code $S = S_S \cdot S_T$ where S_S is the stratigraphic amplification factor and S_T is the topographic

Table 1 Parameters for the definition of spectral shapes as defined by EC8 (CEN 2005) and Italian Building Code (NTC08 2008 and revision NTC18 2018)

Soil class	Eurocode 8 (CEN 2005)								Italian building code (NTC08 2008 and revision NTC18 2018)		
	Type 1 (MS > 5.5)				Type 2 (MS ≤ 5.5)				$T_B = T_C/3$	$T_C = C_C \cdot T_C^*$	$T_D = 4 \cdot a_g/g + 1.6$
	S	T_B (s)	T_C (s)	T_D (s)	S	T_B (s)	T_C (s)	T_D (s)	S_S	C_C	
A	1.00	0.15	0.40	2.00	1.00	0.05	0.25	1.20	1	1	
B	1.20	0.15	0.50	2.00	1.35	0.05	0.25	1.20	$1.00 \leq 1.40–0.40 \cdot F_o \cdot a_g \leq 1.20$	$1.10 \cdot (T_C^*)^{-0.20}$	
C	1.15	0.20	0.60	2.00	1.50	0.10	0.25	1.20	$1.00 \leq 1.70–0.60 \cdot F_o \cdot a_g \leq 1.50$	$1.05 \cdot (T_C^*)^{-0.33}$	
D	1.35	0.20	0.80	2.00	1.80	0.10	0.30	1.20	$0.90 \leq 2.40–1.50 \cdot F_o \cdot a_g \leq 1.80$	$1.25 \cdot (T_C^*)^{-0.50}$	
E	1.40	0.15	0.50	2.00	1.60	0.05	0.25	1.20	$1.00 \leq 2.00–1.10 \cdot F_o \cdot a_g \leq 1.60$	$1.15 \cdot (T_C^*)^{-0.40}$	

amplification factor. For flat topographic surfaces $S_T = 1$ hence, the coefficient S_S of the Italian Building Code is directly comparable with the coefficient S of EC8 (see Fig. 1). As shown in Table 1, the coefficient S_S depends on the soil class and two seismic hazard parameters: a_g and F_o. In the Eurocode 8, F_o is a constant equal to 2.5 whereas in the Italian Building Code F_o depends on the geographical position which is equal to 2.5 on average (e.g. Fig. 6). A similar difference between the two codes is found in the definition of the limits of the structural period. In particular, for each soil class the Eurocode 8 defines constant values of T_B, T_C and T_D for type 1 and type 2 spectra on the base of the "spectral shape ratio" (*SR*) as defined in Rey et al. (2002). On the other hand, T_B, T_C and T_D of the Italian Building Code depend on two seismic hazard parameters: a_g and T_C^*. C_C (see Table 1), which is function of T_C^*, is the coefficient used in the Italian Building Code for the definition of the corner period T_C (see also Fig. 1). As can be viewed from Table 1 and Fig. 2, in the Italian Building Code both S_S and C_C are expressed as a function of site-specific hazard parameters.

Unlike EC8, for which are available several ad-hoc studies on soil classification and related soil factors (e.g. Rey et al. 2002; Pitilakis et al. 2006, 2012, 2013), the Italian Building Code (NTC08 2008 and revision NTC18 2018) does not seem to have been investigated to the same extent. Even though a few studies focusing on soil classification of the Italian Building Code were performed (e.g. Barani et al. 2008), the precise values of soil factors S_S and C_C do not seem to have been calibrated based on specific studies. Moreover, in the revision of the Italian Building Code (NTC18 2018) some modifications have been introduced in the description of the soil categories (see Table 2) however soil factors S_S and C_C have not been modified.

Figure 2 shows the comparison between the soil factor S of Eurocode 8 and the Italian Building Code for flat topographic surfaces (i.e. $S_T = 1$). This comparison is possible because the soil classification in EC8 and Italian Building Code are essentially the same. To facilitate the reader, Table 2 reports a comparison between the soil classes provided by the two building codes. In terms of mechanical parameters the classes are identical. The

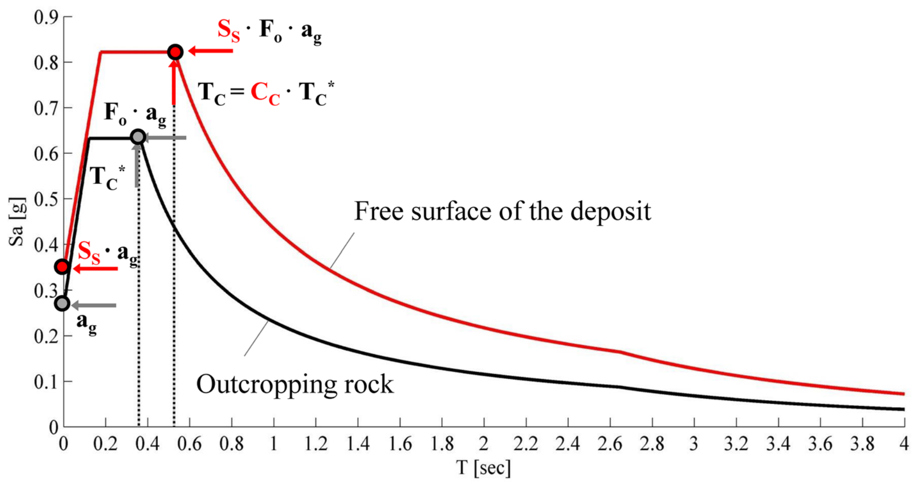


Fig. 1 Definition of elastic, acceleration response spectrum at the free surface of the deposit according to the Italian Building Code. Coefficients S_S and C_C in the Italian Building Code share the same scope, respectively, of S and *SR* in Eurocode 8

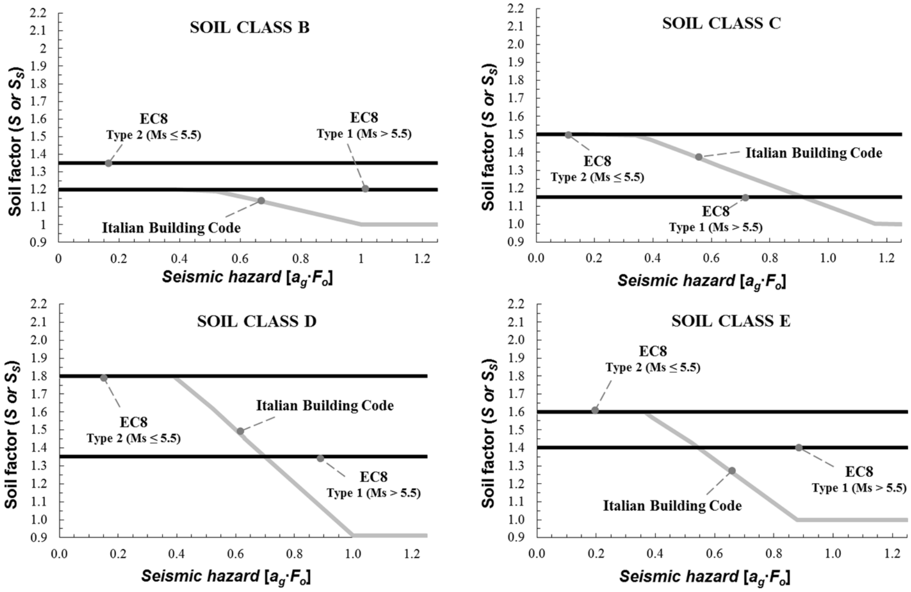


Fig. 2 Comparison between soil factor S in EC8 (CEN 2005) and S_S in Italian Building Code (NTC08 2008 and revision NTC18 2018)

descriptions have yet small differences that however cannot justify the strong differences in terms of soil factors (Fig. 2).

Indeed, one of the aims of the present study is to assess the reliability of current soil factors of Eurocode 8 and Italian Building Code. More in general, the present article presents a methodology to derive hazard-dependent soil factors through the execution of a well-defined and repeatable procedure. This method tries to exclude from the analysis the bias related to engineering judgment. Because of its versatility, we selected a formulation of soil factors similar to that currently implemented in the Italian Building Code.

3 Methodology

The severity and frequency content of ground motion expected at the free surface of the soil deposit depend not only on the properties of the soil but also upon the characteristics of ground motions specified at the top of the bedrock. In this regard, the reliability of the predicted ground motion strongly depends on both epistemic and aleatory uncertainties associated with these pieces of information.

Even in case of detailed seismological and stratigraphic setting (e.g. availability of vertical array data), the assessment of ground amplification is still affected by large uncertainties. If we enlarge the scale of the problem by passing from the investigation of one to several stratigraphic profiles, the uncertainty of the problem strongly increases mainly as consequence of geometrical irregularities, spatial variability of geotechnical parameters and variability of the reference input motion.

Table 2 Comparison between soil classification in EC8 (CEN 2005) and Italian building code (NTC08 2008 and revision NTC18 2018)

Soil class	Description		Parameters		
	Eurocode 8 (CEN 2005)	Italian building code (NTC08 2008 and revision NTC18 2018)	$V_{s,30}^{a}$ (m/s)	NSPT (blows/30 cm)	Cu (kPa)
A	Rock or other rock-like geological formation, including at most 5 m of weaker material at the surface	Outcropping rock or hard soil, including at most 3 m of weaker material at the surface	> 800	–	–
B	Deposits of very dense sand, gravel, or very stiff clay, at least several tens of meters in thickness, characterized by a gradual increase of mechanical properties with depth	Soft rock or very dense cohesionless soil or very stiff cohesive soils, more than 30 meters in thickness, characterized by gradual increase of mechanical properties with depth[b]	360–800	> 50	> 250
C	Deep deposits of dense or medium-dense sand, gravel or stiff clay with thickness from several tens to many hundreds of meters	Medium-dense cohesionless soil or medium-stiff cohesive soils, more than 30 meters in thickness, characterized by gradual increase of mechanical properties with depth	180–360	15–50	70–250
D	Deposits of loose-to-medium cohesionless soil (with or without some soft cohesive layers), or of predominantly soft-to-firm cohesive soil	Deposits of loose cohesionless soil or of soft cohesive soil, more than 30 meters in thickness, characterized by gradual increase of mechanical properties with depth	< 180	< 15	< 70
E	A soil profile consisting of a surface alluvium layer with Vs values of type C or D and thickness varying between about 5 m and 20 m, underlain by stiffer material with Vs > 800 m/s	Soils of class C or D up to 20 meters in thickness underlain by stiffer material with $V_{s,30}$ > 800 m/s[c]	–	–	–

[a] In the NTC18 has been introduced the equivalent shear velocity $V_{s,eq}$. For soils with thickness more than 30 m, it is identical to $V_{s,30}$. Furthermore, the NSPT and Cu parameters have been removed from the classification

[b] In the NTC18 the specification to be more than 30 meters in thickness has been erased

[c] In the NTC18 the threshold of 20 m has been changed to 30 m and the condition on the $V_{s,30}$ of the seismic bedrock has been removed

The scale of the problem is therefore another important factor that affects the predictions of site effects because this scale controls the amount of epistemic versus aleatory uncertainties that come into play. Considering that the simplified approach used in building codes is applied at a national or even continental scale, the soil factors should be defined using a statistical approach. Moreover, since the simplified approach is extensively used in practice, it should ensure conservative results. Therefore, in-depth studies on the definition of soil factors should be conducted by considering a statistically significant number of different stratigraphic profiles and ground motions. If a higher level of accuracy is desired, the designer should select a detailed site-specific ground response analysis, possibly using the stochastic approach.

The aim of the proposed methodology is the definition of hazard-dependent soil factors from a statistically significant number of representative acceleration response spectra: one referring to the reference ground condition (e.g. soil class A in EC8 and Italian Building Code), the other representing the free surface of the soil deposit belonging to a specific soil category. Finally, empirical relationships between soil factors and peak ground acceleration expected at outcropping bedrock site are defined for all soil classes.

An essential step of the proposed methodology is represented by the collection of a large number of free surface acceleration time histories recorded by a large number of seismic stations located on different soil categories. The starting point of the procedure is therefore represented by the selection of ground motions for the reference condition which is the outcropping rock site with flat topological surface (i.e. stiff sites with $V_{S,30} \geq 800$ m/s). This first set of records will be represented by natural time histories with different levels of intensity (e.g. in terms of PGA). In the present state-of-the-practice of seismic hazard studies, the variability of the ground-motions is taken into account using a broad range of earthquakes, sites, and regions to analyze the hazard at a single site from a single small source region (Al Atik et al. 2010). Such practice assumes that the variability in ground motion at a single site-source combination is the same as the variability in ground motion observed in a more global dataset and is referred to as the "*ergodic assumption*" (Anderson and Brune 1999). In recent years, the availability of well recorded ground motions at single sites from multiple occurrences of earthquakes in the same regions allowed researchers (e.g. Chen and Tsai 2002; Atkinson 2006; Morikawa et al. 2008) to estimate the ground-motion variability without including the ergodic assumption (i.e. "non-ergodic assumption").

In the proposed procedure, if the time histories with different levels of intensity at the outcropping rock site with flat topological surface are selected according to the "*ergodic assumption*", the maximum level of severity of this set of ground motions should be consistent with the regional seismotectonic and seismogenic setting of the reference site. One possible option is to select spectrum-compatible records according to the requirements of a specific building code (e.g. Corigliano et al. 2012; Rota et al. 2012).

The other set of time histories should represent ground motions of the same seismic events selected for the reference site (Fig. 3) and conditions that differ only for the soil category of the recording station (e.g. soil class B, C, D and E in EC8 and Italian Building Code). This second set of ground motions can be: (a) natural recordings; (b) time histories reproduced through ground response analysis. Hereafter in the article, the application of the procedure to obtain soil factors using natural accelerograms is named "*empirical approach*". On the other hand when the accelerograms at the free surface of the soil deposit are obtained by means of ground response analyses, the procedure is named "*numerical approach*". The definition of a suite of accelerograms is different depending on the selected approach. The "numerical approach" only requires the selection of outcropping rock

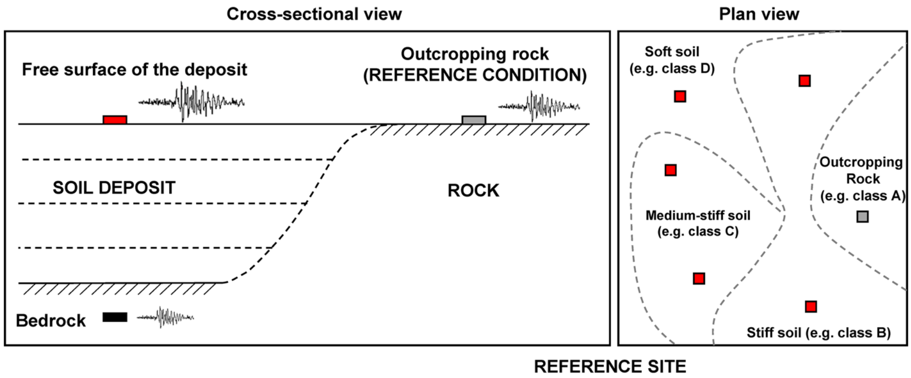


Fig. 3 Graphical representation of a typical reference site as considered in this study. For each reference site and for each soil class, the soil amplification factors have been defined comparing the response spectrum at the free surface of the deposit (i.e. red box) with that at the outcropping rock (i.e. grey box), generated by the same earthquake

motions classified on the basis of the PGA. On the other hand, the "*empirical approach*" involves also the selection of recordings by stations located in different soil classes. It is worth noting that, for unbiased comparisons of the response spectra referring respectively to the free surface of the deposit and the outcropping rock, the two set of ground motions need to be generated by the same earthquake. The "*empirical approach*" coupled with the use of Ground Motion Prediction Equations (GMPE), which may help reducing the influence of epicentral distance on the ground motion intensity, is not addressed in this paper. A procedure of selection compatible with this approach can be found in the paper by Pitilakis et al. (2012, 2013). On the contrary, this article describes in detail the application of the "*numerical approach*".

3.1 Definition of soil factors

Figure 4 describes schematically the procedure for the definition of the hazard-dependent soil factors proposed in this article. Once the suite of code spectra at the outcropping bedrock site and the relative sets of elastic response spectra representative of the free surface of the deposit (e.g. 50th or 84th percentile) have been collected considering different soil classes and increasing severity of the earthquakes, both the numerical and the empirical approach share the subsequent steps of the procedure. At this stage, independently from the selected approach, for each level of PGA specified at the outcropping bedrock, we should organize two different types of data referring to the same earthquake: (1) a code spectrum representative of the soil class A at outcropping rock (see step 1.1a in Fig. 4); (2) for each soil class (e.g. B, C, D and E), an elastic, acceleration response spectrum representative of the soil free surface (see step 1.1b in Fig. 4). As described more in detail in the next sub-sections of the article (Sects. 3.1.1, 3.1.2), soil factors (e.g. S, T_B, T_C and T_D) are used as variable parameters to modify the shape of the code spectrum in order to find the best match with the response spectrum at the free surface of the deposit (i.e. step 1.1 and 1.2 of Fig. 4). The definition of the soil factors that produce the best fit is carried out by means of the least square method.

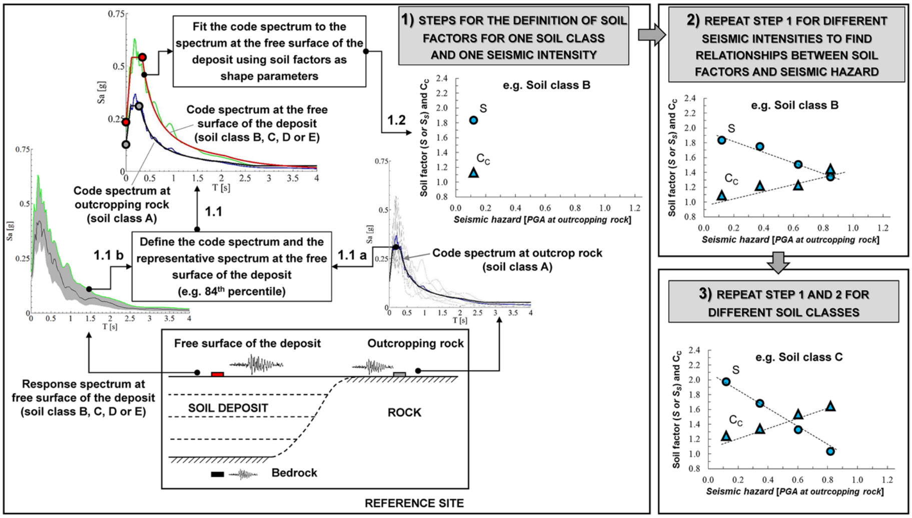


Fig. 4 Fundamental steps for the definition of the empirical relation between soil factors and the horizontal PGA. Once the code spectrum at outcropping bedrock (step 1.1a) and the relative elastic, response spectrum at the free surface of the soil deposit (step 1.1b) have been defined, the least square method has been used to find the soil factors that best fit the code spectrum to the response spectrum at the free surface of the deposit (step 1.1 and 1.2). The same procedure has been repeated for different levels of PGA and soil classes (step 2)

Independently of each soil class, the curve-fitting procedure is repeated for different intensity levels of the input motion. Subsequently, from the values of fitting parameters and the associated PGA at the outcropping bedrock site, an empirical relationship between the soil factors and PGA is proposed for each soil class as shown in Fig. 4 (Step 2). To fit the response spectra, we have selected the code spectrum provided by Eurocode 8 with the introduction of two soil factors (S_S and C_C) mimicking a formulation similar to that of the Italian Building Code (NTC08 2008 and revision NTC18 2018). In the next sub-sections Sects. 3.1.1, 3.1.2) we provide the details for the definition of two series of soil factors that correspond to different percentiles of the response spectrum at the free surface of the deposit (i.e. 50th and 84th percentile).

Considering that the proposed methodology has been thought for the definition of code-based response spectra using the simplified method, the 84th percentile is considered as a conservative reference suggested by the authors.

3.1.1 Curve-fitting technique

Equations (1) through (4) represent 4 branches of the code spectrum of Eurocode 8 (CEN 2005) and Italian Building Code (NTC08 2008 and revision NTC18 2018). They are used as shape functions to fit the code spectrum to the free surface, elastic acceleration response spectrum using soil factors S_S and C_C as shape parameters (Fig. 4). Considering that the code spectrum of EC8 and Italian Building Code is a piece-wise nonlinear function, to carry out this operation we make use of nonlinear least square method by selecting the Levenberg–Marquardt algorithm (Seber and Wild 2003) available in MATLAB. The shape function has been defined by introducing the followings parameters:

$$S = S_S = p_1 \tag{5}$$

$$C_C = p_2 \cdot (T_C^*)^{p_3} \tag{6}$$

$$T_B = T_C / p_4 \tag{7}$$

$$T_C = C_C \cdot T_C^* \tag{8}$$

$$T_D = 4 \cdot a_g / g + 1.6 \tag{9}$$

where $g = 9.81$ m/s^2, p_1 is the parameter that modifies the amplitude of the spectral ordinates (S in EC8 and S_S in Italian Building Code) while p_2 and p_3 are introduced for the definition of C_C, a coefficient that controls the extension of the plateau at large structural periods, comparable to *SR* in Eurocode 8 (Rey et al. 2002). For the coefficient S, or S_S, we used 4 parameters to have T_B independent from T_C and hence having the possibility to work with a more adaptive shape function. By substituting Eqs. (5) through (9) into Eqs. (1) through (4) the following parameterized, shape functions are obtained:

$$S_a(T) = \begin{cases} a_g \cdot p_1 \cdot \left[1 + \frac{T}{p_2 \cdot (T_C^*)^{p_3} \cdot T_C^* / p_4} \cdot \left(\eta \cdot F_o - 1\right)\right] & 0 \le T \le \frac{p_2 \cdot (T_C^*)^{p_3} \cdot T_C^*}{p_4} \quad (10) \\ a_g \cdot p_1 \cdot \eta \cdot F_o & \frac{p_2 \cdot (T_C^*)^{p_3} \cdot T_C^*}{p_4} \le T \le p_2 \cdot (T_C^*)^{p_3} \cdot T_C^* \quad (11) \\ a_g \cdot p_1 \cdot \eta \cdot F_o \cdot \left[\frac{p_2 \cdot (T_C^*)^{p_3} \cdot T_C^*}{T}\right] & p_2 \cdot (T_C^*)^{p_3} \cdot T_C^* \le T \le T_D \quad (12) \\ a_g \cdot p_1 \cdot \eta \cdot F_o \cdot \left[\frac{p_2 \cdot (T_C^*)^{p_3} \cdot T_C^* \cdot T_D}{T^2}\right] & T_D \le T \quad (13) \end{cases}$$

The starting value of the updating parameters is defined as: $p_1 = 1.0$; $p_2 = 1.0$; $p_3 = -0.1$ and $p_4 = 3$.

The Italian Building Code (NTC08 2008 and revision NTC18 2018) provides all the parameters required for the definition of site-specific spectral shape for the reference condition (a_g, F_o and T_C^*). For this reason, once the outcropping bedrock accelerograms are selected according to the spectrum- and seismo-compatible criteria specified by Eurocode 8, the proposed curve-fitting technique is applied directly to the elastic response spectrum representative for the soil deposit.

The final value of the soil factor S (or S_S) for each reference site is represented by the maximum between the model parameter p_1 and the ratio between the peak ground accelerations at the free surface of the soil deposit and at the outcropping bedrock site (PGA_{soil}/$PGA_{class,A}$) as imposed by Eq. (1) for $T = 0$. The former PGA is calculated from the response spectrum representative of the soil free surface at zero structural period while the latter is the average PGA between the seismo- and spectrum-compatible accelerograms which expresses the PGA expected at the reference site.

3.1.2 Definition of hazard-dependent soil factors (S or S_S and C_C)

Once the values of S or S_S have been defined for all soil classes and for different levels of PGA expected at outcropping bedrock, the empirical relationships between this soil factor and the seismic intensity can be defined by means of the least square method (see step 2 in Figs. 4, 5a).

The main purpose of the soil factor C_C is to shift the plateau at longer periods and hence its effects is essentially decoupled from that of soil factor S_S, at least for the first

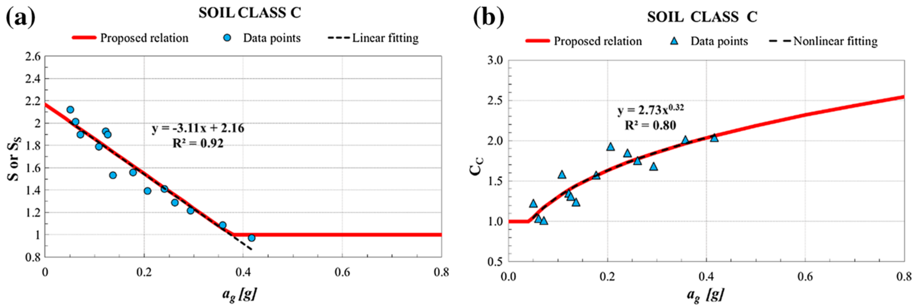


Fig. 5 Example of the empirical relationship between soil factors and seismic hazard expressed in terms of peak ground acceleration expected at the outcropping bedrock site. **a** Soil factor S or S_S. **b** Soil factor C_C

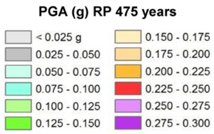
two branches of the spectrum. At this stage of the procedure, parameter p_1 is now a constant equal to soil factor S or S_S. Moreover, since in the Italian Building Code p_4= 3 and considering that the effect of p_4 can be absorbed by the parameter p_2, the values of C_C have been defined for all soil classes and for different levels of seismic intensity by setting p_4 to be a constant equal to 3 and using the Levenberg–Marquardt algorithm with only the two free parameters p_2 and p_3. This approach allowed to reduce the number of model parameters to be determined without significantly reduce the accuracy. Once the values of C_C have been defined, also the relation between this soil factor and peak ground acceleration expected at outcropping bedrock (a_g) can be established (see step 2 in Figs. 4 and 5b). Figure 5 shows an example of determining soil factors for soil class C. The regressions provides a good fitting for soil factors S or S_S and C_C.

4 Application of the methodology

With reference to the "*numerical approach*", the complete procedure has been applied for the definition of hazard-dependent soil factors with the objective to assess and update the coefficients provided by Eurocode 8 (CEN 2005) and Italian Building Code (NTC08 2008 and revision NTC18 2018).

About 112,000 one-dimensional equivalent-linear, fully stochastic ground response analyses have been carried out by using 98 seismic- and spectrum-compatible natural accelerograms recorded on stiff ground (i.e. soil class A of Eurocode 8). Monte Carlo simulations, coupled with the Latin hypercube sampling technique, have been used to randomly generate realizations of soil profiles with the only restriction to yield geotechnical and geophysical models consistent with the prescriptions of soil categories provided by the corresponding building codes (i.e. soil class B, C, D and E).

The variability of seismic intensity has been introduced by selecting 14 reference sites in Italy with increasing seismic hazard (Fig. 6). For each site, a suite of 7 seismic- and spectrum-compatible natural accelerograms, recorded at stations located on soil class A with flat topological surface, have been selected. The following sections outline the main phases of the procedure.



Reference site	Accelerograms	Seismic hazard		
	mean a_g [g]	a_g [g]	F_o	T_C^* [s]
1) Trapani	0.05	0.05	2.47	0.32
2) Bolzano	0.06	0.05	2.60	0.35
3) Taranto	0.07	0.06	2.75	0.41
4) Bergamo	0.11	0.12	2.42	0.27
5) Palermo	0.12	0.13	2.38	0.29
6) Firenze	0.13	0.13	2.40	0.30
7) Treviso	0.14	0.14	2.46	0.33
8) Rimini	0.18	0.18	2.49	0.30
9) Perugia	0.21	0.22	2.41	0.31
10) Ateleta	0.24	0.25	2.32	0.35
11) Lamezia	0.26	0.27	2.43	0.37
12) Catania*	0.29	0.28	2.42	0.44
13) Catania (SF 1.22)*	0.36	0.34	2.42	0.44
14) Gioia Tauro*	0.42	0.35	2.46	0.39
* RP 950 years		mean=	2.46	

Fig. 6 Geographical location and seismic hazard parameters of the 14 reference sites selected in this study with superimposed the zonation of the Italian territory in terms of PGA for a return period of 475 years (published by the Italian Department of Civil Protection, www.protezionecivile.gov.it)

4.1 Selection of seismo- and spectrum-compatible natural records for the reference condition

The input motions for the reference condition (outcropping rock or stiff sites with $V_{S,30} \geq 800$ m/s and flat topological surface) adopted in the present study have been selected according to the "*ergodic assumption*" and using the web portal named SEISM-HOME (www.eucentre.it/seismhome.html). This web-application allows an automatic definition, at any location over the entire Italian territory, of the seismic input represented by suites of 7, spectrum- and seismo-compatible real accelerograms recorded at the outcropping bedrock sites with flat topographic surface and for the return period of 475 years. SEISM-HOME relies on a wide database of accelerograms which was constructed from accredited strong-motion databases such as the European Strong motion Database, the PEER-NGA database, the K-Net database and ITACA. Details of the procedure implemented in SEISM-HOME can be found in Rota et al. (2012).

For the first 11 sites (Fig. 6) the seismic hazard is referred to a return period (RP) of 475 years whereas for the remaining 3 sites (from 12 to 14) the latter was increased to 950 years. At these 3 sites the accelerograms were selected using ASCONA, a computer program for the selection of natural accelerograms described in detail in Corigliano et al. (2012). The selection of the recordings for site 13 was carried out using the seismic hazard of site 12 after applying a scaling factor (SF) of 1.22.

The range of considered PGA is important for the characterization of the empirical relationships between soil factors and seismic hazard in relation to the level of soil nonlinearity mobilized into each soil class. This is particularly relevant for large values of PGA. In this sense, the introduction of a return period of 950 years allowed us to populate the sample also for large values of PGA thus well-constraining the empirical relations.

Figure 7 illustrates the variability of the ground motions used in the stochastic, ground response analyses in terms of peak ground acceleration (PGA) versus epicentral distance

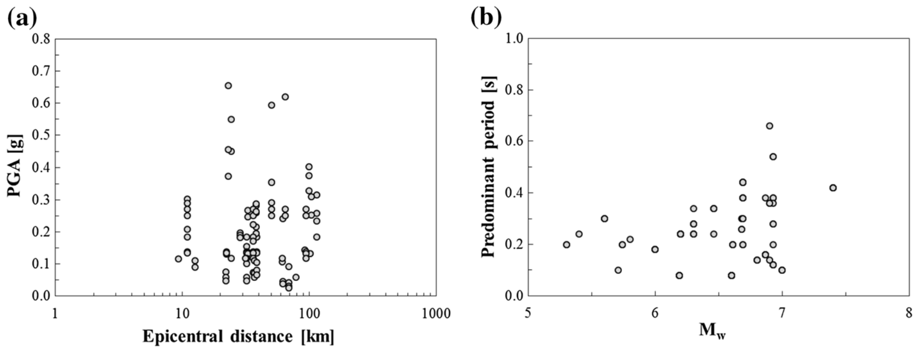


Fig. 7 Data coverage of the 98 ground motions recorded at outcropping rock (reference condition), in terms of: **a** Peak Ground Acceleration (PGA) versus Epicentral distance and **b** predominant period (period at which the maximum spectral acceleration occurs in an acceleration response spectrum with $\xi = 5\%$) versus Moment magnitude (M_w)

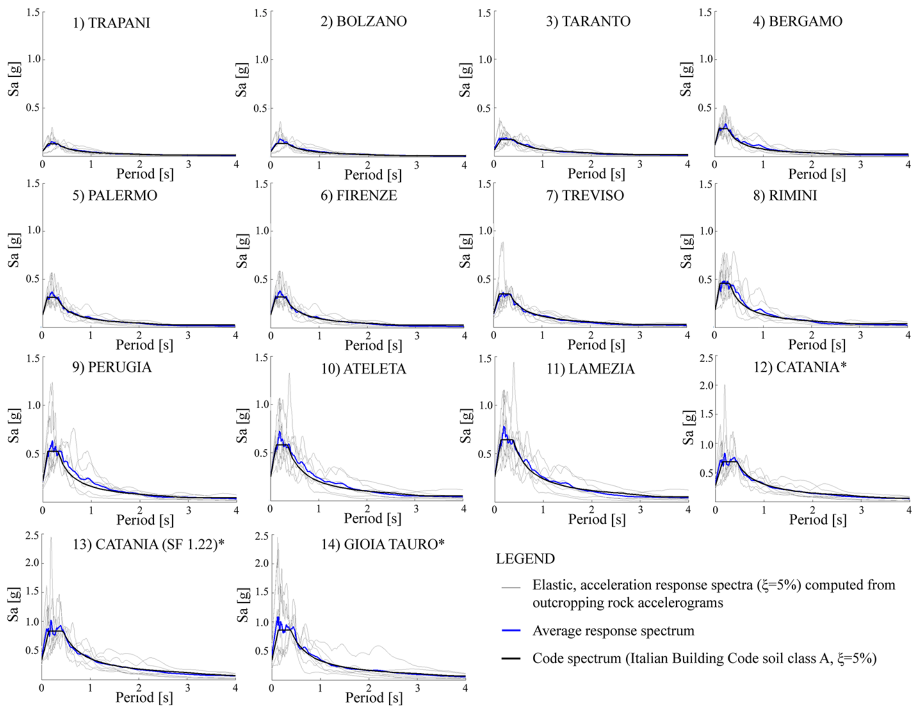


Fig. 8 Comparison between the code spectrum according to the Italian Building Code (NTC08 2008 and revision (NTC18 2018) for soil class A and the average acceleration response spectrum computed, at each reference site, from the suite of 7 seismic- and spectrum- compatible natural accelerograms

and predominant period (period at which the maximum spectral acceleration occurs in an acceleration response spectrum with $\xi = 5\%$) versus moment magnitude (M_w). Figure 8 shows a comparison between the code spectrum defined according to the prescriptions of the Italian Building Code (NTC08 2008 and revision NTC18 2018) for soil class A and the average acceleration response spectrum computed, for each reference site, from the suite of 7 seismic- and spectrum-compatible natural accelerograms.

4.2 Stochastic ground response analyses for the definition of the response spectra

A preliminary sensitivity analysis has helped us to optimize the number of soil profiles required to stabilize results of the numerical simulations. A total of 2000 soil profiles for each soil category (i.e. soil class B, C, D and E) having characteristics on average equal for the 14 reference sites were randomly generated according to the prescriptions of EC8 (CEN 2005) and Italian Building Code (NTC08 2008 and revision NTC18 2018). For each soil class, the stochastic procedure based on Monte Carlo simulations, randomly generated 2000 soil profiles compatible with the prescriptions of the building codes for the soil class under consideration (e.g. Andreotti et al. 2013; Zembaty et al. 2015). Subsequently, for each soil profile, a conventional, linear-equivalent viscoelastic analysis is carried out in the frequency domain using SHAKE91 (Idriss and Sun 1992), with a randomly selected (assuming a uniform distribution) spectrum-compatible real accelerogram. Finally, for each level of seismic intensity (i.e. for the 14 reference sites with increasing seismic hazard) the procedure computes the response spectrum at the free-surface of the soil deposit correspondent to a predefined percentile (e.g. 50th or 84th percentile).

Considering a single reference site, in other words a single PGA expected at outcropping bedrock, the methodology can be described by the following steps:

1. Generation of a Monte Carlo sample of 2000 soil models belonging to a specific soil class (e.g. B, C, D and E) to randomly simulate the variability of soil deposits;
2. For each of the 2000 soil models generated in the previous step, random realization of the shear modulus and damping variation with shear strain curve using the analytical formulation proposed by Darendeli (2001) with the parameters of the soil profile;
3. Random selection of input motions from the suite of 7 records (i.e. real earthquakes) on outcropping bedrock conditions to model the variability of the seismic demand;
4. For each of the 2000 soil profiles, a conventional viscoelastic, equivalent-linear analysis is carried out in the frequency domain using SHAKE91 (Idriss and Sun 1992). As described more in detail in the next sub-sections (Sects. 4.2.1, 4.2.2, 4.2.3), given the characteristics of one soil profile with the related G/G_{max} and D variation with shear strain curves, a conventional viscoelastic, equivalent-linear analysis is carried out with SHAKE91 using one input motion randomly selected from the suite of 7 records;
5. Computation of the representative elastic acceleration response spectrum at the free surface of the deposit (e.g. 50th or 84th percentile spectrum), for $\xi = 5\%$.

Excluding the preliminary sensitivity analysis, the total number of the analyses used for the definition of the soil factors is 112,000 (2000 analysis for each soil profile within the soil class under examination × 14 reference sites with increasing seismic hazard × 4 soil classes).

4.2.1 Definition of soil models

The variation of a parameter is commonly described with a coefficient of variation (CoV) because of the advantages of being dimensionless as well as providing a meaningful measure of the relative dispersion of the data around the sample mean. Some typical CoV values for soil properties were summarised by several authors (e.g. Alonso 1976; Phoon et al. 1995; Becker 1996; Alawneh et al. 2006). Although the log-normal distribution provides a better variability's model of soil parameters since they cannot assume negative values (e.g. Brejda et al. 2000; Fenton and Griffiths 2003), for CoV $\leq$ 30% the normal distribution can be used (e.g. Fenton and Griffiths 2008; Arnold et al. 2012), the use of the normal distribution to characterize the uncertainty of soil properties is widespread because it is easier to handle and it still provides reasonable results (e.g. Lumb 1970; Tobutt 1982; Duncan 2000; Baecher and Christian 2003; Fenton and Griffiths 2008; Arnold et al. 2012). For this reason the normal distribution has been adopted in the stochastic approach presented in this study. To avoid negative values of soil parameters including the thickness of soil layers, a truncated normal distribution was used (e.g. Duncan 2000; DNV 2012; Wu 2013). It is worth noting that an algorithm for the detection of negative values of soil parameters has been implemented in the stochastic procedure in order to avoid unrealistic outcomes.

Each soil profile consists of a discrete set of horizontal layers whose properties vary according to a random realization. Considering the descriptions of soil classes given in Eurocode 8 (CEN 2005) and Italian Building Code (NTC08 2008) (Table 2) for soil classes B, C and D, the depth of bedrock has been set to vary between 30 and 100 m. All soil profiles have been generated using the Monte Carlo method starting from the definition of 8 horizontal macro-layers where the thickness h_{ij} (where i indicates the number of the layer inside a subsoil model j) of the first six layer has been forced to vary according to a truncated normal distribution (e.g. Duncan 2000; DNV 2012; Wu 2013) with mean 5 m and coefficient of variation (CoV) 40%. The mean thickness of the 7th layer has been set to 10 m with CoV = 20% while for the 8th layer the thickness has been considered to vary according to a uniform distribution with a minimum and maximum values set to 1 and 50 m respectively.

Soil profiles of class E were defined with a depth to a bedrock fixed at 20 m. The realizations of soil profiles for this class follow the same rule of the other classes however, in this case, only the first 4 layers were considered with a truncation of thickness at 20 m depth.

For each soil category, the procedure generates a minimum of one and a maximum of two layers of cohesive soils with the total maximum thickness lower than 8 m. Each layer is subsequently subdivided in sub-layers with thicknesses varying between 1.5 and 2.5 m. Special attention was given to make sure that the minimum thickness of soil layers was compatible with the frequency content of the input motion.

Once the geometry of a single soil profile was generated, the other geotechnical parameters were randomly generated using normal distributions with the following means and coefficients of variation: unit volume (mean value = 19.5 kN/m^3 and CoV = 5%), plasticity index (mean value = 30% and CoV = 20% for cohesive layers, zero for non-cohesive layers).

4.2.2 Definition of shear wave velocity profiles

The definition of the shear wave velocity profiles follows a different approach. It is worth noting that the issue related to the soil classification of the current standards (e.g. EC8 and Italian Building Code) is not addressed in this paper. As already mentioned, the main goal of the present study is to critically scrutinize the validity of the soil factors. This is performed following a methodology that aims to be technically objective and repeatable. Bearing in mind these objectives, the variability of the shear wave velocity profile is constrained to the definition of the soil categories enforced by the aforementioned building codes. More specifically, the variability of the shear wave profile is linked to $V_{S,30}$ intervals and the depth of the bedrock's roof specified by the standards for each soil category. Considering that the soil categories addresses the seismic action at a national and continental scales, soil classification reflects both intra-site variability (i.e. variability at a specific site) as well as inter-site variability (i.e. variability between soil profiles at different sites). Therefore, the population of shear wave velocity profiles has been generated by accounting for both intra-site and inter-site uncertainty (see Fig. 9).

The shear wave velocity profiles were generated for each subsoil model *j* following two different models of variation of V_S with depth:

(1) *parabolic profile* (Santamarina et al. 2001; Corigliano et al. 2012):

$$V_S(z) = V_{So,1} \cdot \sigma_{vo}^{p} \tag{14}$$

where $V_{So,1}$ is the shear wave velocity at the free surface and σ_{vo} is the total vertical overburden stress (assuming a constant value of the soil unit weight) and *p* is a model parameter (see Fig. 9). Parameters $V_{So,1}$ and *p* were considered uncorrelated, random variables, sampled from a uniform distribution. In particular $V_{So,1}$ was assumed to vary between 0.5÷1 times the minimum value of $V_{S,30}$ of soil class under consideration, whereas *p* was assumed to vary within the interval 0.1÷0.3.

(2) *hyperbolic profile* (see Fig. 9) according to Gibson 2nd kind model (Gibson 1967; Awojobi 1975):

$$V_S(z) = V_{So,2} \cdot \sqrt{\frac{H^*}{H^* - z}} \tag{15}$$

where $V_{So,2}$ and H^* were assumed as uncorrelated random variables of the model sampled from a uniform distribution; $V_{So,2}$, which represents the shear wave velocity at the ground surface, is assumed to vary between half the minimum value of $V_{S,30}$ of the soil class under consideration and the value of V_S of the seismic bedrock at depth *H*. H^* is introduced to increase the variability of the soil model and represents the value of *H* scaled by the parameter *k*, which has been assumed to vary between 1 and 2.

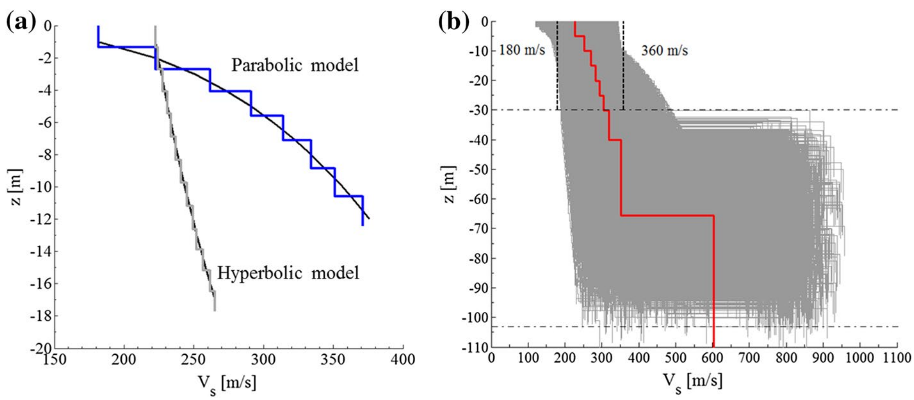


Fig. 9 Random generation of shear wave velocity profiles. **a** Plot of the two different laws of variation of V_S with depth; **b** 2000 randomly generated *Vs* profiles using the two models for soil class B (EC8 and Italian Building Code). The red line represents the average profile

At each run of the analyses, one model of variation of V_S with depth is randomly selected assuming equal probability of being sampled (uniform distribution). If the random combination of the parameter generates a shear velocity profile with a value of $V_{S,30}$ outside the interval of the soil class under consideration, this profile is disregarded and a new one is generated with the same model, however with different model parameters. This operation is performed until the value of $V_{S,30}$ falls within the boundaries of a given soil class. The V_S values are then assigned to each sub-layer of the soil model every 1.5–2.5 m. The V_S value of seismic bedrock is randomly assigned to each lithostratigraphic model according to two different scenarios with the same probability of being sampled. In the first scenario, a V_S value is sampled from a normal distribution with mean $V_S = 800$ m/s and coefficient of variation CoV = 6.5% to simulate the impedance of a bedrock half-space. In the second scenario, a V_S value was assigned considering the seismic bedrock as a natural continuation of the deposit using the same law of variation of V_S adopted for the soil model. This approach has been adopted in order to account for possible occurrence of very deep soil deposits with seismic bedrock located at hundreds of meters below the ground surface. The second option has been adopted also to avoid unrealistic impedance contrasts that may generate unrealistic strong nonlinearities, especially in soft soils.

4.2.3 Definition of shear modulus and damping ratio variation with shear strain

The viscoelastic, equivalent-linear constitutive model implemented in SHAKE91 (Idriss and Sun 1992) allows approximating the soil nonlinear dynamic response by using strain-compatible values of shear modulus (G) and material damping ratio (D) from shear modulus and damping ratio curves. From the parameters of the soil profile, the procedure randomly generated G/G_{max} and D variation with shear strain curves for each layer (*i*) within each subsoil model (*j*) according to the empirical formulation by Darendeli (2001) and following the randomization approach described in Kottke and Rathje (2009).

The value of mean confining pressure (p') at the mean depth of each layer *i* of a subsoil *j* is computed from the geometric and geotechnical properties of each soil profile, by setting the coefficient of earth pressure at rest equal to 0.5.

For each layer, mean G/G_{max} and D variation with shear strain curves are computed with the associated standard deviations (σ_G and σ_D) using the empirical equations proposed by Darendeli (2001) with the mean confining pressure calculated at the mean depth of the layer and the plasticity index previously defined. All the other parameters were introduced as constant parameters (OCR = 1; 10 cycles and frequency of excitation equal to 1 Hz).

As shown in Fig. 10, for each layer (*i*) of each subsoil model (*j*), the procedure randomly generated the G/G_{max} and D variation with shear strain curves to be used as input in the analysis from the mean value and the associated standard deviation (Kottke and Rathje 2009).

4.2.4 Special considerations for the definition of soil factors for class D

The dynamic response of a soil deposit is better represented by a truly nonlinear formulation rather than by an equivalent-linear model (e.g. Kaklamanos et al. 2013, 2015, Andreotti and Lai 2017). This can be considered as a first-order approximation, especially in case of severe ground shaking. The simplicity and the low computational burden of the equivalent-linear method fit well with the requirements of the stochastic approach that is characterized by several thousands of automatically repeated ground

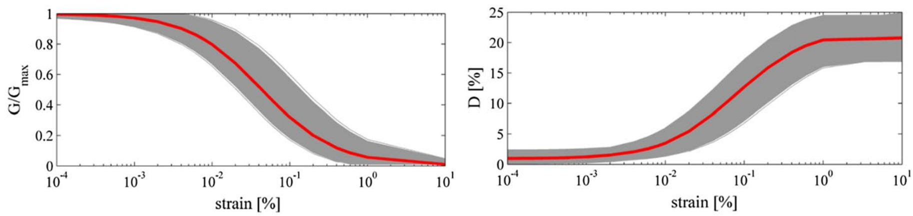


Fig. 10 Example of 2000 random realizations of shear modulus (G/G_{max}) and damping ratio (D) variation with shear strain curves for a layer *i*, within the subsoil models defined for a soil class (e.g. B, C, D or E). The red line represents the mean curve

response analyses. Nevertheless, one important issue of the equivalent-linear method is the underestimation of acceleration in case of deep deposits constituted by soft soils (Kausel and Assimaki 2002; Yoshida et al. 2002). The mechanism of this underestimation is rather clear. It comes from the fact that the equivalent-linear approach uses constant values of shear modulus and damping ratio for the entire spectrum of frequencies. This means that larger damping ratios and smaller shear moduli (which may result from large effective shear strains typically occurring at low frequencies) are used even at high frequencies where the amplitude of shear strain is generally smaller than at low frequencies. The usage of inconsistent values of shear modulus and overdamping at high frequencies brings to the underestimation of ground acceleration. This is particularly evident in deep deposits composed by soft soils where the fundamental frequencies are significantly lower than in other soil profiles.

A workable solution to this problem is to introduce frequency-dependent shear modulus and damping ratio as proposed by Yoshida et al. (2002) and Kausel and Assimaki (2002). Another option, as suggested by Yoshida et al. (2002), is to reduce the value of the parameter "α" that controls the definition of effective strain ($\gamma_{eff} = \alpha \cdot \gamma_{max}$ where γ_{eff} is the effective shear strain and γ_{max} is the maximum shear strain). The range of variation of α proposed by Yoshida et al. (2002) is between 0.2 and 1, however, in the engineering practice, a constant value of $\alpha = 0.65$ is usually adopted without much consideration of earthquake characteristics, contrary to the suggestion by Idriss and Sun (1992) who related the value of α to the magnitude ($\alpha = 0.1 \cdot [M-1]$).

To estimate the severity of the problem in relation to the purposes of the present study, we performed a series of comparisons between equivalent-linear and nonlinear analyses by considering several randomly generated subsoil models belonging to different soil categories. In most cases, the underestimation of acceleration occurs in soil profiles belonging to class D (EC8 and Italian Building Code) whereas for other soil categories this issue seemed to be less important. To overcome the problem, for soil class D it was decided to decrease the coefficient "α". Furthermore, exclusively for this soil class, we made the conservative choice of assuming the lower boundary of the coefficient "α" to be equal to 0.2. This actually means that for soil category D, the equivalent-linear analysis approaches a linear analysis because the strain-compatible shear modulus and damping ratio are defined for an effective strain corresponding to a 80% reduction of the maximum shear strain. This choice is obviously conservative with regard to the objectives of the study because for soil class D the PGA is now most likely overestimated. For all other soil classes, coefficient α has been defined according to the relation suggested by Idriss and Sun (1992): $\alpha = 0.1 \cdot [M-1]$, where M is the magnitude.

5 Results

Figure 11 shows the comparison between the free surface response spectra computed from the stochastic site response analysis carried out for all the reference sites and the code spectra provided by the current version of Eurocode 8 (CEN 2005) and Italian Building Code (NTC08 2008 and revision NTC18 2018).

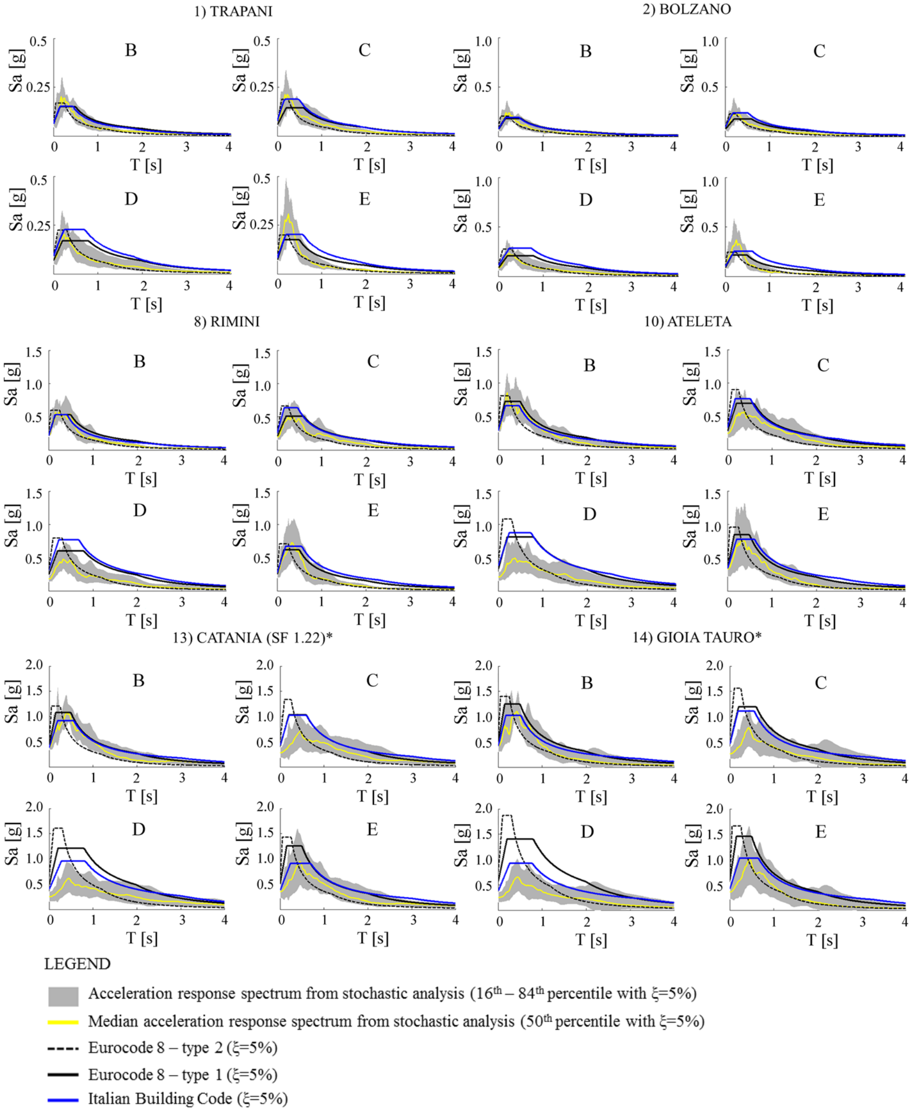


Fig. 11 Comparison between the free surface response spectra computed from the stochastic ground response analyses and the code spectra specified by Eurocode 8 (CEN 2005) and Italian Building Code (NTC08 2008 and revision NTC18 2018) for the same soil category

By focusing the attention on soil classes B and E, it is noted that both building codes underestimate the numerical spectral ordinates corresponding to the 84th percentile, with a general tendency to underrate also the spectral accelerations referred to the 50th percentile (e.g. sites with relatively low seismic hazard). With regard to soil class C, the response spectra of the Italian Building Code (NTC08 2008 and revision NTC18 2018) are consistent with the spectra corresponding to the 84th percentile whereas this is not the case for the spectra specified by Eurocode 8. Finally, the response spectra of both building codes for soil class D tend to overestimate the spectral accelerations (e.g. sites with relatively high seismic hazard). It is reminded here that this is not necessarily due to a shortcoming of the equivalent-linear method because, after having assumed $\alpha = 0.2$ for soil class D, the stochastic analysis has the tendency to overestimate the spectral ordinates.

Figure 12 shows the results of the curve-fitting technique using the same symbols of Fig. 4 where the methodology was schematically reproduced and discussed. In this figure it is possible to check graphically the goodness of fit of the analysis and compare the results with reference to the response spectra for soil class A prescribed by Eurocode 8 (CEN 2005) and Italian Building Code (NTC08 2008 and revision NTC18 2018).

In Fig. 13 is reported the variation of the amplification function $A(f)$, which is defined as the modulus of the transfer function, with the variation of the PGA at outcropping rock, for one soil class. This figure shows the 84th percentile amplification functions of several reference sites with an increasing level of seismic hazard. In the conventional, equivalent-linear analysis (e.g. SHAKE analysis), the strain-compatible values of shear modulus (G) and damping ratio (D) used in each analysis come from an iterative process based on the concept of effective shear strain (γ_{eff}). Since the demand of shear strain depends on the level of PGA of the input motion at the outcropping bedrock, it is worth noting that also the values of strain-compatible shear modulus (G) and damping ratio (D) used in the site response analysis depend on the PGA. This phenomenon makes the amplification function dependent on the PGA expected at outcropping bedrock. The most tangible consequence of this event is that the ordinates of the amplification function at high frequencies, which are more sensitive to the value of the damping ratio than those at low frequencies, tend to decrease rapidly with the increase of the PGA of the input motion. This phenomenon occurs because the shear strain demand increases with the increase of the severity of the input and the value of the strain-compatible damping ratio used in the analysis is higher.

The results of the next step of the procedure are reported in Fig. 14 where the values of soil factor S_S and the newly proposed empirical relationships for Italian Building Code are shown. To be consistent with the current version of the code, the relationship has been established between soil factor S_S and the peak ground acceleration at outcropping bedrock conditions (a_g) multiplied by the hazard parameter F_o that in the Italian Building Code depends on the geographical position (i.e. seismic hazard). Figure 15 shows the same results recomputed for the updating of soil factor S of Eurocode 8, where the newly proposed hazard-dependent empirical relationships link the soil factor S to the peak ground acceleration at outcropping rock (a_g). Excluding soil class D and with reference to the 84th percentile, from Figs. 14 and 15 it can be noted how Eurocode 8 and Italian Building Code tend to underestimate the value of soil factor S and S_S.

The newly proposed empirical equations between soil factors and peak ground acceleration (PGA or a_g) at the outcropping bedrock conditions (Figs. 14, 15) have a clear physical meaning. For low levels of seismic intensity, the response of the soil deposit is essentially elastic and the ground amplification is higher for soft soils than for stiff soils because this effect is controlled by the impedance contrast. With the increase of the hazard intensity, the nonlinear behaviour is more pronounced in soft rather than in stiff soils. This is expressed

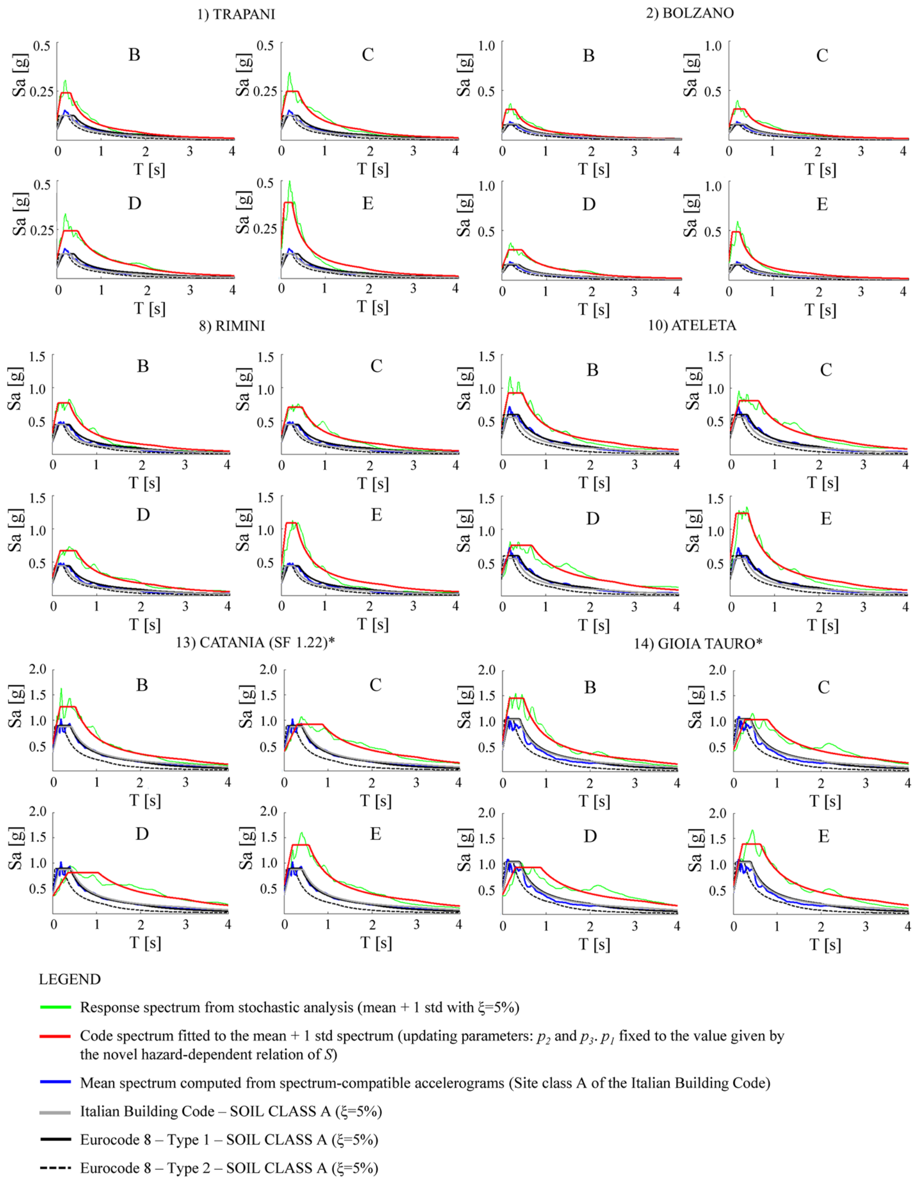


Fig. 12 Results from the implementation of the curve-fitting technique. Comparison between the code spectra fitted to the 84th percentile spectrum obtained from stochastic ground response analyses and the reference spectrum (soil class A) for different soil classes and six representative reference sites with increasing seismic hazard

through larger slopes in the empirical relation for soft soils compared to stiff soils (i.e. soft soils have lower values of soil factor S and S_S for high seismic intensities).

As can be seen from Fig. 14, with regard to soil classes B, C and D, for low values of PGA the proposed empirical relations between the soil factor S or S_S and the PGA expected

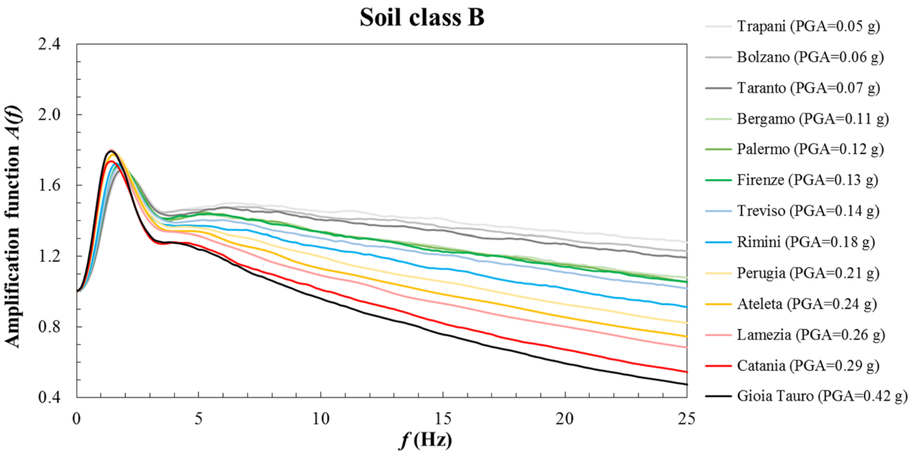


Fig. 13 Variation of the amplification function A(f) with the increase of PGA of the input ground motions for the soil class B. 84th percentile amplification functions of several reference sites with increasing level of seismic hazard

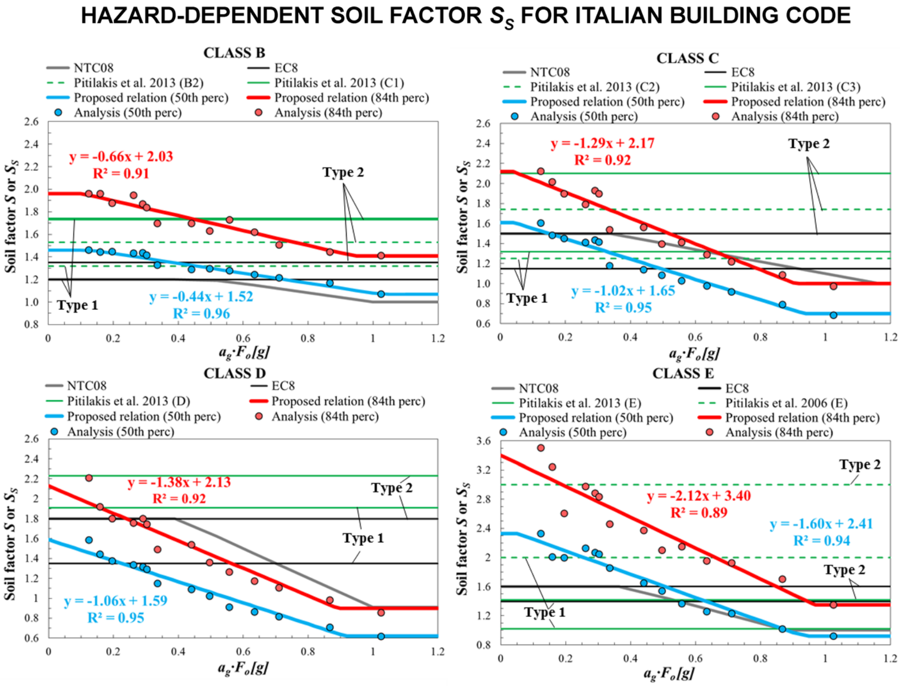


Fig. 14 Empirical relations between stratigraphic soil factor S or S_S (for flat topographic surfaces $S_T = 1$ hence, $S = S_S$ in the Italian Building Code) and the peak ground acceleration expected at the outcropping bedrock, multiplied by the hazard parameter F_o (2.5 in Eurocode 8 and equal on average to 2.5 in the Italian Building Code). The S values by Pitilakis et al. (2013) are the suggested value of the weighted average (Tables 7 and 8 in Pitilakis et al. 2013)

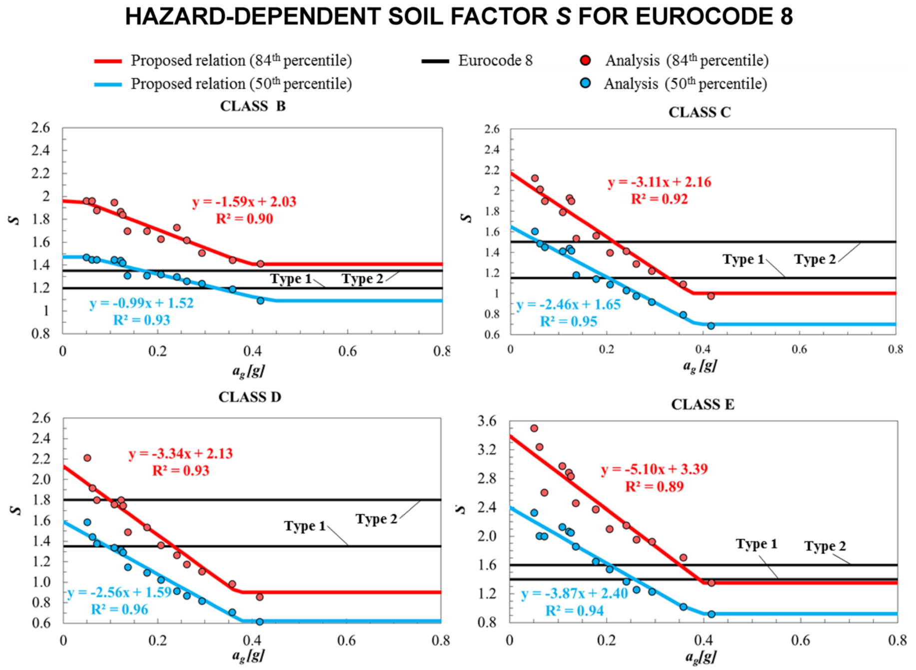


Fig. 15 Newly proposed empirical relations between soil factor S (Eurocode 8) and peak ground acceleration expected at the outcropping bedrock

at the outcropping bedrock seem to be consistent with the findings of the recent study by Pitilakis et al. (2013) who focused on Eurocode 8 and only used natural accelerograms ("*empirical approach*"). For soil class E (see Fig. 14), the maximum values of the soil factors obtained from our study are distinctly larger with respect to the work by Pitilakis et al. (2013) nevertheless, they are comparable with the work by Pitilakis et al. (2006) where the approach was numerical (Fig. 14). It is worth noting that, in the study by Pitilakis et al. (2013) the S values computed for the soil class E have not been proposed for EC8, due to the relatively small dataset. Figure 16 shows the empirical relations between soil factor C_C, which controls the corner period of the spectrum (T_C), and peak ground acceleration at outcropping rock. This relation reflects the effects of frequency content of input ground motions and the filtering effect of the soil deposit. Also in this case, a physical meaning can be attributed to the empirical relations because the increasing value of C_C with a_g can be explained with the fact that high values of PGA tend to be generated by strong ground motions that have a tendency to excite high periods because they typically show higher energy at low frequency. In addition, soft soils have lower fundamental frequencies than stiff soils with the resulting effect to lengthen the plateau of the code spectrum towards longer structural periods. The empirical relationships between C_C and a_g show a correlation coefficient which is considered acceptable by the authors whereas a lower correlation was found between the coefficient C_C and the of site-specific, seismic hazard parameter T_C^*.

Finally, in Fig. 17 we show the comparison between the empirical relations that come from the stochastic analysis according to the soil classification given in the previous version of the Italian Building Code (NTC08 2008) and those obtained by repeating the

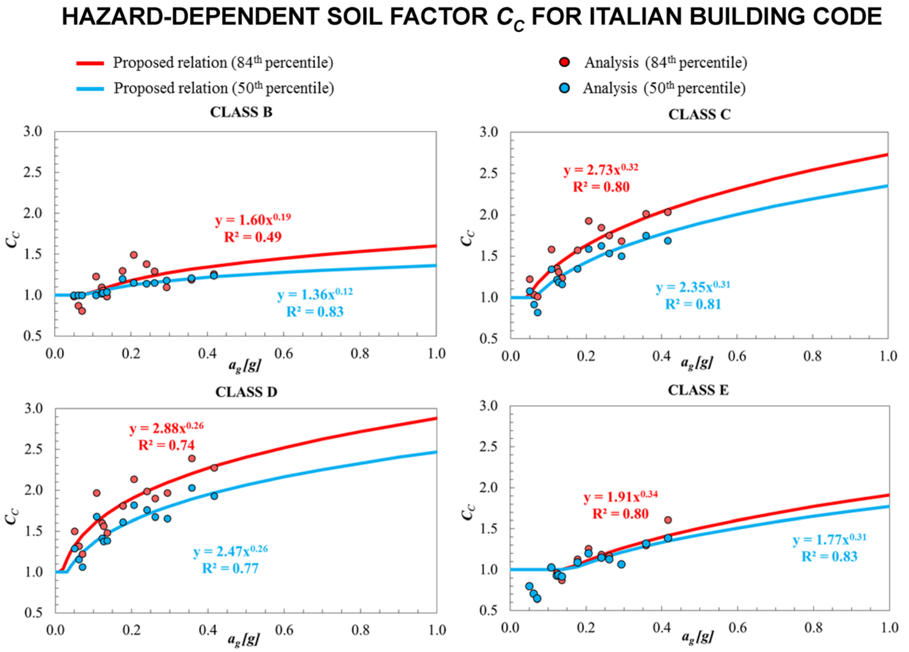


Fig. 16 Empirical relations between soil factor C_C and the peak ground acceleration expected at the outcropping bedrock

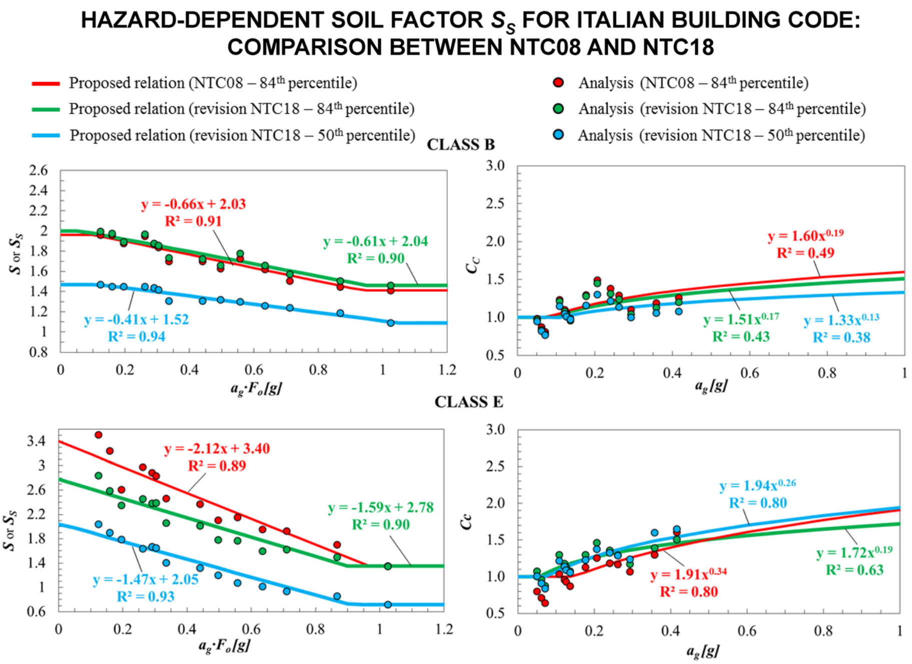


Fig. 17 Comparison between the empirical relations obtained according to the soil classification provided by the old version of the Italian Building Code (NTC08 2008) and the revision of the same technical norm (NTC18 2018)

Table 3 Newly proposed empirical relations between soil factors S_S and C_C and site-specific hazard parameters (a_g in g, F_o and T_C^*) correspondent to the 84th percentile response spectra

Soil class	S_S	$T_B = T_C/3$ C_C	$T_C = C_C \cdot T_C^*$	$T_D = 4 \cdot a_g/g + 1.6$
Italian building code (NTC08 2008) 84th percentile				
A	1	1		
B	$1.41 \le 2.03–0.66 \cdot F_o \cdot a_g \le 1.96$	$1.00 \le 1.60 \cdot (a_g)^{0.19}$		
C	$1.00 \le 2.17–1.29 \cdot F_o \cdot a_g \le 2.12$	$1.00 \le 2.73 \cdot (a_g)^{0.32}$		
D	$0.90 \le 2.13–1.38 \cdot F_o \cdot a_g \le 2.13$	$1.00 \le 2.88 \cdot (a_g)^{0.26}$		
E	$1.35 \le 3.40–2.12 \cdot F_o \cdot a_g \le 3.50$	$1.00 \le 1.91 \cdot (a_g)^{0.34}$		

Table 4 Newly proposed empirical relations between soil factors S_S and C_C and site-specific hazard parameters (a_g in g, F_o and T_C^*) correspondent to the 84th percentile response spectra (percentile suggested by the authors)

Soil class	S_S	$T_B = T_C/3$ C_C	$T_C = C_C \cdot T_C^*$	$T_D = 4 \cdot a_g/g + 1.6$
Revision of Italian building code (NTC18 2018) 84th percentile				
A	1	1		
B	$1.46 \le 2.04–0.61 \cdot F_o \cdot a_g \le 2.00$	$1.00 \le 1.51 \cdot (a_g)^{0.17}$		
C	$1.00 \le 2.17–1.29 \cdot F_o \cdot a_g \le 2.12$	$1.00 \le 2.73 \cdot (a_g)^{0.32}$		
D	$0.90 \le 2.13–1.38 \cdot F_o \cdot a_g \le 2.13$	$1.00 \le 2.88 \cdot (a_g)^{0.26}$		
E	$1.35 \le 2.78–1.59 \cdot F_o \cdot a_g \le 2.78$	$1.00 \le 1.72 \cdot (a_g)^{0.19}$		

procedure after considering the prescriptions given in the revision of the Italian Building Code (NTC18 2018) where soil class B and D are different. The only noticeable effect is in soil class E, where the new classification leads to a decrease of the soil factor $S_{S.}$

6 Newly proposed hazard-dependent soil factors

6.1 Italian Building Code (NTC08 2008)

Table 3 summarizes the newly proposed empirical relationships between soil factor S_S and C_C with the site-specific hazard parameters: a_g (peak ground acceleration expected in soil class A with flat topographic surface) and F_o (ratio between the maximum value of the horizontal acceleration response spectrum and a_g). The analytical expressions of S_S and C_C were obtained, respectively, from data reported in Figs. 14 and 16.

6.2 Revision of the Italian building code (NTC18 2018)

Whereas the prescriptions of soil classes B and E in the revision of the Italian Building Code (NTC18 2018) are different from the previous version of the Italian Building Code (NTC08 2008), the prescribed soil factors parameters are the same. In Tables 4 and 5 we report the suggested parameters of hazard-dependent empirical relationships for the

Table 5 Newly proposed empirical relations between soil factors S_S and C_C and site-specific hazard parameters (a_g in g, F_o and T_C^*) correspondent to the 50th percentile response spectra

Soil class	S_S	$T_B = T_C/3$ C_C	$T_C = C_C \cdot T_C^*$	$T_D = 4 \cdot a_g/g + 1.6$
Revision of Italian building code (NTC18 2018) 50th percentile				
A	1	1		
B	$1.09 \le 1.52–0.41 \cdot F_o \cdot a_g \le 1.47$	$1.00 \le 1.33 \cdot (a_g)^{0.13}$		
C	$0.68 \le 1.65–1.02 \cdot F_o \cdot a_g \le 1.61$	$1.00 \le 2.35 \cdot (a_g)^{0.31}$		
D	$0.62 \le 1.59–1.06 \cdot F_o \cdot a_g \le 1.59$	$1.00 \le 2.47 \cdot (a_g)^{0.26}$		
E	$0.72 \le 2.05–1.47 \cdot F_o \cdot a_g \le 2.05$	$1.00 \le 1.94 \cdot (a_g)^{0.26}$		

definition of soil factor S_S and C_C according to soil classification of the revision of the Italian Building Code (NTC18 2018). The analytical expression of S_S and C_C were obtained from the data shown in Figs. 14 and 17.

6.3 Proposal of hazard-dependent soil factor *S* for Eurocode 8 (CEN 2005)

The key factor of this study in relation to Eurocode 8 (CEN 2005) is the definition of hazard-dependent empirical relations between soil amplification factor (*S*) and peak ground acceleration (a_g) expected at outcropping bedrock with flat topological surface (i.e. soil class A), taking into account the level of soil nonlinearity. In this regard, even if the sites selected in this study belong in the Italian territory, the empirical relations proposed herein are valid for the whole European territory given that the adopted soil profiles were consistent with the soil classes of EC8 and the input accelerograms were selected among worldwide seismic events. Indeed, the most important concern at the beginning of the study was to well-constrain the empirical relations with the selection of an adequate range of seismic intensities (i.e. PGA of ground motions recorded at outcropping bedrock). We want to emphasize the fact that the use of ground motions with larger PGA with respect to those defined in the present study could only be useful for a better definition of the minimum value of *S*, which in most soil categories is already close to 1. However, since most of ground motions used in the analyses correspond to earthquakes with magnitude larger than 5.5, the results can be considered valid only for Type 1 EC8 spectrum.

Tables 6 and 7 defines the newly proposed empirical relationships between soil factor *S* and peak ground acceleration (a_g) expected at outcropping bedrock with flat topological surface (soil class A). No change was made to the values of T_B, T_C and T_D.

6.4 Comparison between newly proposed soil factors and stochastic ground response analyses

Figure 18 shows the comparison between the code spectra defined with the newly proposed parameters (i.e. Tables 4, 6) and the 84th percentile spectrum obtained from the stochastic ground response analyses.

It can be noted that the newly proposed code spectra for EC8 and Italian Building Code fit the shape of the numerical 84th percentile spectra better than those prescribed by current building codes (Fig. 11). The maximum misfit of the proposed spectra with respect to

Table 6 Newly proposed empirical relations between soil factor S and peak ground acceleration at outcropping bedrock (a_g in g) for Type 1 EC8 response spectrum correspondent to the 84th percentile response spectra (percentile suggested by the authors)

Soil class	S	Type 1 ($M_S > 5.5$)		
		T_B (s)	T_C (s)	T_D (s)
EUROCODE 8 (European Committee for Standardization (CEN) 2005) 84th percentile				
A	1	0.15	0.40	2.00
B	$1.41 \le 2.03–1.59 \cdot a_g \le 1.96$	0.15	0.50	2.00
C	$1.00 \le 2.16–3.11 \cdot a_g \le 2.12$	0.20	0.60	2.00
D	$0.90 \le 2.13–3.34 \cdot a_g \le 2.13$	0.20	0.80	2.00
E	$1.35 \le 3.39–5.10 \cdot a_g \le 3.50$	0.15	0.50	2.00

Table 7 Newly proposed empirical relations between soil factor S and peak ground acceleration at outcropping bedrock (a_g in g) for Type 1 EC8 response spectrum correspondent to the 50th percentile response spectra

Soil class	S	Type 1 ($M_S > 5.5$)		
		T_B (s)	T_C (s)	T_D (s)
EUROCODE 8 (European Committee for Standardization (CEN) 2005) 50th percentile				
A	1	0.15	0.40	2.00
B	$1.09 \le 1.52–0.99 \cdot a_g \le 1.47$	0.15	0.50	2.00
C	$0.68 \le 1.65–2.46 \cdot a_g \le 1.61$	0.20	0.60	2.00
D	$0.62 \le 1.59–2.56 \cdot a_g \le 1.59$	0.20	0.80	2.00
E	$0.92 \le 2.40–3.87 \cdot a_g \le 2.40$	0.15	0.50	2.00

those obtained from the numerical simulations occurs along the flat part of the spectrum which is intrinsically related to the shape of the code spectrum.

Most differences between the newly proposed spectral shapes for the Italian and EC8 building codes come from using a different approach for the definition of F_o, T_B, T_C and T_D. These parameters are site-specific in the Italian building code and constant values in EC8. These differences are negligible for large values of seismic intensity.

7 Conclusions

This article describes a methodology to derive hazard-dependent soil factors that are widely used within the simplified method of most building codes worldwide, for the definition of site-specific response spectra.

One of the major objectives of the study was the definition of empirical relationships, for different soil classes, between soil factors and level of seismic intensity expected at the outcropping bedrock with flat topological surface (i.e. reference conditions). These relationships have been established between the value of soil factor and peak ground acceleration expected at outcropping bedrock (PGA or a_g). The methodology was applied to define updated soil factors: S in Eurocode 8 (CEN 2005) and S_S and C_C in Italian Building Code (NTC08 2008 and revision NTC18 2018).

An inversely proportional relationship was found between soil factors S and S_S, and peak ground acceleration at outcropping bedrock as consequence of the increased level of

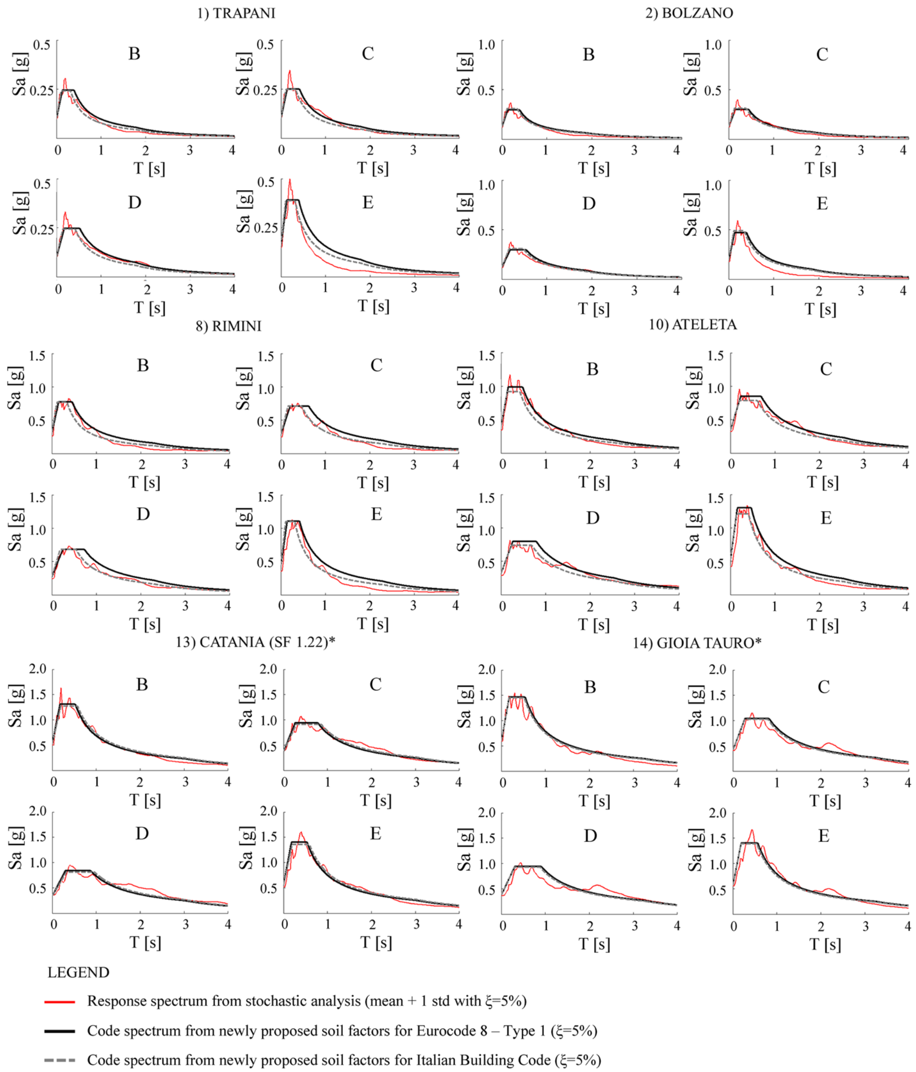


Fig. 18 Comparison between the code spectra defined with the newly proposed soil factors (84th percentile) and the 84th percentile spectrum obtained from the stochastic ground response analysis, for six representative reference sites with increasing seismic hazard

soil nonlinearity. The slope of the relation, which is an indicator of the level of nonlinearity mobilized within a given soil class, is larger for soft rather than for stiff soils. This means that for high level of PGA, soft soils exhibit lower amplifications than stiff soils do. On the other hand, for low values of PGA, corresponding to the case when soil nonlinearity is virtually vanishing, the amplification is higher in soft soils.

Two series of soil factors that correspond to different percentiles of the response spectrum at the free surface of the deposit have been defined (i.e. 50th and 84th percentile). Considering that the simplified method used in building codes is applied at a national or even continental scale and thus it is extensively used in practice, this method should ensure conservative results. The 84th percentile is considered by the authors as a conservative reference. Furthermore, the results corresponding to this percentile are consistent with the work carried out by Pitilakis et al. (2006, 2013). Should a higher level of accuracy be desired, the designer must perform a detailed site-specific ground response analysis.

Results from this study highlight the fact that Eurocode 8 (CEN 2005) and Italian Building Code (NTC08 2008 and revision NTC18 2018) for some soil classes tend to underestimate the value of soil factors S and S_S whereas they overestimate the amplification for other soil categories. More specifically, for soil classes B, C and E the current Italian and European building codes distinctly underestimate ground amplification whereas for soil class D there is a tendency to overestimate the soil factors as also reported by Peruš and Fajfar (2014).

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