The paper was published in the proceedings of the 7th International Conference on Earthquake Geotechnical Engineering and was edited by Francesco Silvestri, Nicola Moraci and Susanna Antonielli. The conference was held in Rome, Italy, 17 – 20 June 2019.

Earthquake Geotechnical Engineering for Protection and Development of Environment and Constructions – Silvestri & Moraci (Eds)
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Towards the revision of EC8: Proposal for an alternative site classification scheme and associated design response spectra, considering complex subsurface geometry

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ABSTRACT: The paper presents an alternative site classification scheme and associated design response spectra, aiming to contribute to the ongoing revision of Eurocode 8 (EC8). The new classification scheme introduces the approximate depth to seismic bedrock, H_B, and the fundamental period, T_0, as classification parameters for the estimation of seismic actions in addition to $V_{s,30}$. The main features of the new seismic design actions are summarized in the use of two anchoring spectral values, for short and intermediate periods, instead of only one of the present version of Eurocode 8 (i.e. PGA), and the scalar intensity variation of site amplification factors to account for soil nonlinearity. A first attempt towards the introduction of basin effects in the definition of EC8 elastic response spectra is made through the proposal of an "aggravation factor", which expresses the additional effect of the 2D response of the basin above the corresponding 1D response of the isolated soil columns, which is supposed to be accounted for in building codes.

1 INTRODUCTION

Eurocode 8-Part 1 (CEN, 2004) accounts for site effects through the suggestion of appropriate site-dependent elastic design spectra based on different soil classes. The main adopted parameter for site classification in the current version of Eurocode 8 (EC8) is $V_{s,30}$, i.e. the average shear wave velocity of the upper 30m of the soil profile, calculated from the total time needed for a shear wave to travel these 30m. $V_{s,30}$ is used along with NSPT blow count, plasticity index PI and undrained shear strength S_u to define five soil types (A to E), while two extra special ground types (S1 and S2) are also proposed for special soils (i.e. liquefaction prone sites etc). The seismic hazard parameter used in the current version of EC8 to define the elastic response spectra is the effective ground acceleration at rock site conditions (V_s>800m/s), a_g, amplified by a soil amplification factor, S, which is dependent on the site class to account for local soil and site effects. Elastic response spectra are anchored to $S \cdot a_g$, and their shapes, defined by the corner periods T_B, T_C, T_D are controlled by the site classes.

To indirectly account for soil nonlinearity, EC8 proposes different elastic response spectra for two different levels of seismicity and seismic action, Type 1 and Type 2. Type 1 spectra have more energy in long-period motions and are proposed for use in regions having high seismic activity and stronger earthquakes (M_s>5.5), while Type 2 spectra are recommended for $M_s \leq 5.5$, having larger normalized spectral amplitudes at short periods.

The use of $V_{s,30}$ as a proxy to seismic amplification has been questioned by several recent works and more specifically for cases of deep, low damping stiff deposits lying on much harder rock (Dobry and Iai, 2000), for cases of a shallow velocity inversion (Di Giacomo et al., 2005), for sites with velocity profiles which are not monotonically increasing with depth or do not exhibit a strong impedance contrast in the first dozen meters (Mucciarelli and

Gallipoli, 2006) or in basin type structures like Adapazari basin in Turkey (Ozcep et al., 2011). It is therefore more and more being argued that $V_{s,30}$ is not in all cases and site conditions the most appropriate indicator of soil amplification, resulting in the suggestion of alternative or supplementary indicators, such as depth-to-basement (e.g. Steidl, 2000), average shear wave velocity over depths other than 30 m (e.g. 10-20 m) (e.g. Boore and Joyner 1997) or predominant site period/frequency (e.g. Cadet et al., 2012), as well as the proposal of alternative cite classification schemes (e.g. Zhao et al., 2016). Within this context, Pitilakis et al. (2013) proposed a new soil classification scheme appropriate for EC8, based on a comprehensive analysis of a worldwide database of strong ground motion records from sites which dispose a very well-documented soil profile (SHARE-AUTH database). The main parameters considered for site classification are the average shear wave velocity of the entire soil deposit, $V_{s,av}$, the approximate thickness of the soil deposit above the seismic bedrock, H_b and the fundamental period of soil deposit, T_0, together with appropriate descriptive parameters of the geotechnical conditions. Moreover, following the basic rationale of the current version of EC8, i.e. the use of Type 1 and Type 2 elastic response spectra anchored to effective ground acceleration, Pitilakis et al. (2013) proposed accompanying elastic response spectra for the soil classes of their soil classification scheme based on the conceptual assumption that the general spectral equations of the code should be higher than the median value and closer to the 84th percentile of the spectra of the strong-motion records of the SHARE-AUTH database, in order to account as much as possible for the uncertainties associated with the nature of the problem.

However, the most recent international seismic codes, as NEHRP 2015 (BSSC, 2015) in U.S.A., have moved to a more refined definition of elastic response spectra, where seismic hazard is introduced with two parameters, namely S_s (i.e. reference spectral acceleration at short periods) and S_1 (i.e. reference spectral acceleration at the vibration period T =1 s), instead of only one (effective ground acceleration) and nonlinearity in ground response is accounted for through a scalar variation of the site amplification factors F_a (for short periods) and F_v (for 1 s) for increasing seismic intensities. Reference national seismic hazard maps in U.S.A. have historically been produced for a site condition of $V_{s,30}$=760 m/s, a practice which is currently under debate.

In line with the current version of NEHRP, which is summarized in (i) the use of two anchoring spectral values instead of only one (effective ground acceleration) and (ii) the scalar intensity variation of site amplification factors to account for soil nonlinearity, the present study presents a proposal for a new classification scheme and amplification factors, which is an evolution of the recent work by Pitilakis et al. (2013), aiming to contribute to the ongoing revision of Eurocode 8.

2 PROPOSED SOIL CLASSIFICATION SCHEME

Largely inspired from the soil and site characterization scheme initially proposed by Pitilakis et al. (2013), the proposed classification scheme comprises six main soil classes, i.e. A, B, C, D, E and X, with sub-classes for site class B and C according to Table 1. The main classification parameters are the average shear wave velocity of the upper 30 m of the soil profile, $V_{s,30}$, the thickness of the soil deposit, i.e. approximate depth to “seismic” bedrock, H_b, and the fundamental period of soil deposit, T_0, along with the dominant soil profile description, average shear wave velocity of the entire soil deposit, $V_{s,av}$, and average values of standard penetration test blow count, N-SPT, plasticity index, PI and undrained shear strength, S_u. Depth of “seismic bedrock”, H_b, is generally defined as the depth below which V_s exceeds 800 m/s. In most cases this is quite difficult to accurately estimate and hence we are referring to “approximate” values. Moreover, for deep rather soft soil deposits, the horizon of an “equivalent” seismic bedrock may be defined with a lower V_s threshold, e.g. 600 m/s. Parameters derived from other field tests like the cone penetration test CPT or pressuremeter may be also used. To obtain T_0 and $V_{s,30}$ or $V_{s,av}$, invasive (in-hole measurements) or non-invasive (e.g. surface-waves analysis) techniques at small shear strains are suggested. In case of absence of direct measurement parameters, adequate correlations with SPT and CPT may be applied. Ranges of H_b, $V_{s,30}$, T_0 and $V_{s,av}$ for site classes of Table 1 were derived based on statistics from good

Table 1. Proposed site categorization

Site class	Description	H_B (m)	$V_{s,30}$ (m/s)	T_0 (s)	Remarks
A	- Rock formations - Slightly weathered/segmented rock formations with thickness of weathered layer <5.0 m - Geologic formations resembling rock formations in their mechanical properties and their composition (e.g. conglomerates)		≥ 800	≤ 0.2	For a surface weathered layer with H<5m: $V_{s,av}$ ≥ 300 m/s
B1	- Soft rock formations - Formations which resemble soft rock in their mechanical properties (e.g. stiff marls) - Very dense sands and gravels - Hard and very stiff clays	≤ 30	400-800	0.1 - 0.3	$V_{s,av}$: 400 - 800 m/s N-SPT > 50 S_u> 150 kPa
B2	Formations of very dense sands and gravels and/or very stiff to hard clay, whose mechanical properties increase with depth	30 - 60	350-500	0.3 - 0.6	$V_{s,av}$: 400 - 600 m/s N-SPT > 50 S_u> 150 kPa
C1	Formations of dense sand and gravels and/or stiff clays, of great thickness	> 60	350-500	0.6 - 1.0	$V_{s,av}$: 400 - 600 m/s N -SPT> 50 S_u > 150 kPa
C2	Formations of medium dense sand and gravels and/or medium stiffness clays (PI > 15, fines percentage > 30%) of intermediate thickness	30 - 60	250-400	0.3 - 1.0	$V_{s,av}$: 250 - 400 m/s N -SPT> 20 150 kPa> S_u>70 kPa
C3	Formations like C2 of great thickness	> 60	250-400	0.6 - 1.4	$V_{s,av}$: 300 - 400 m/s N -SPT> 20 150 kPa> S_u >70 kPa
D	Recent soil deposits of great overall thickness with prevailing formations being soft to medium thickness clays and/or loose sandy to sandy-silt formations with substantial fines percentage (not susceptible to liquefaction)	> 60	150-300	1.4 - 3.0	$V_{s,av}$: 200 - 400 m/s N-SPT < 20 S_u < 70 kPa The dominant soil formations may be interrupted by layers of very soft clays (Su<25 kPa, W>40%, PI>25) or sands and sandy clays of relatively small thickness (<10m)
E	Shallow soil formations of small thickness, small strength and stiffness, generally classified as category C and D according to its geotechnical properties, which overlie category A formations	< 20	not applied	≤ 0.5	$V_{s,av}$: 150- 300 m/s
X	Loose fine sandy-silty soils beneath the water table, susceptible to liquefaction (unless a special study proves no such danger, or if the soil's mechanical properties are improved) Soils near obvious tectonic faults Steep slopes covered with loose soil deposits Loose granular or sot silty-clayey soils, provided they have been proven to be hazardous in terms of dynamic compaction or loss of strength. Recent loose landfills Soils with a very high percentage in organic material Peat and/or highly organic clays (H>3m) and/or very high plasticity clays (H>8m) and/or very thick. soft/medium stiff clays (H>30m) Special soils requiring site-specific evaluations				

quality experimental data from the SHARE-AUTH database and when needed from theoretical analyses of representative models of realistic soil conditions (Pitilakis et al., 2004, 2006) applying classical statistics.

3 ELASTIC RESPONSE SPECTRA

In line with the present practice in modern international seismic codes, the seismic hazard is proposed to be described in terms of two parameters, namely S_{sRP} (i.e. the reference maximum spectral acceleration, corresponding to the constant acceleration branch of the horizontal 5% damped elastic response spectrum on site class A) and S_{1RP} (i.e. the reference spectral acceleration at the vibration period T = 1 s of the horizontal 5% damped elastic response spectrum on site class A) instead of only one, a_g (i.e. the effective ground acceleration on site class A). S_{sRP} and S_{1RP} should be provided in the National Annex of each European country for the reference return period T_{ref} (e.g. 475 years), depending also on the local seismic hazard. For the horizontal components of the seismic action, the elastic response spectrum Se(T) for 5% damping is defined by the following expressions:

$$0 \leq T \leq T_A : \ S_e(T) = \frac{S_S}{F_0} \tag{1}$$

$$T_A \leq T \leq T_B : S_e(T) = \frac{S_S}{T_B - T_A}\left[n \cdot (T - T_A) + \frac{T_B - T}{F_0}\right] \tag{2}$$

$$T_B \leq T \leq T_C : S_e(T) = n \cdot S_S \tag{3}$$

$$T_C \leq T \leq T_D : S_e(T) = n \cdot \left[\frac{S_1 \cdot T_1}{T}\right] \tag{4}$$

$$TT_D : S_e(T) = n \cdot T_D \left[\frac{S_1 \cdot T_1}{T^2}\right] \tag{5}$$

where T is the vibration period of a linear single-degree-of-freedom system; S_s is the maximum response spectral acceleration (5% damping) corresponding to the constant acceleration range of the elastic response spectrum; S_1 is the 5% damping response spectral acceleration at the vibration period T1=1s; T_A is the short-period cut-off associated to the effective ground acceleration; F_0 is the ratio of S_s with respect to the effective ground acceleration; $T_C = S_1 \bullet T_1 / S_s$ is the upper corner period of the constant spectral acceleration range; $T_B = T_C / \kappa$ is the lower corner period of the constant spectral acceleration range, with $0.05 \leq T_B \leq 0.1$s, whatever value of T_C; κ is the ratio of T_C and T_B; T_D is the corner period at the beginning of the constant displacement response range of the spectrum; η is the damping correction factor, with a reference value of η = 1 for 5% viscous damping.

Table 2 presents generic values for parameters T_A, κ, F_0 and T_D. These values are still debated in the sense that for example F_0 could be higher (e.g. 2.75) for lower seismicity countries and slightly lower (e.g. 2.3) for the high seismicity ones.

The spectral accelerations S_s and S_1 are defined as follows:

$$S_S = F_T \cdot F_B \cdot F_S \cdot S_{sRP} \tag{6}$$

Table 2. Recommended values for seismic hazard parameters defining the elastic response spectrum

T_A (s)	κ	F_0	T_D (s)
0.03	5	2.5	2 if $S_{1RP} \leq 0.1$g $1+10 \cdot S_{1RP}$ if $S_{1RP} > 0.1$g

$$S_1 = F_T \cdot F_B \cdot F_1 \cdot S_{1RP} \tag{7}$$

where F_s is the short period site amplification factor, F_1 is the intermediate period (T_1=1s) site amplification factor, F_T is an amplification factor related to topography and F_B is an aggravation factor related to basin effects (see Section 4).

To account for soil nonlinearity, site amplification factors F_s and F_1 for the different soil classes are proposed for distinct values of S_{sRP} (reference maximum spectral acceleration at rock site conditions). Following the rationale of the Boore et al. (2014) GMPE, amplification factors F_i (i=s,1) are considered to comprise two additive terms, i.e. a linear component, $F_{i,lin}$, which is practically independent of the amplitude of shaking, and a nonlinear component, $F_{i,nl}$, which modifies the linear term in order to decrease amplification for increasing shaking intensity:

$$F_i = \ln\left(F_{i,lin}\right) + \ln\left(F_{i,nl}\right), \ i = s, 1 \tag{8}$$

For the linear component, $F_{i,lin}$, soil amplification factors proposed by Pitilakis et al. (2013) for Type 2 (low seismicity) were adopted, which were estimated using a subset of the SHARE-AUTH database, consisting of 715 strong-motion records with surface wave magnitude $M_s \geq 4$, $PGA \geq 20cm/s^2$ and usable spectral period $T \geq 2.5s$. For the nonlinear term, $F_{i,nl}$, we used the nonlinear site amplification model developed by Seyhan and Stewart (2014) and adopted in the Boore et al. (2014) GMPE.

Site amplification factors F_s and F_1 were finally estimated for distinct values of S_{sRP}, equal to 0.125, 0.25, 0.5, 0.75, 1.0 and 1.25g as the sum of the linear and nonlinear components. The proposed values for F_s and F_1 (Tables 3 and 4) were obtained after adequate rounding. For intermediate values of S_{sRP}, straight line interpolation of the values of F_s and F_1 of Tables 3 and 4 is suggested. For the computation of site amplification factors of site class X and for buildings of importance classes III or IV based on the current version of EC8(CEN, 2004) located on sites classified as D or E, site-specific geotechnical investigation and dynamic site response analyses should be performed.

The values for F_s and F_1 proposed in the present study follow in general the same trend as the respective site amplification factors F_a and F_v of NEHRP (BSSC, 2015) with the discrepancies between most of the respective soil classes not exceeding 10%. An important exception however is observed for the wide soil class D in NEHRP corresponding to soil classes C1, C2 and C3 in the present proposal; for example the intermediate-period site amplification factor F_v in NEHRP (equal to 2.4) is about 40% higher than the respective amplification factor F_1 for soil class C1 and 25% lower than the one for soil class C3 for S_{sRP}=0.25g. This observation further emphasizes the need for a more refined soil classification system than the ones adopted in the current seismic codes including NEHRP.

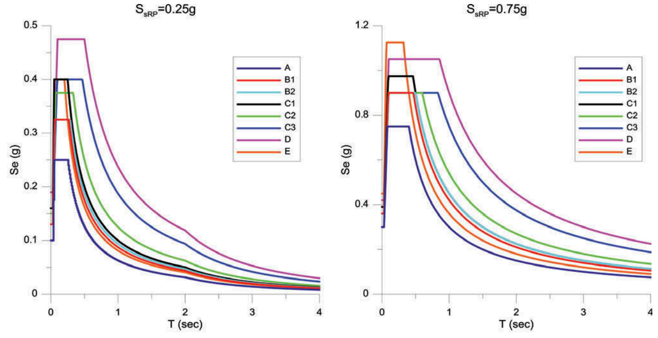
Figure 1 presents examples of the proposed elastic design response spectra for two different S_s, S_1 pairs corresponding to S_{sRP} equal to 0.25g and 0.75g (corresponding to a_g equal to 0.1g and 0.3 respectively) for all site classes.

Table 3. Proposed values for short period site amplification factor F_s

Site class	S_{sRP} (maximum response spectral acceleration at short period on site class A in g)					
	S_{sRP}<0.25	S_{sRP}=0.25	S_{sRP}=0.5	S_{sRP}=0.75	S_{sRP} =1.0	S_{sRP} ≥1.25
A	1.00	1.00	1.00	1.00	1.00	1.00
B1	1.30	1.30	1.20	1.20	1.20	1.20
B2	1.40	1.30	1.30	1.20	1.10	1.10
C1	1.70	1.60	1.40	1.30	1.30	1.20
C2	1.60	1.50	1.30	1.20	1.10	1.00
C3	1.80	1.60	1.40	1.20	1.10	1.00
D	2.20	1.90	1.60	1.40	1.20	1.00
E	1.70	1.60	1.60	1.50	1.50	1.50
X	-	-	-	-	-	-

Table 4. Proposed values for intermediate period site amplification factor F_1

	S_{sRP} (maximum response spectral acceleration at short period on site class A in g)					
Site class	$S_{sRP}<0.25$	$S_{sRP}=0.25$	$S_{sRP}=0.5$	$S_{sRP}=0.75$	$S_{sRP}=1.0$	$S_{sRP}\geq 1.25$
A	1.00	1.00	1.00	1.00	1.00	1.00
B1	1.40	1.40	1.40	1.40	1.30	1.30
B2	1.60	1.50	1.50	1.50	1.40	1.30
C1	1.70	1.60	1.50	1.50	1.40	1.30
C2	2.10	2.00	1.90	1.80	1.80	1.70
C3	3.20	3.00	2.70	2.50	2.40	2.30
D	4.10	3.80	3.30	3.00	2.80	2.70
E	1.30	1.30	1.20	1.20	1.20	1.20
X	-	-	-	-	-	-



(a) (b)

Figure 1. Elastic response spectra for the proposed site classes of Table 1 and two different S_s, S_1 pairs corresponding to S_{sRP} equal to (a) 0.25g and (b) 0.75g.

4 AGGRAVATION FACTORS

To estimate the additional effect of the 2D response at different locations at the surface of the basin with respect to the corresponding 1D response, period-dependent seismic aggravation factors (AGF) are used, computed as the ratio between 2D ($S_{e,2D}$) and corresponding 1D ($S_{e,1D}$) acceleration response spectra at the basin surface (Chávez-García and Faccioli, 2000):

$$AGF(T) = \frac{S_{e,2D}\ (T)}{S_{e,1D}(T)} \tag{9}$$

In order to identify the maximum amplification of ground motion that can be attributed to the 2D response of the basin, Riga et al. (2016) performed extensive numerical analyses of the linear viscoelastic response of homogeneous trapezoidal sedimentary basins in order to investigate the sensitivity of their 2D seismic response attributes and, consequently of the respective aggravation factors, to parameters related to the geometry of the basin (width, thickness and inclination angles of lateral boundaries) and the dynamic soil properties (shear and compressional wave velocities, soil density and attenuation). Table 5 summarizes the median, 16th and 84th percentile values for the maximum values of AGF for the five regions of regions a_1 to e_1 shown in Figure 2 and for two ranges of fundamental period at the center of the basin, $T_{0,c}$, i.e. $T_{0,c}\geq$ 3.0s and $T_{0,c}$<3.0s (Riga et al., 2016). It is observed that above the sloping edge of the basin (regions a_1 and b_1), maximum values of aggravation factors less than one may occur, meaning that 2D response is deamplified with respect to the corresponding 1D response, something which is more pronounced for steep slopes. On the contrary, at the nearly constant-depth

Table 5. Influence of fundamental period at the center of the basin $T_{0,c}$ on the maximum aggravation factor max AGF: Median, 16th and 84th percentile values for max AGF per region for the symmetrical models

$\mathbf{T_{0,c}}$		**Region $\mathbf{a_1}$**	**Region $\mathbf{b_1}$**	**Region $\mathbf{c_1}$**	**Region $\mathbf{d_1}$**	**Region $\mathbf{e_1}$**
$T_{0,c} < 3.0$ s	median	1.01	0.79	1.18	1.11	1.10
	16^{th}	0.93	0.65	1.12	1.05	1.04
	84^{th}	1.10	1.20	1.31	1.30	1.24
$T_{0,c} \geq 3.0$s	median	1.14	1.19	1.51	1.50	1.87
	16^{th}	0.85	0.68	1.26	1.40	1.44
	84^{th}	1.98	1.42	1.69	1.91	2.30

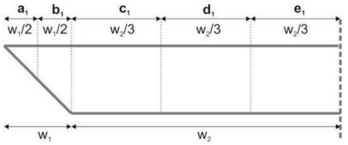


Figure 2. Division of the half-width of the basin surface into five regions (a1, b1, c1, d1 and e1).

part of the basin, maximum aggravation factors were found to be higher and to exhibit a larger scattering for basins with higher values of fundamental period at the center $T_{0,c}$. The highest values for max AGF appear in region e_1, with median equal to 1.87 and 84th percentile as high as 2.30 for the long-period basins. Riga et al. (2018) extended the work by Riga et al. (2016) in order to explore the potential additional effects of sediments inhomogeneity and nonlinearity on aggravation factors and found that the replacement of an inhomogeneous soil with an equivalent homogeneous might lead to underestimation of aggravation in the vicinity of the edges and overestimation of aggravation at the flat part of the basin, while consideration of soil nonlinearity may result in a decrease of aggravation factors for the flat part of the basin

Based on these findings, a preliminary recommendation for the coefficient F_B of equations (6) and (7) for nearly trapezoidal basins could be as follows:

- For shallow basins:

$F_B = 1.0$ for the regions above the sloping edge of the basin
$F_B = 1.2$ for the regions above the nearly constant-depth part of the basin

- For deep basins:

$F_B = 1.2$ for the regions above the sloping edge of the basin
$F_B = 1.5$ for the regions above the nearly constant-depth part of the basin

The limit value of $T_{0,c}$ for the distinction between shallow (low- $T_{0,c}$) and deep (high-$T_{0,c}$) basins could be indicatively set to 3.0 s.

5 CONCLUSIONS

An alternative site classification scheme and associated intensity-dependent spectral amplification factors have been presented aiming to contribute to the ongoing revision of Eurocode 8. The new classification scheme, introduces among the main classification parameters the fundamental period T_0 of the site and the approximate depth to seismic bedrock, H_b, while the main features of the amplification factors and the new seismic design actions are summarized in the use of two anchoring spectral values, for short (0.2s-0.3s) and intermediate (1.0s) periods, instead of only one of the present version of Eurocode 8, and the scalar intensity variation of site amplification factors to account for soil nonlinearity. In addition, a first attempt has been made towards the introduction of basin effects in the definition of EC8 elastic response spectra, through the proposal of an "aggravation factor", which expresses the additional effect of the 2D response of the basin above the corresponding 1D response of the isolated soil columns, which is supposed to be accounted for in building codes. It should be highlighted that the aggravation factors proposed herein are based on the maximum values derived from extensive numerical analyses of the seismic response of sedimentary basins (Riga et al., 2016; 2018), while the period-dependency of these factors may also need to be taken into consideration.

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