13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 2904

DESIGN RESPONSE SPECTRA AND SOIL CLASSIFICATION FOR SEISMIC CODE PROVISIONS

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SUMMARY

We are proposing improved spectral amplification factors for different site conditions based on an extensive theoretical and experimental study of the characteristics of seismic ground response. We have analyzed a large set of worldwide well-documented strong motion recordings and we have performed a large number of theoretical analyses (~600) of various representative models of realistic site conditions. Special emphasis is given to the non-linear soil behavior, the impedance contrast between bedrock and soil deposits, the thickness of soil deposits and the presence of a lower stiffness soil layer near the ground surface. The selected soil models and the applied numerical code were validated with real recordings at about 100 well-documented sites in Greece and worldwide. We determined statistically the basic parameters that influence the characteristics of seismic vibration in the defined soil categories and we are presenting herein an improved categorization of subsoil conditions (including parameters like the thickness of the soil deposits, the depth of the bedrock, the fundamental period of the site, the stratigraphy, the soil type, the mean Vs value of the whole deposit etc.) and corresponding response spectra, aiming to contribute to the ongoing discussion on the improvement of seismic regulations (i.e. EC8 Draft).

INTRODUCTION

Seismic ground response characteristics, defined generally as “site effects”, are inevitably reflected in seismic code provisions. The selection of appropriate elastic response spectra according to soil categories and seismic intensity is the simplest way to account for site effects both for engineering projects and for a general-purpose microzonation study. Contemporary seismic codes (IBC 2000, UBC97, EC8) have largely accepted the significant role of site effects and attempt to incorporate their influence either by means of a

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constant amplification factor exclusively dependent on the soil class or including additional parameters like the shaking intensity, near field conditions, etc. Even though concerning site classification different approaches exist, the basic idea of the mean value of shear wave velocity over the last few decades of meters (30m or other) is considered to be a sound parameter for site classification. However soil classification exclusively based in terms of $V_{S,30}$ assumption, is a rather simplified hypothesis, misleading in many cases, which can potentially lead to erroneous results, especially in cases of deep soil formations or abrupt stiffness change between the soil layer at -30m and the bedrock laying deeper, (Seed [3], Borcherdt [4], Martin [5], Dickenson [6], Dobry [7], Marek [8], Pitilakis [9]) On the other hand, recent studies based on different sites, where the soil dynamic profile from the surface to the bedrock was well known, have shown that for low to medium intensity shaking (i.e. less than 0.2g or 0.1g), a linear approach for the assessment of the amplification functions could be satisfactory for a considerable number of soils. Nevertheless, such an approach has the obvious draw back of ignoring soil non-linearity, which might become important in the case of strong ground shaking intensity according to the soil type, stiffness and depth. Table 1 compares soil classification schemes in modern seismic codes worldwide applying the $V_{S,30}$ criterion. Current, design practice, either uses an oversimplified approach to soil classification (e.g. soil type in EAK2000), or ignores the effect of depth by accounting only for the average shear wave velocity over the 30m of a site profile. (e.g. EC8, UBC97).

Table 1. Comparison of soil classification in modern seismic codes worldwide

$V_{s,30}$ (m/sec)	**180**	**360**	**760**	**1500**	
UBC/97 IBC/2000	**S_E**	**S_D**	**S_C**	**S_B**	**S_A**
GREEK SEISMIC CODE EAK2000	**D – C**	**C B A**		**Á**	
EC8 (ENV1998)	**C**	**C B A**		**A**	
EC8 (prEN1998) (Draft4, 2001)	**D**	**C**	**B**	**A**	
New Zealand, 2000 (Draft)	**D** (T>0.6s =>$V_{s,30}$<200)	**C** (T<0.6s =>$V_{s,30}$>200)	**B**	**A**	
Japan, 1998 (Highway Bridges)	**III** (T>0.6s->$V_{s,30}$<200)	**II (I)** (T=0.2-0.6 s -> $V_{s,30}$=200-600)		**I** (T<0.2s ->$V_{s,30}$>600)	
Turkey/98	**$Z_4 – Z_3$**	**$Z_3 – Z_2$**	**$Z_3–Z_2– Z_1$**	**Z_1**	
AFPS/90	**$S_3 – S_2$**	**$S_3–S_2–S_1$**	**$S_1 – S_0$**	**S_0**	

Among the important seismic site response factors are the impedance ratio between surface and underlying deposits, the soil type and the stratigraphy, the material damping and its potential variation with the intensity of the ground. Following the above, a site classification system should include adequate parameters describing the dynamic stiffness of the site and the depth of the deposit. Although earlier codes made use of natural ground period (To) as a means to classify site conditions (e.g. UBC 1976), recent codes as UBC97 and EC8 adopt the $V_{S,30}$ as the primary parameter for site classification, requiring a relatively extensive field investigation and overlooking the potential importance of depth to bedrock as a dominant factor in the site response.

The objective of this work is to develop site amplification factors that are both intensity and frequency dependent, based on a more refined site classification system that includes soil type, stratigraphy, depth and stiffness as key parameters.

METHODOLOGY

The procedure applied herein to propose site –dependent amplification factors is shown below:

- Creation of an extended database of high quality geotechnical and geophysical data of representative soil profiles in Greece and worldwide
- Selection of well constrained strong ground motion recordings with different PGA values, Mw magnitudes and covering a wide range of seismo-tectonic background. The good knowledge of site conditions such as soil stratification, Vs profile, shear modulus degradation curves, damping (G/Go-γ-D curves) and depth of the bedrock, was the basic criterion for the selection of the aforementioned recordings.
- Detailed analyses of the spectral characteristics of the selected recordings, comparison with code site classification categories (EC8, NEHRP, EAK), and evaluation of potential important differences due to the site classes defined
- Elaboration of improved representative site classification matrix using (a) the database, (b) the previous analyses of the recordings, (c) the soil categories proposed in modern codes (EC8, NEHRP) and (d) an engineering judgment based on the most common soil profiles found in Greece and worldwide. The classification scheme was deemed to perform adequate theoretical 1D equivalent linear computations of ground response with different soil profiles in terms of impedance contrast, dynamic soil properties, relative thickness and depth of the rigid or non-rigid bedrock.
- Selection of various “bedrock” input motion excitations, describing the essential characteristics of recordings on rock or on very stiff sites (frequency content, PGA values, seismo-tectonic background).
- Validation of the selected herein dynamic soil properties and soil profiles soil models with in-situ and laboratory data at similar soil and site conditions.
- Validation of the results of many 1D equivalent linear analyses (Schnabel [10]), in different well-documented soil profiles where reliable recordings were also available.
- Performance of an extended program of 1D analyses (>600).
- Elaboration of the results of the parametric studies in order to define homogeneous site response spectral characteristics, including spectral amplification factors for different site-soil classes, considering the soil type, the thickness of soil deposit, and the soil stiffness.

The soil models that were used in the analyses of seismic response cover an important breadth of different realistic soil conditions. Figure 1 presents the selected limits of certain characteristic parameters which, grouped as follows:

- Thickness of soil deposit varying from 20 to 110m.
- Shear wave velocity of bedrock varying from 750m/s to 2000m/s
- Fundamental period of site varying from 0.1sec to 1.5sec
- Mean shear wave velocity of upper 30m varying from 120m/sec to 837m/s
- Mean shear wave velocity of whole soil deposits varying from 100m/s to 858m/s
- Impedance ratio varying from 1.4 to 15.0

Depending on the criteria applied for the selection of the representative 1D profiles, the set of parametric analyses is separated in three groups:

- Soil models according to the EC8 site classification having (a) three different thickness (20m, 40m and 60m), (b) different mean Vs values for the whole profile (figure 2a) and c) shear wave velocity of the bedrock equal to 1500m/s.
- Homogenous clayey and sandy as well as "mixed soil" models, with various physical and mechanical properties (e.g. plasticity, relative density, etc) and shear wave velocity of bedrock varying from 750m/s to 2000m/s (Figure 2b).
- Non-homogeneous soil profiles having at different depths a "lower stiffness" soil layer of various thickness (Figure 2(c)). This particular case of soil conditions may be defined as a special site category in seismic codes (e.g. category E in EC8); this category is of specific interest as it is often met in practice in regions with loose soil deposits.

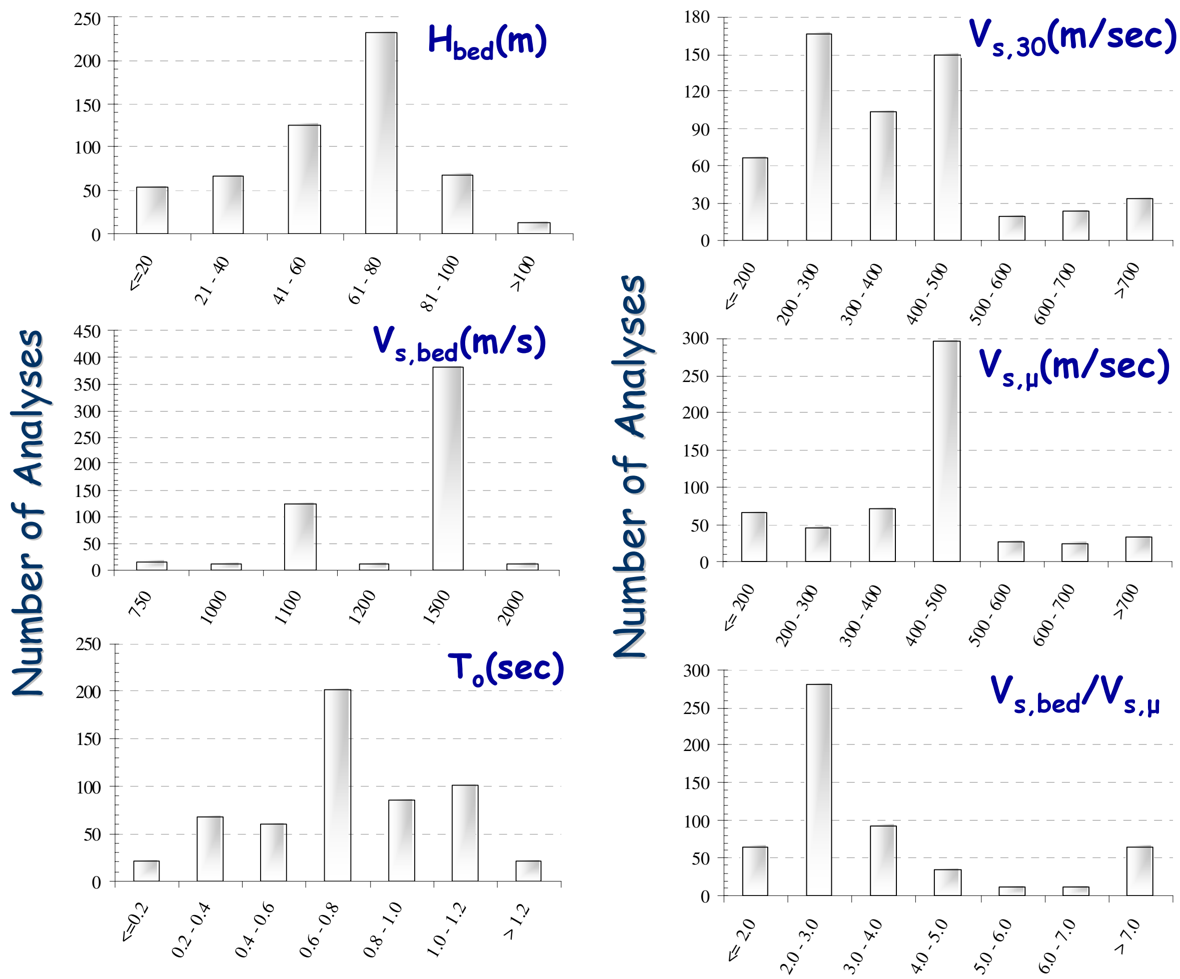

Figure 1. Soil models used in the theoretical analyses: Variation of (a) depth of bedrock, (b) Vs of bedrock ($Vs_{,bed}$) , (c) fundamental period of soil deposit, (d) fluctuation of mean value of $Vs_{,30}$, (e) mean shear wave velocity of soil deposit $Vs_{,m}$ and (f) impedance ratio $Vs_{,bed}$ / $Vs_{,m}$.

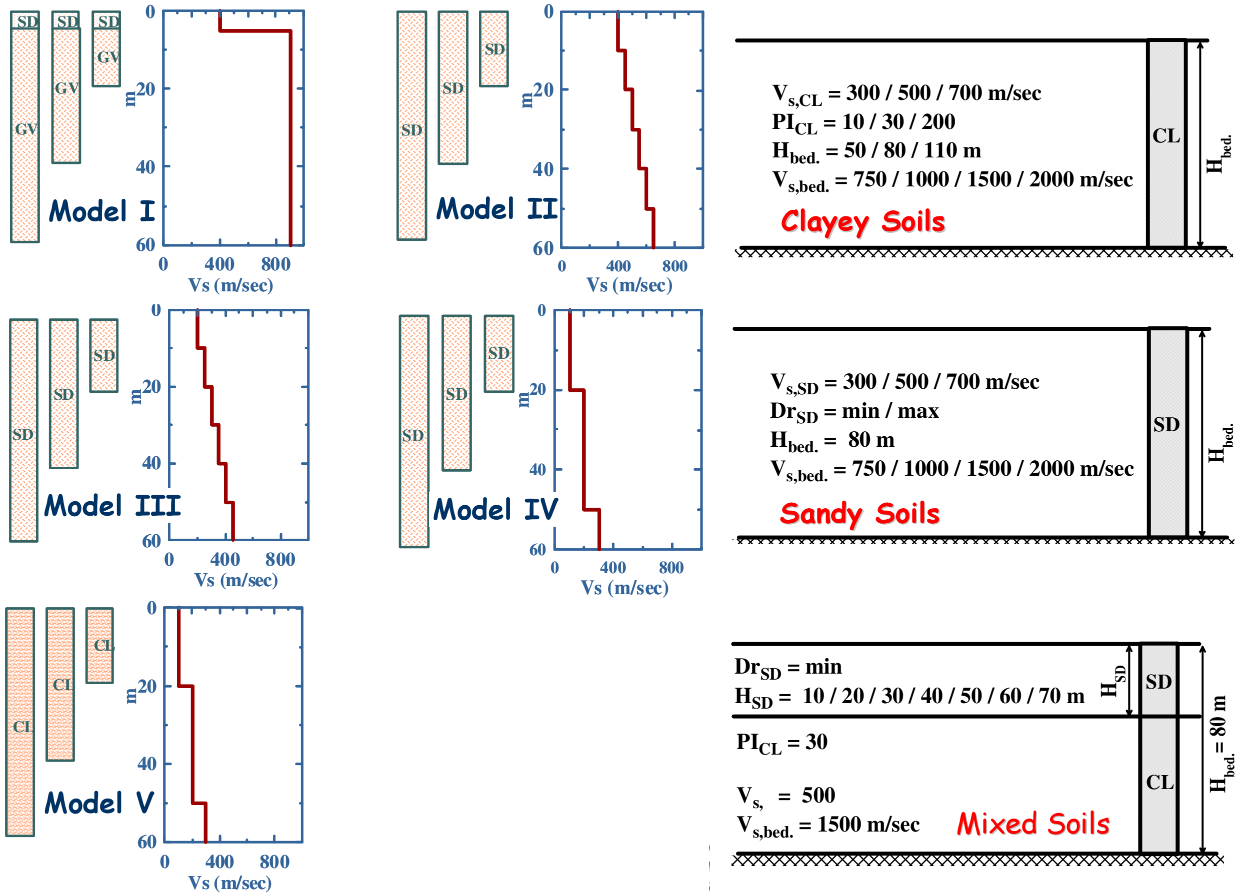

Figure 2. (a) Soil models according to EC8 classes, (b) Clayey, sandy and mixed soil models used in theoretical analyses.

For the seismic response study twelve real accelerograms were considered in the analyses. They were carefully selected to satisfy the following criteria: a) been recorded at rock sites, b) cover a wide range of peak acceleration values (0.01g to 0.7g) and frequency content and c) match the response spectra provided by Eurocode 8 and Greek seismic code for rock-site conditions.
The normalized acceleration response spectra for the proposed input motions are given in figure 3a, while figure 3b shows the comparison with EC8 and UBC97 response spectra, as well as with response spectra provided by empirical attenuation relationships (Ambraseys [11], Sabetta [12]).

Equivalent linear site response analyses were performed using CYBERQUAKE computer code [13]. Shear modulus reduction curves G/Go and damping ratio D_S, both depending on the shear strain specified from resonant column tests (Pitilakis [14,15,16]) and from the literature. Results of site response analysis in frequency domain using the equivalent linear approximation are considered accurate for the determination of PGA up to 3sec for generic purpose projects (Finn [17], Martin [5], Durward [18], Dobry [7], Dickenson [6]). For each earthquake-site model, a nonlinear site response analysis is performed in order to generate acceleration time history and the corresponding response spectrum with 5% damping ratio at ground surface. In total, more than 600 theoretical analyses of various well-documented soil models were performed.

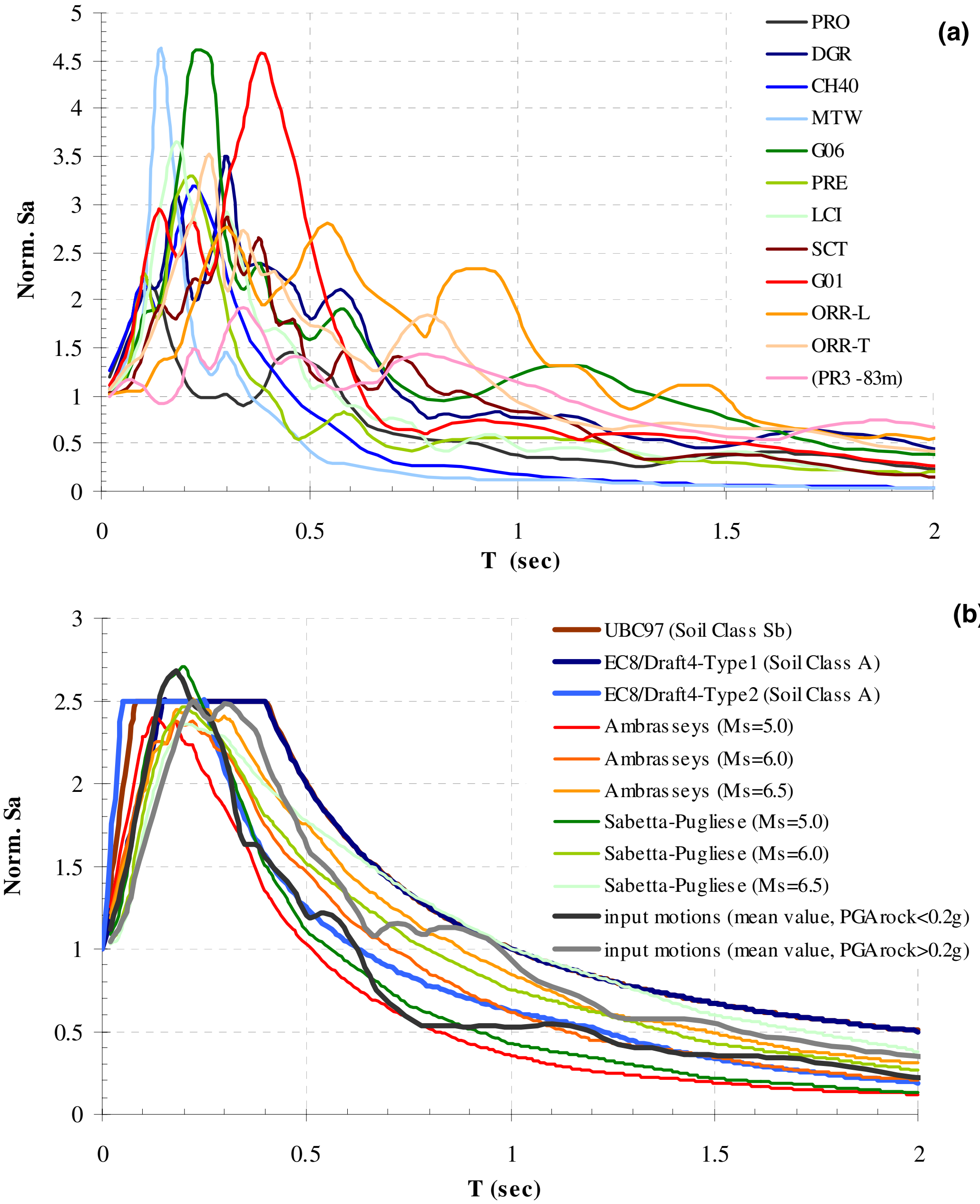

Figure 3. (a) Normalized acceleration response spectra of the 12 selected seismic excitations used in theoretical analyses, (b) acceleration response spectra at 'rock' sites: comparison of values proposed by seismic codes and empirical attenuation relationships.

PROPOSED SOIL AND SITE CLASSIFICATION

The classification of a site using simple qualitative criteria, as it is proposed by the Greek Seismic code (EAK), does not correspond to the present needs of an improved soil classification for site effect analyses or to the present state of knowledge. The absence of quantitative description parameters that constitute characteristic attributes of soil materials and site conditions, increase the uncertainty of choosing of suitable category. The majority of international seismic regulations (NEHRP/97, UBC/97, Ec8-prEN1998/Draft4) recognizing the need for quantitative parameters adopts the $Vs_{,30}$ criterion in the definition of the site category. Even though the classification based on $Vs_{,30}$ overcomes the qualitative description's shortcomings ,it can potentially lead to erroneous results, according to the results of theoretical and experimental analyses that were done elsewhere (Pitilakis [16]) and have been conducted in the framework of this study. Many experimental and theoretical studies (Pitilakis [9], Raptakis [19], Makra [20]) confirm the important role of the basin and deep soil layers. The site classification proposed herein (Table 1) is an attempt to encompass the factors affecting seismic site response while minimizing the amount of data required for site characterization. Simple and widely used soil parameters are used for the description of different soil categories (N-SPT, mean shear wave velocity Vs, undrained strength Su).

The basic parameters that were adopted for the site classification scheme are summarized in below:

a) Qualitative description of common the soil-rock types like: healthy/slightly weathered/ segmented rock formations, very stiff to soft clays, very dense to loose sands etc. This qualitative description refers also to the proposed range of values of mean shear wave velocities.
b) Average estimated depth to the real bedrock or to a so-called "seismic bedrock" formation which is assigned to Vs>800 m/s.
c) Mean shear wave velocity Vs over the whole soil column until the bedrock.
d) The fundamental period of the site, which constitutes an indirect measure of stiffness and thickness of soil deposits.
e) Values from SPT tests, which constitute the most common in-situ geotechnical test and are commonly used to characterize soil deposits and to estimate the values of Vs.
f) The undrained shear strength and the plasticity index used for clayey soils.

According to the proposed site classification scheme the sites are classified into six basic categories (A, B, C, D, E and X) by their qualitative description and stiffness characteristics. This general form follows the general categories proposed by EC8, introducing at the same time some extra sub-classes that were pointed out at the theoretical study of seismic response, corresponding to common cases that are met in engineering practice. The subdivision of the basic categories A, B, C and D in sub-categories was based on the results of theoretical analyses highlighting the influence of depth to bedrock in the characteristics of seismic response.

SITE DEPENDED AMPLIFICATION FACTORS AND RESPONSE SPECTRA

For each soil category of Table 1 and for two levels of expected seismic intensity in rock site (Type 1 – PGArock>0.2g, Type 2 – PGArock<0.2g) spectral acceleration factors at the surface were determined. Figure 4 depicts a representative example of calculation procedure for site class C1.
The determination of smoothed acceleration spectra at the surface for each soil category was based on the estimated average spectral amplifications factors multiplying the EC8 rock site spectra. The applied procedure has as follows:

- Classification of soil models for seismic response analyses according to the defined soil categories.
- Statistical elaboration of the results of the theoretical 1D nonlinear ground response analyses in terms of spectral amplification factors (variation of mean values as a function of the period and the level of the expected intensity).

Table 1. Soil and Site Characterizatrion (Pitilakis [16]).

SOIL CATEG.		DESCRIPTION	To (sec)	REMARKS
A	**A_1**	Healthy rock formations		Vs ≥1500 m/s
	A_2	Slightly weathered/segmented rock formations,(thickness of weathered layer < 5.0m)	≤0.2	Weak layer: $V_s \geq 300$ m/s Rock form.: $V_s \geq 800$ m/s
		Geologic formations which resemble to rock formations in their mechanical properties and their composition (e.g. conglomerates)		$V_s \geq 800$ m/sec
B	**B_1**	Highly weathered rock formations whose weathered layer has a considerable thickness of 5.0 - 30.0m	≤ 0.4	Weathered layer: $V_{s\,(1)} \geq 300$ m/s
		Soft rock formations of great thickness or formations of similar stiffness and mechanical properties (e.g. stiff marls)		V_s = 400 - 800 m/s $N_{SPT(2)} > 50$ $S_{u(3)}$>200KPa
		Homogeneous soil formations of very dense sand – sand gravel and/or very stiff clay, and small thickness (less than 30.0m)		V_s = 400 - 800 m/s $N_{SPT} > 50$ S_u >200Kpa
	B_2	Homogeneous soil formations of very dense sand – sand gravel and/or very stiff clay, and medium thickness (30.0 - 60.0m), whose mechanical properties and stiffness increase with depth	≤0.8	V_s = 400 - 800 m/s $N_{SPT} > 50$ S_u >200Kpa
C	**C_1**	Soil formations of dense to very dense sand–sand gravel and/or stiff to very stiff clay, of great thickness (>60.0m), whose mechanical properties and strength are constant and/or increasing with depth	≤1.2	V_s = 400 - 800 m/s $N_{SPT} > 50$ S_u >200KPa
	C_2	Soil formations of medium dense sand – sand gravel and/or medium stiffness clay (PI > 15, fines percentage > 30%) of medium thickness (20.0m – 60.0m)	≤1.2	V_s = 200 - 400 m/s $N_{SPT} > 20$ S_u >70KPa
	C_3	Category C2 soil formations of great thickness (>60.0 m), homogenous or stratified that are not interrupted by any other soil formation with a thickness of more than 5.0m and of lower strength and Vs velocity	≤1.4	V_s = 200 - 400 m/s $N_{SPT} > 20$ Su >70KPa
D	**D_1**	Recent soil deposits of substantial thickness (up to 60m), with the prevailing formations being soft clays of a high plasticity index (PI>40), with a high water content and low values of strength parameters	≤ 2.0	V_s ≤200 m/s $N_{SPT} < 20$ Su <70KPa
	D_2	Recent soil deposits of substantial thickness (up to 60m), with prevailing fairly loose sandy to sandy-silty formations with a substantial fines percentage (so as not to be considered susceptible to liquefaction)	≤2.0	V_s ≤200 m/s $N_{SPT} < 20$
	D_3	Soil formations of category C with Vs >300m/s and great overall thickness (>60.0m), interrupted at the first 40 meters by soil layers of category D1 or D2 of a small thickness (5 – 15m),	≤ 1.2	
E		Surface soil formations of small thickness (5m - 20m), small strength and stiffness, likely to be classified in category C or D according to geotechnical properties, which overlie category A formations (Vs≥ 800 m/s).	≤ 0.5	Surface soil layers: V_s = 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 well documented seismically active tectonic faults. - Steep slopes covered with loose lateral deposits. - Loose granular or soft 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.		
(1), (2), (3) : *mean values over the whole soil column until the bedrock.*				

- Determination of normalized acceleration spectra for each site category, which result from the application of mean amplification factors to the equivalent normalized spectra for rock site conditions, described by the following equations:

$$0 \le T \le T_B : \quad \frac{S_a(T)}{PGA_{rock}} = S \cdot \left[1 + \frac{T}{T_B} \cdot (\beta - 1)\right] \tag{1}$$

$$T_B \le T \le T_C : \quad \frac{S_a(T)}{PGA_{rock}} = S \cdot \beta \tag{2}$$

$$T_C \le T \le T_D : \quad \frac{S_a(T)}{PGA_{rock}} = S \cdot \beta \cdot \frac{T_C}{T} \tag{3}$$

$$T_D \le : \quad \frac{S_a(T)}{PGA_{rock}} = S \cdot \beta \cdot T_C \left(\frac{T_D}{T^2}\right) \tag{4}$$

where, PGA_{rock} =design ground acceleration at rock-site conditions, T_B, T_C =limits of the constant spectral acceleration branch, T_D =value defining the beginning of the change of the slope branch and value defining the constant displacement response range of the spectrum, S =soil amplification parameter and β =spectral amplification parameter.

Table 2 and Figures 5 to 6 present the defined parameters and the acceleration response spectra for each site category of Table 1 and two levels of earthquake intensity (Type 1 – PGArock > 0.2g, Type 2 – PGArock < 0.2g).

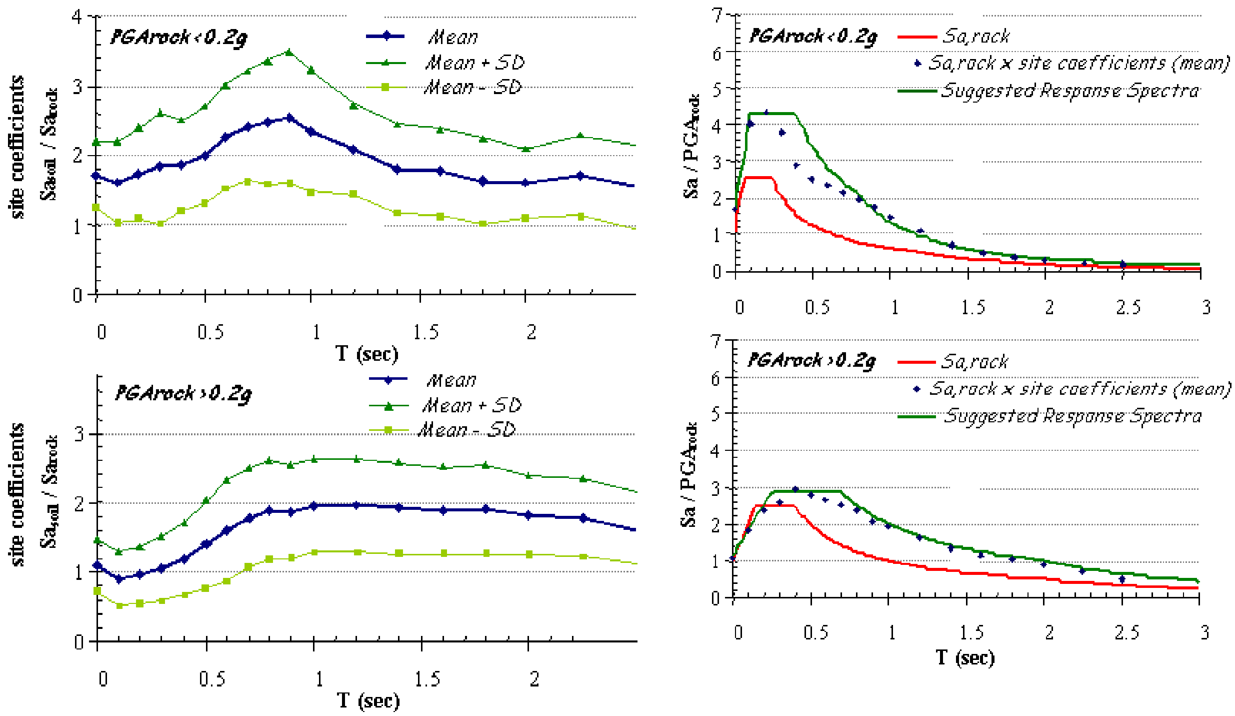

Figure 4. Site category C1: (a) Spectral amplification factors – Results of theoretical seismic response, (b) Proposed acceleration response spectra.

Table 2. Parameters of proposed acceleration response spectra.

Soil Category	*Proposed Acceleration Response Spectra*									
	PGA_{rock}<0.2g					*PGA_{rock}>0.2g*				
	T_B (sec)	*T_C (sec)*	*T_D (sec)*	*S*	*β*	*T_B (sec)*	*T_C (sec)*	*T_D (sec)*	*S*	*β*
A	0,05	0,25	1,2	1,0	2,5	0,15	0,4	2,0	1,0	2,5
B_1	0,05	0,25	0,5	2,0	3,0	0,15	0,45	0,8	1,6	3,0
B_2	0,05	0,35	0,7	2,0	3,0	0,20	0,55	1,0	1,3	3,0
C_1	0,1	0,4	0,8	1,7	2,5	0,25	0,7	2,0	1,1	2,5
C_2	0,1	0,5	0,8	2,0	2,5	0,25	0,8	2,0	1,1	2,5
C_3	0,1	0,5	1,2	1,4	2,5	0,25	0,9	2,2	1,0	2,5
D_1	0,1	0,7	1,2	1,8	2,5	0,25	1,0	2,0	1,2	2,5
D_2	0,1	0,7	1,2	1,1	2,5	0,25	1,0	2,0	0,8	2,5
D_3	0,1	0,7	1,2	1,1	2,5	0,25	1,2	2,0	1,0	2,5
E	0,05	0,25	0,4	3,0	3,0	0,1	0,4	0,7	2,0	3,0

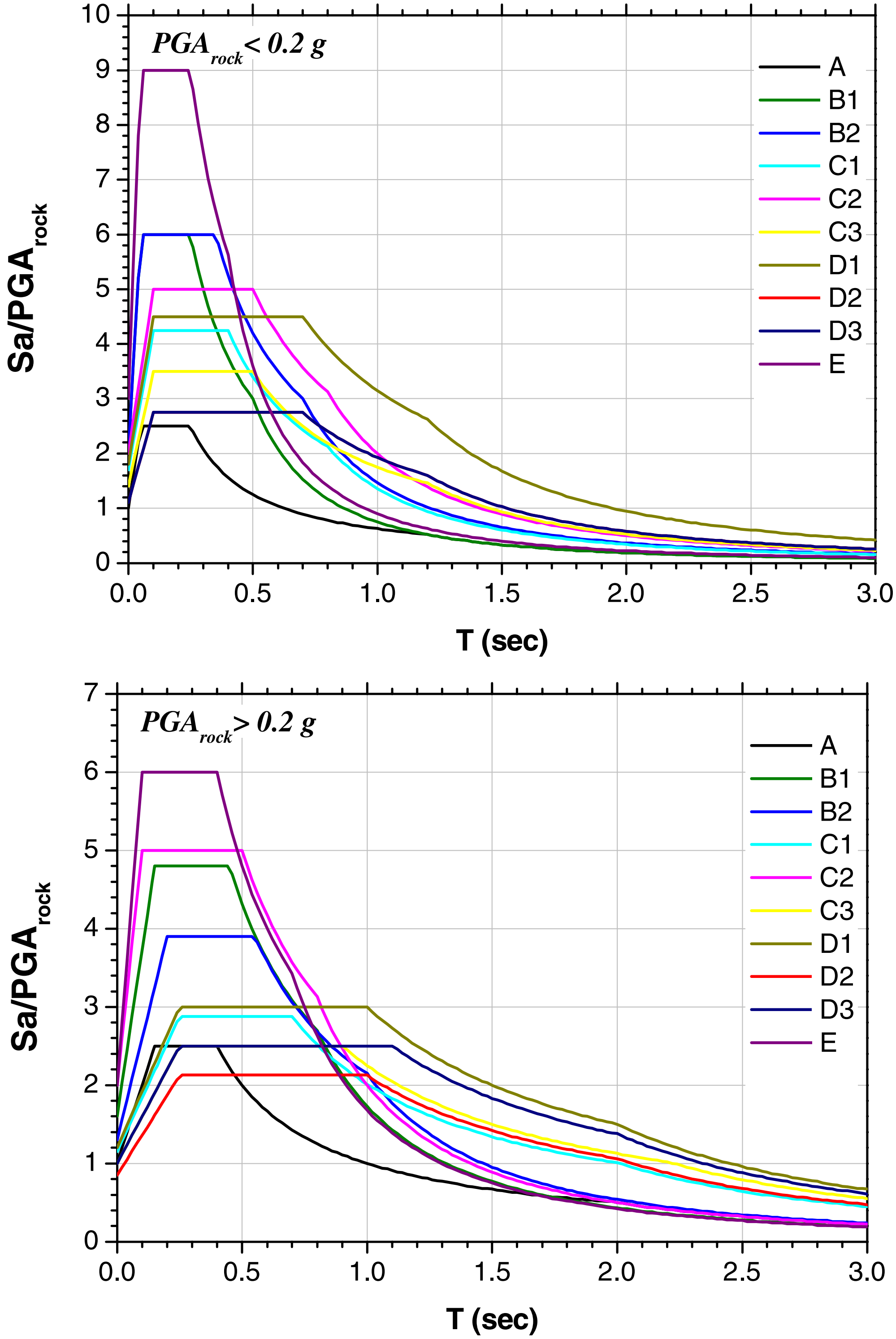

Figure 5. Proposed acceleration response spectra for each site category of table 1 and two levels of expected intensity (PGA_{rock} <0.2g and PGA_{rock}>0.2g) normalized with respect to the maximum acceleration at 'rock' site conditions (PGA_{rock}).

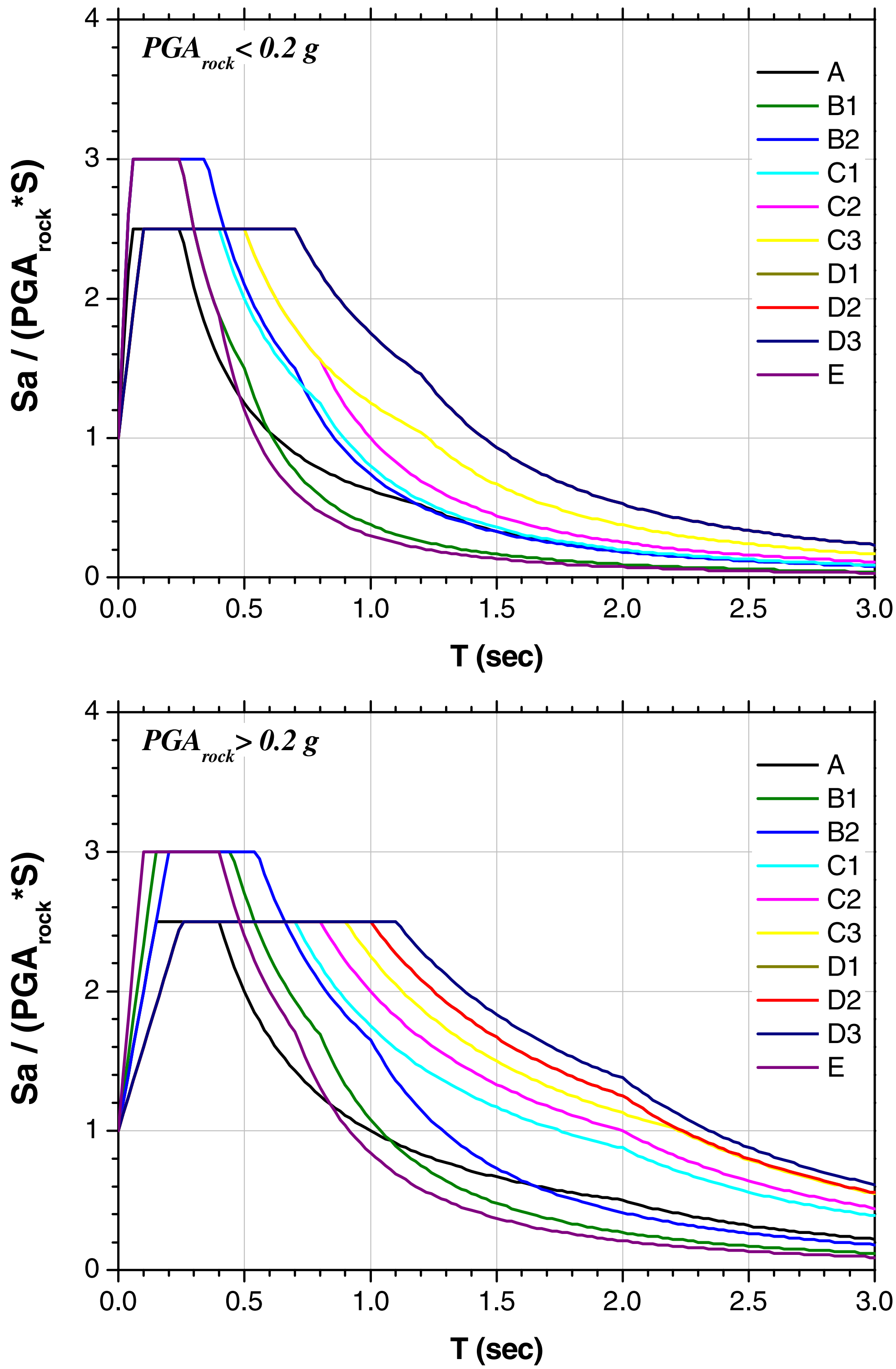

Figure 6. Normalized acceleration response spectra for each site category of Table 1 and two levels of earthquake intensity (PGA_{rock} <0.2g and PGA_{rock}>0.2g); normalized with respect to the maximum ground acceleration (PGA_{rock}*S).

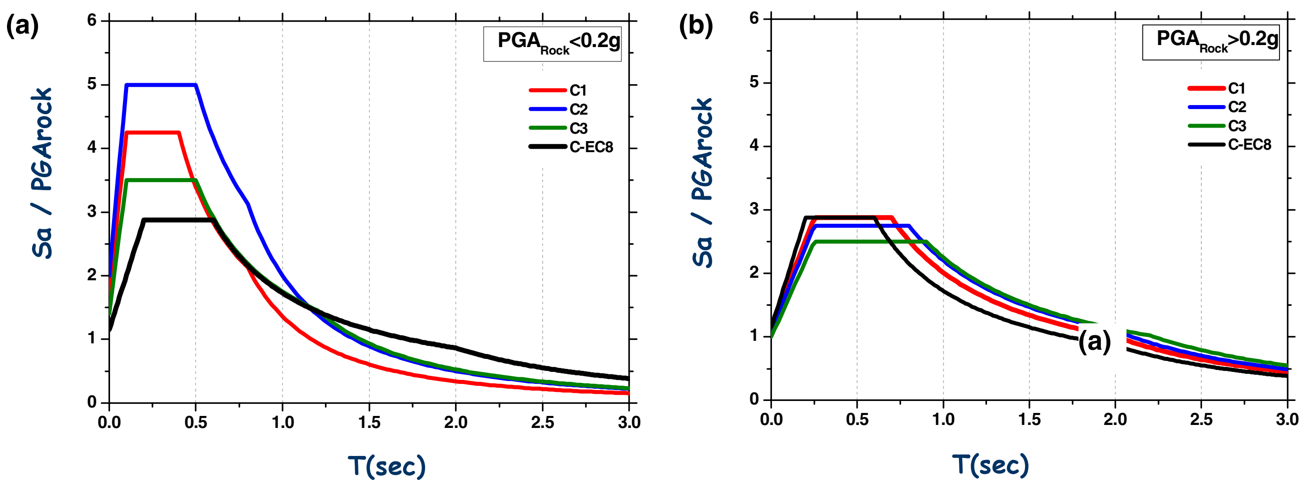

Figure 7. Acceleration response spectra for C soil sites: Comparison of proposed values with those provided by EC8 for (a) $PGA_{rock}<0.2g$ and (b) $PGA_{rock}>0.2g$

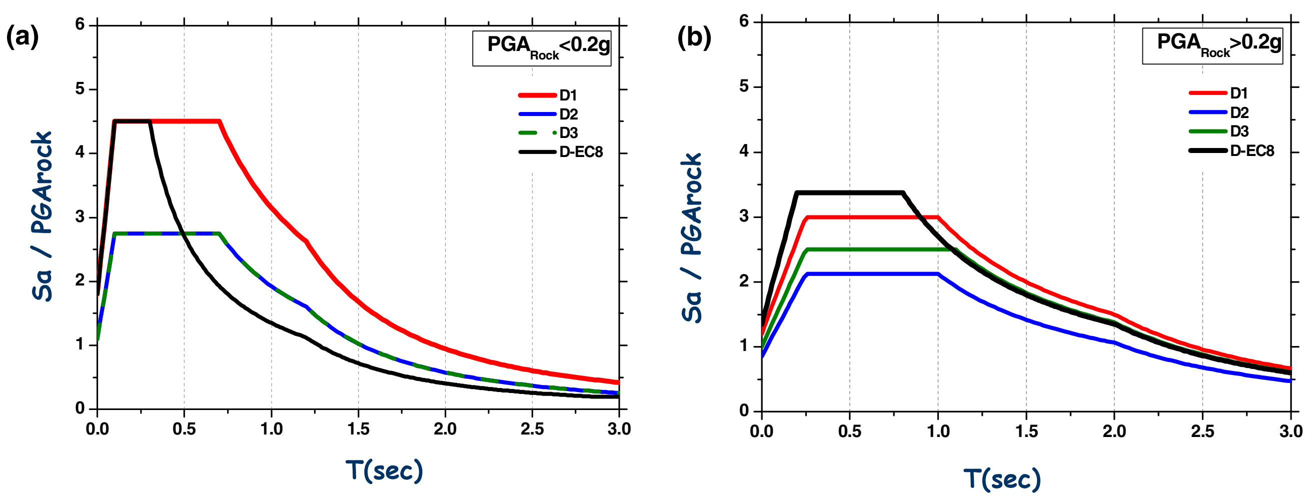

Figure 8. Acceleration response spectra for D soil sites: Comparison of proposed values with those provided by EC8 for (a) $PGA_{rock}<0.2g$ and (b) $PGA_{rock}>0.2g$

In Figures 7 and 8 the proposed acceleration response spectra for C and D classes are compared with the EC8 spectra. The calculated values for C class (figure 7a), at low ground shaking intensity sites ($PGA_{rock}<0.2g$) show high amplification at low periods (0.1 to 0.5sec) presenting noticeable differences from those curves proposed by EC8. On the contrary, for high seismicity zones, where expected ground shaking acceleration at 'rock-like' conditions is higher than 0.2g (figure 7b), the proposed values fit reasonably well with EC8 spectra, except for C3 class. The calculated values for D1 class (figure 8a) at low ground shaking intensity sites ($PGA_{rock}<0.2g$) exhibit high spectral values at periods ranging from 0.1sec to 0.7sec, while D2, D3 classes exhibit lower spectral amplification, presenting noticeable differences compared to EC8. Moreover, in the case of strong ground shaking intensity ($PGA_{rock}>0.2g$) at

D class sites the proposed values exhibit lower spectral amplification from those provided by EC8, due to the influence of strong non-linear behavior. The differences reflect the effects of induced ground shaking intensity, soil depth, soil type, stiffness and stratification on the surface spectral amplification under 1D wave propagation.

CONCLUSIONS

Geotechnical and geophysical data stemming for various sites in Greece and Europe along with results from instrumental and theoretical methods were analyzed to evaluate an improved and refined geotechnical site classification scheme, to account for site effects in engineering design practice. The proposed classification scheme is based on a general characterization of the site conditions that includes soil thickness and bedrock depth, deposit stiffness and fundamental period. For each site category spectral amplification factors for two levels of expected intensity of "outcropping" ground shaking were determined. Finally, mean response acceleration spectra for each soil category with two level of ground shaking intensity are proposed, normalized to the response spectra provided by Eurocode 8 for rock-site conditions. We believe that the proposed site amplification coefficients, and normalized response spectra, reflect better the actual site conditions, while they take into consideration more accurately the effect of shaking intensity on soil non-linearity. However, further investigation has to be undertaken, enriching the number of the well-documented soil profiles and simultaneous strong motion recordings at different soil-site conditions.

ACKNOWLEDGMENTS

Financial support was provided by the Organization for Seismic Planning and Protection of Greece. This contribution is acknowledged.

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