DESIGN ENERGY SPECTRA FOR TURKEY

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SUMMARY:
This work proposes design energy spectra in terms of velocity, derived through linear dynamic analyses on Turkish registers and intended for regions with design peak acceleration 0.3 g or higher. In the long and mid period ranges the analyses are linear, taking profit of the rather insensitivity of the spectra to the structural parameters other than the fundamental period; in the short period range, the spectra are more sensitive to the structural parameters and nonlinear analyses would be required. The selected records are classified in eight groups according to the design input acceleration, the soil type, the earthquake magnitude and the near-source effects. For each of these groups, median and characteristic spectra are proposed (50% and 95% percentiles). These spectra have an initial linear growing branch in the short period range, a horizontal branch in the mid period range and a descending branch in the long period range.

Keywords: design energy spectra, input energy, linear time history analysis, Turkey

1. INTRODUCTION

In conventional earthquake-resistant design of buildings (and other constructions) the dynamic effect of the input is represented by static equivalent forces, which are obtained from acceleration response spectra defined as the ratio between the peak ground acceleration (PGA) and the maximum absolute acceleration in the top of the building. This approach presents several drawbacks: (i) these equivalent forces are strongly coupled to the elastic and hysteretic characteristics of the structure, thus making the seismic design cumbersome, (ii) after the onset of yielding, the correlation between the design forces and the structural damage is rather low, and (iii) the damage caused by the cumulative inelastic excursions is not accounted for. More recently, the displacement-based design procedures have been proposed [Priestley, Calvi, Kowalsky, 2007]; in these strategies, the dynamic effect of the input is represented by imposed displacements, that are obtained from displacement response spectra relating the PGA to the maximum relative displacement in the top of the building. This formulation uncouples partially the input effect in terms of displacement from the characteristics of the structure and allows a satisfactory correlation between the imposed displacement and the structural damage. Conversely, the cumulative component of damage cannot be appropriately considered. A more rational seismic design approach, which overcomes also this difficulty, is to express the dynamic input effect through energy response spectra. This approach has three major advantages: (i) the input effect in terms of energy and the structural resistance are basically uncoupled, (ii) except in the short period range, the input energy, E_I, introduced by a given ground motion in a structure is a stable quantity, governed primarily by the natural period T and the mass m, and scarcely by other structural properties such as resistance, damping and hysteretic behavior, and (iii) the consideration of the cumulative damage fits well with this formulation. In the energy-based methods the design criterion is constituted by the comparison

between the energy absorption capacity of the structure (i.e. its seismic resistance) and the input energy (i.e. the effect of the ground motion). It is then necessary to establish the input energy spectrum corresponding to the expected earthquake, i.e. design input energy spectrum.

This work consists of proposing energy spectra for earthquake-resistant design based on accelerograms registered in high seismicity regions of Turkey. The spectra have been derived through linear dynamic analyses on the selected Turkish accelerograms. In the long and mid period ranges the analyses are linear, taking profit of the rather low sensitivity of the spectra to the structural parameters other than the mass and the fundamental period. Conversely, in the short period range, the spectra are more sensitive to the structural parameters and, hence, the analyses should to be nonlinear.

The considered registers are selected among those available in Turkey. The chosen records are treated (base-line correction and filtering) and classified according to the design input acceleration (e.g. the seismic zone), the soil type of the seismic station (following the classification of the Eurocode 8), the magnitude of the earthquake and the relevance of the near-source effects, namely the velocity pulses. The design energy spectra are envelopes of the actual spectra, in terms of (relative) velocity, corresponding to each input (pair of horizontal components); the influence of the vertical components has been disregarded. These derived spectra have an initial growing branch (starting from zero) in the short period range, a horizontal branch in the mid period range and a descending branch in the long period range. Median and characteristic spectra are proposed; regardless of the statistical distribution of the spectral ordinates, such levels are intended to correspond to 50% and to 95% percentiles, respectively.

2. SEISMIC DESIGN BASED ON INPUT ENERGY SPECTRA

The equation of motion of a SDOF system subjected to a horizontal ground motion is given by:

$$m\,\ddot{y} + c\,\dot{y} + Q(y) = -m\,\ddot{z}_{g} \tag{1}$$

In equation (1) m is the mass, c is the damping coefficient, $Q(y)$ is the restoring force, y is the relative displacement, and $\ddot{z}_{g}$ is the ground acceleration. Multiplying equation (1) by $dy = \dot{y}\,dt$ and integrating along the duration of the earthquake gives the energy balance equation

$$E_{k} + E_{\zeta} + E_{a} = E_{I} \tag{2}$$

In equation (2), E_{k} is the relative kinetic energy, E_{ζ} is the energy dissipated by the inherent damping, E_{a} is the energy absorbed by the spring, and E_{I} is the relative input energy:

$$E_{k} = \int \dot{y}\,m\,\ddot{y}\,dt = \tfrac{1}{2}m\,\dot{y}^{2} \qquad E_{\zeta} = \int c\,\dot{y}^{2}dt \qquad E_{a} = \int Q(y)\,\dot{y}\,dt \qquad E_{I} = -\int m\ddot{z}_{g}\,\dot{y}\,dt \tag{3}$$

E_{I} can be normalized by the mass m and expressed in terms of equivalent velocities V_{E}:

$$V_{E} = \sqrt{2E_{I}/m} \tag{4}$$

For a given ground motion, the relationship between the input energy E_{I} expressed in terms of the equivalent pseudo-velocity V_{E} and the natural period of the system, T, is defined as the energy input spectrum. Akiyama [Akiyama 1985] proposed a three-step method to obtain the

design energy input spectrum for a given region from the individual energy input spectra obtained for each available ground motion record:

1. Calculate the energy input spectrum, V_E vs. T corresponding to an elastic SDOF system with 10% damping ($\zeta = 0.10$) for each ground motion recorded in the region, by quadratic combination of the energy input, in terms of pseudo-velocity, obtained for the north-south, $V_{E,NS}$, and east-west, $V_{E,EW}$, horizontal components through linear dynamic response analyses, according to equation (3).
2. Draw a two piecewise bilinear envelope of the V_E vs. T curves. The first line goes through the origin and envelops the energy input spectra in the short period. The second line is horizontal and represents the energy input in the medium/high period range.
3. Multiply the slope of the first line by 1.20 to take into account the fact that in the short period range, the lengthening of the vibration period associated with the plastification of the structure tends to increase the input energy.

It is worth emphasizing that the energy input spectrum obtained elastically is also valid for inelastic systems because the total energy input is scarcely affected by the strength and plastification level of the system, as pointed out in the Introduction. This work considers a similar approach for proposing design input energy spectra. It consists of performing the linear analyses of the first step of the Akiyama's approach while the second and third steps are modified. In the second step there are two major modifications: (i) two envelopes are proposed, corresponding to median and characteristic values, respectively, and (ii) the envelopes are not bilinear but contain also a descending branch in the long period range.

3. TURKISH REGISTERS

A dataset from 1976 to 2006 [Akkar et al. 2010] constitutes the main base for this work. It covers 4203 registers from 2818 seismic events; such accelerograms have been recorded in 327 stations. Within the aforementioned 4203 registers, 1320 ones corresponding to earthquakes with $M_w > 4$ are selected; among them, 540 high quality waveform registers from 131 earthquakes are kept. Among them, 149 registers with PGA ≥ 0.01 g corresponding to 80 earthquakes have been finally kept for this study. The highest moment magnitude is 7.6, Kocaeli earthquake (17/08/1999). The latest earthquakes of Kütahya-Simav (19/05/2011) and Van-Muradiye-Merkez (23/10/2011) have been also incorporated; from the Kütahya-Simav 17 registers have PGA ≥ 0.01 g are kept while from the Van-Muradiye-Merkez 4 registers with PGA ≥ 0.01 g have been also added. Finally, 169 registers corresponding to 82 seismic events and being recorded in 90 stations are considered in this study. Every register contains horizontal (NS and EW) and vertical accelerograms; vertical components are disregarded.

The severity of the earthquakes is characterized by the local, moment and surface magnitudes, denoted by M_L, M_W, and M_S, respectively. The soil is classified in: soft soil, stiff soil and rock. When the shear wave velocity averaged in the top 30 m ($v_{s,30}$) is available (in 175 stations), the classification is based on that parameter; soft soil, stiff soil, and rock sites correspond to 180 m/s $< v_{s,30} < 360$ m/s, 360 m/s $< v_{s,30} < 800$ m/s and $v_{s,30} > 800$ m/s, respectively. In the EC-8 [EN 1998 2004], these three categories correspond to ground types C, B and A, respectively; no stations with $v_{s,30} < 180$ m/s exist, hence, this study does not cover soil types D and E. In 5 stations the soil classification is not based on $v_{s,30}$ and in 13 stations (corresponding to 13 registers) the soil type is not known; such 13 registers are disregarded. The seismic zone corresponds to the Turkish design code [TSC 2007]; for seismic zones 1, 2 and 3 the design seismic acceleration is 0.4 g, 0.3 g and 0.2 g, respectively. The impulsive characteristics of the ground motions is characterized by dimensionless index I_D [Manfredi 2001]:

$$I_{\text{D}} = \frac{\int \ddot{z}_{\text{g}}^2 dt}{\dot{z}_{\text{g}}^{\max} \dot{z}_{\text{g}}^{\max}} \tag{5}$$

The integral extends to the ground motion bracket duration. Impulsive ground motions show typically low values of I_{D} (say, less than 10) whereas non-impulsive ground motions exhibit large I_{D} (say, greater than 10).

The registers are treated with baseline correction and with bi-directional, zero-shift ("acausal"), 4th-order Butterworth filtering. The purpose of the band-pass filtering is to remove long-period and short-period noise. The low and high-cut frequencies are decided case by case by an iterative procedure, carried out on the Fourier spectra, until the resulting velocity and displacement traces are considered as visually acceptable. The low-cut frequency ranges generally in between 0.05 and 0.5 Hz (2 and 20 s) and the high-cut frequency ranges in between 15 and 40 Hz (0.067 and 0.025 s).

For the proposal of design energy spectra, the registers are classified in 12 groups according to the following issues:

- **Soil type**. The three aforementioned soil types (rock / stiff soil / soft soil) are considered.
- **Magnitude of the earthquake**. The Eurocode 8 [EN 1998 2004] proposes two different design spectra, termed as Type 1 and Type 2; since they correspond to registers from earthquakes with surface magnitude higher and smaller than 5.5, respectively, the registers are classified in those arising from earthquakes with $M_{\text{s}} > 5.5$ and $M_{\text{s}} \leq 5.5$.
- **Near-fault effects**. Impulsive and vibratory registers are separately considered; as discussed after equation (5), such categories correspond to $I_{\text{D}} \leq 10$ and to $I_{\text{D}} > 10$, respectively.

Given the scarcity of results corresponding to rock, only stiff soil and soft soil are considered; therefore, 8 groups of registers are finally analysed: stiff soil / soft soil, $M_{\text{s}} > 5.5$ / $M_{\text{s}} \leq 5.5$ and impulsive / vibratory. However, for rock, some incomplete results about design spectra are also proposed; the lack of seismic information for Turkey is partially compensated by the one provided by other sources.

4. PROPOSAL OF DESIGN INPUT ENERGY SPECTRA

This section describes the proposal of linear design input energy spectra in terms of velocity, V_{E}. These spectra are derived from linear dynamic analyses for the considered registers. As indicated in the Introduction, in the mid and long period ranges the input energy is a rather stable quantity that is primarily governed by the total mass and fundamental period T of the structure, being scarcely affected by its strength or hysteretic properties; therefore, in these period ranges the linear spectra can be also used for nonlinear design. Conversely, in the short period range the energy spectral ordinates are not as clearly independent on the resistance and the hysteretic behavior; therefore, nonlinear dynamic analyses should be carried out. The spectra are proposed for each of the aforementioned eight groups (stiff soil / soft soil, impulsive / vibratory, $M_{\text{s}} > 5.5$ / $M_{\text{s}} \leq 5.5$); given the scarcity of registers out of the seismic zone 1 (see Figure 1) and their rather low intensity, only inputs from zone 1 are considered. For each of these eight groups, median and characteristic spectra are proposed; such levels are intended to correspond to 50% and to 95% percentiles, respectively. The observation of the obtained spectra [Yazgan 2012] shows that they do not fit any statistical distribution; therefore, the median and characteristic values are determined regardless of the statistical distribution.

Given the proportionality between the relative velocity spectra and the V_E spectra, the proposed spectra are expected to be basically shaped as the result of multiplying the design acceleration spectra proposed by the Eurocode 8 [EN 1998 2004] by factor $T / 2\pi$. Therefore, these spectra have three branches, corresponding roughly to the short, medium and long period ranges, respectively; the first branch is linear starting from zero, the second branch is constant, and the third branch is decreasing. Figure 1 shows a sketch of such a spectrum; T_C and T_D are the corner periods separating the aforementioned three branches.
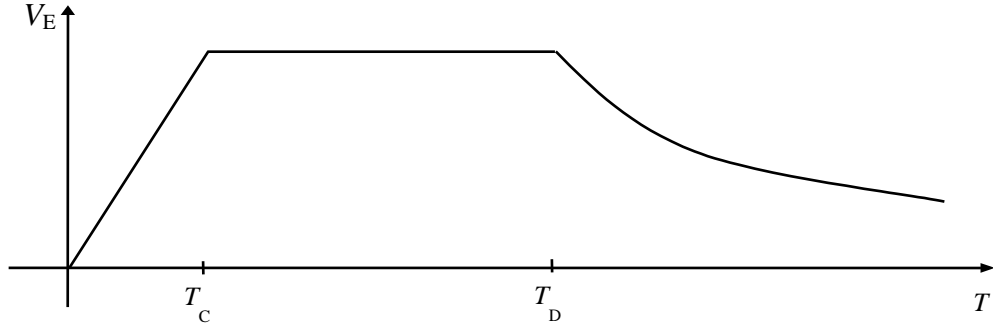

Figure 1. Proposed linear V_E design spectra

In Figure 1 the descending branch (for $T \geq T_D$) follows the equation

$$V_E = V_E^{max} \left(\frac{T_D}{T} \right)^a \tag{6}$$

In equation (6), V_E^{max} is the spectral ordinate of the plateau and a is an exponent. Figure 1 and equation (6) show that every linear proposed spectrum is characterized by the periods T_C and T_D, by the plateau ordinate V_E^{max} and by the exponent a.

The proposal of the linear design input energy spectra in terms of velocity (V_E) in the range of periods $0 - T$ consists of deriving separately normalized spectra ($V_E / \|V_E\|_T$) and spectral factors ($\|V_E\|_T$); the proposed V_E design spectra are obtained by multiplying the normalized spectra by the spectral factors. The norm $\|V_E\|_T$ is defined as the integral of the V_E spectrum:

$$\left\| V_E \right\|_T = \int_0^T V_E \, dT \tag{7}$$

The normalized spectra are obtained from the linear analyses carried out on the considered Turkish registers. However, given the scarcity of available strong inputs, the spectral factors are obtained from the Turkish recordings only in the group where the inputs are more demanding ("Soft Soil / $M_s > 5.5$ / Impulsive"); in the other groups the available registers are too small, and this lack of seismic information is complemented with the information provided by other studies [Decanini, Mollaioli 1998] and by some of the major design codes [EN 1998 2004; BSL 2009; UBC 1997]. The linear analyses consist of determining the value of E_I in equation (3) for SDOF systems with damping factor $\zeta = 0.10$ and for natural periods T ranging in between 0.02 and 8 s.

The criteria for estimating, for each of the aforementioned eight groups (section 3), the values of the parameters T_C, T_D, max(V_E / ‖V_E‖$_T$) and a that characterize every normalized spectrum are described next.

- **Period T_C.** For each of the aforementioned eight groups, the procedure to estimate the median and characteristic values of the corner period T_C consists of the following consecutive steps: (i) for each individual normalized spectrum, T_C is initially defined as the intersection between their initial (linear, starting from the origin) and maximum (horizontal) envelopes; (ii) for all the individual normalized spectra considered in this group, the median and characteristic values of such T_C periods are determined; (iii) the initial median and characteristic branches are finally obtained by joining the origin and the points of the abovementioned maximum linear envelopes that correspond to the median and characteristic values of T_C, respectively.
- **Period T_D.** Given that the Eurocode 8 proposes separate design spectra for registers corresponding to $M_s > 5.5$ and to $M_s \leq 5.5$ (Type 1 and Type 2, respectively) and that in both cases the values of T_D do not depend on the soil type, we have tried to preserve these features in this study. Eurocode 8 states $T_D = 2$ s and $T_D = 1.2$ s for Type 1 and Type 2 spectra, respectively; in this study values $T_D = 1.6$ s and $T_D = 0.9$ s have provided better fits and are adopted for registers corresponding to $M_s > 5.5$ and to $M_s \leq 5.5$, respectively. Remarkably, these values are considered regardless of the soil type and the near-source effects; as well, no distinction is made between median and characteristic spectra.
- **Plateau ordinate max(V_E / ‖V_E‖$_T$).** For each of the aforementioned eight groups (section 3), the maximum normalized spectral ordinates are estimated, in the range $T_C - T_D$, as the average of the median and characteristic values of the normalized spectra. In this operation the spectra that came from individual spectra with smallest norms have been disregarded.
- **Exponent a.** For each of the aforementioned eight groups (section 3), the exponent a is determined as providing the best fit, in the range $T_D - T$.

Since most of the civil engineering constructions correspond to periods not exceeding 4 s, in this study $T = 4$ s, i.e. the proposed design spectra are limited to the range 0 – 4 seconds. However, the linear dynamic analyses have been carried out along the interval 0 – 8 seconds; when relevant peaks have been detected for periods $4 < T < 8$ seconds, this information has been considered for modifying the descending branch. For each of the aforementioned eight groups (section 3), Table 1 shows the actual number of the considered registers (n) and the values of the parameters T_C, T_D, max(V_E / ‖V_E‖$_T$) and a for the median / characteristic V_E / ‖V_E‖$_4$ normalized spectra; Figure 2 displays those spectra. Each of the eight groups of plots inside Figure 2 contains the individual normalized spectra, the median and characteristic ones and the proposed (smoothed) median and characteristic normalized spectra.

Table 1. Parameters for the median / characteristic normalized spectra V_E / ‖V_E‖$_4$							
Soil type	Magnitude	Pulses	n	T_C (s)	T_D (s)	max(V_E / ‖V_E‖$_4$) (s^{-1})	a
Stiff Soil	$M_s > 5.5$	Impulsive	12	0.41 / 0.18	1.60 / 1.60	0.28 / 0.46	0.55 / 0.5*
		Vibratory	5	0.22 / 0.17	1.60 / 1.60	0.35 / 0.47	1.0 / 1.2
	$M_s \leq 5.5$	Impulsive	8	0.30 / 0.20	0.90 / 0.90	0.52 / 0.85	1.3 / 1.5
		Vibratory	9	0.27 / 0.19	0.90 / 0.90	0.49 / 0.78	1.2 / 1.2
Soft Soil	$M_s > 5.5$	Impulsive	19	0.54 / 0.32	1.60 / 1.60	0.34 / 0.53	1.0 / 0.8*
		Vibratory	13	0.53 / 0.28	1.60 / 1.60	0.33 / 0.50	0.9 / 0.65
	$M_s \leq 5.5$	Impulsive	11	0.29 / 0.21	0.90 / 0.90	0.46 / 0.70	0.9 / 1.0
		Vibratory	18	0.26 / 0.18	0.90 / 0.90	0.41 / 0.69	0.7 / 0.9

(*) These values have been modified to fit the peaks inside the range from 4 to 8 s.

(a) Stiff soil. $M_s > 5.5$. Impulsive

(b) Stiff soil. $M_s > 5.5$. Vibratory

(c) Stiff soil. $M_s \leq 5.5$. Impulsive

(d) Stiff soil. $M_s \leq 5.5$. Vibratory

(e) Soft soil. $M_s > 5.5$. Impulsive

(f) Soft soil. $M_s > 5.5$. Vibratory

(g) Soft soil. $M_s \leq 5.5$. Impulsive
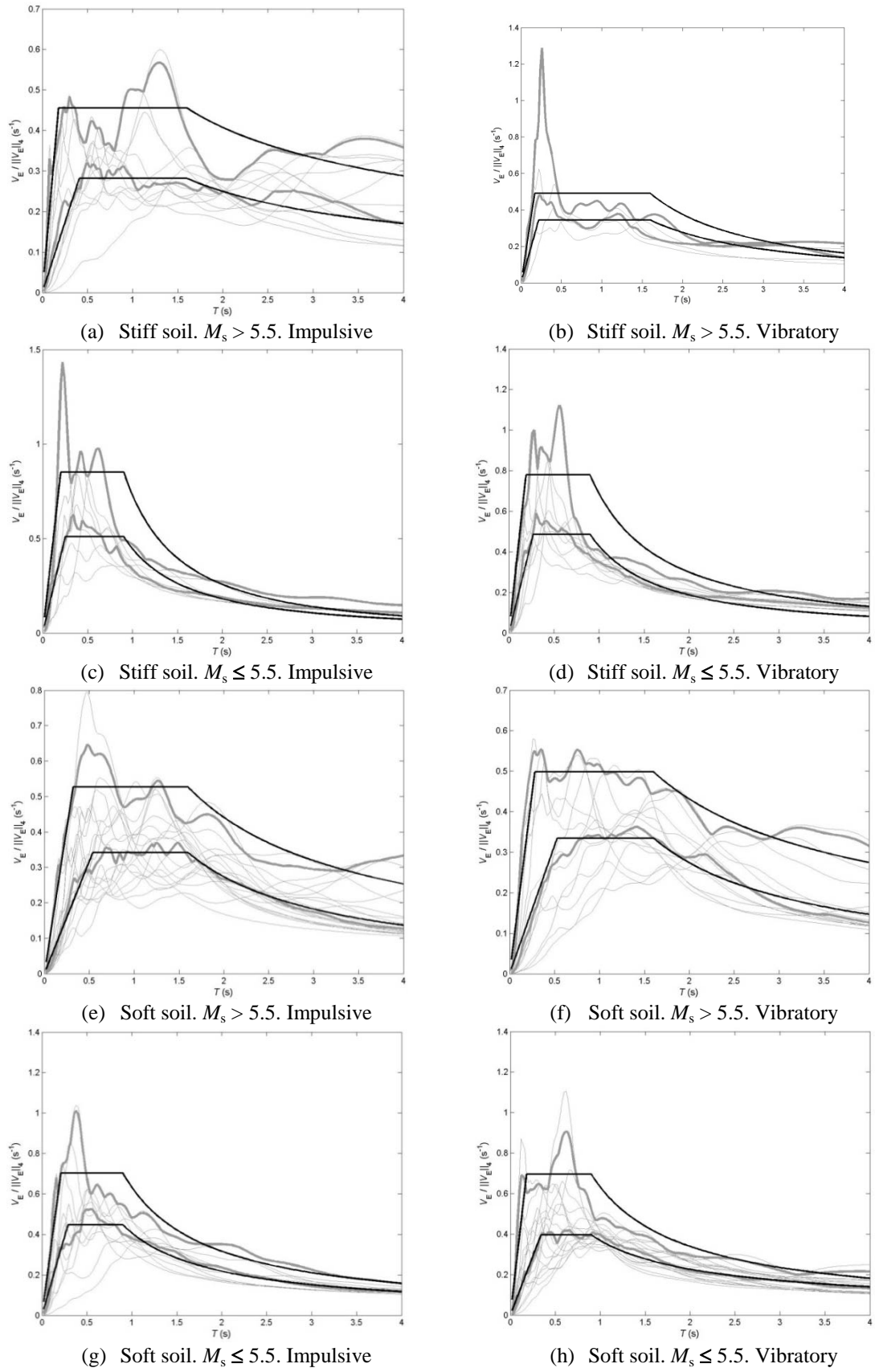
(h) Soft soil. $M_s \leq 5.5$. Vibratory

Figure 2. Proposed normalized $V_E / \|V_E\|_4$ design spectra

As discussed previously, the proposed V_E design linear spectra are obtained by multiplying the smoothed (three-branched) normalized spectra shown in Figure 2 by the spectral factors‖V_E‖$_4$. To obtain such factors, Table 2 displays the plateau ordinates V_E^{max} of several V_E spectra. First column contains the spectral values described in the reference [Decanini, Mollaioli 1998] and second, third and fourth columns contain the design quantities according to the Eurocode 8 [EN 1998 2004], the Japanese code [BSL 2009] and the UBC-97 [UBC 1997], respectively; in all these codes, the design ground acceleration is 0.4 g. Last two columns exhibit the values obtained in this study and the proposed ones, respectively. Deeper descriptions of the criteria considered to select the figures shown in the first four columns in Table 2 are listed next.

- **Decanini, Mollaioli 1998**. Those spectra were proposed after linear analyses on registers classified according to soil conditions, earthquake magnitude and source-to-site distance. Values in Table 2 have been selected to correspond to conditions similar to those in this study [Yazgan 2012]. In Table 2, left / right figures correspond to mean and to mean + standard deviation values, respectively.
- **Eurocode 8**. The Eurocode 8 does not propose energy spectra, the V_E values have been estimated as discussed in [Yazgan 202]. The cases for magnitude higher and smaller than 5.5 correspond to Type 1 and to Type 2 spectra, respectively. The obtained quantities have been assigned to vibratory registers and to characteristic values.
- **BSL 2009**. The spectral ordinates have been derived from the input energy design spectra proposed by the Japanese code.
- **UBC 1997**. The input energy has been determined following the same approach than in the Eurocode 8. For earthquakes with $M_s > 5.5$ the values for impulsive registers are obtained by multiplying those from the vibratory ones by factor N_v; it is assumed that $N_v = 1.6$.

Table 2. V_E design values of the constant-velocity branches (V_E^{max}) (cm/s)								
Soil type	M_s	Velocity pulses	Decanini, Mollaioli (1998)	Eurocode 8	Japanese code	UBC-97	This study	Proposal
Rock	$M_s > 5.5$	Impulsive	– / –	– / –	– / –	– / 142	– / –	168 / 260
Rock	$M_s > 5.5$	Vibratory	– / –	– / 89	– / 234	– / 88	– / –	84 / 129
Rock	$M_s \le 5.5$	Impulsive	– / –	– / –	– / –	– / 88	– / –	51 / 80
Rock	$M_s \le 5.5$	Vibratory	– / –	– / 56	– / 234	– / 88	– / –	28 / 43
Stiff Soil	$M_s > 5.5$	Impulsive	312 / 361	– / –	– / –	– / 199	56 / 93	235 / 364
Stiff Soil	$M_s > 5.5$	Vibratory	155 / 179	– / 133	– / –	– / 123	17 / 22	117 / 181
Stiff Soil	$M_s \le 5.5$	Impulsive	95 / 110	– / –	– / –	– / 123	37 / 60	72 / 112
Stiff Soil	$M_s \le 5.5$	Vibratory	52 / 60	– / 75	– / –	– / 123	11 / 17	39 / 60
Soft Soil	$M_s > 5.5$	Impulsive	338 / 419	– / –	– / –	– / 227	255 / 395	255 / 395
Soft Soil	$M_s > 5.5$	Vibratory	228 / 283	– / 153	– / 312	– / 142	69 / 104	172 / 266
Soft Soil	$M_s \le 5.5$	Impulsive	129 / 160	– / –	– / –	– / 142	27 / 41	97 / 150
Soft Soil	$M_s \le 5.5$	Vibratory	72 / 89	– / 83	– / 312	– / 142	21 / 34	54 / 84

Fifth column in Table 2 contains the constant-velocity spectral ordinates obtained in this study for seismic zone 1 in Turkey (design ground acceleration 0.4 g); left / right figures correspond to median / characteristic values, respectively. Comparison among these quantities and the figures indicated in the previous four columns shows that only in the group "Soft Soil / $M_s > 5.5$ / Impulsive" the number of available strong registers is enough to provide highly demanding results; in the other groups, the obtained spectral ordinates are too small to represent the actual seismicity. Therefore, this lack of data has to be compensated with the information provided by the previous four columns. Last column in Table 2 displays the constant-velocity spectral ordinates proposed in this study. The proposed median values have been determined taking into account the first four columns while the characteristic values are obtained from the median ones

by assuming that the median / characteristic ratios are the same than in the group "Soft Soil / M_s > 5.5 / Impulsive". For stiff and soft soil the median values are determined according to the mean values obtained by Decanini and Mollaioli; for rock, such values are estimated by dividing those for stiff soil by 1.4 as indicated by the UBC-97 (fourth column) for earthquakes with M_s > 5.5. The proposed V_E design linear spectra are shaped like the normalized spectra shown in Figure 2 but the plateau ordinates V_E^{max} are taken from Table 2; in other words, the corner periods T_C and T_D and the exponent a are selected from Table 1 while the norm $\|V_E\|_4$ is chosen according to the figures in Table 2. Figure 3 displays the proposed V_E linear spectra corresponding to stiff soil and to soft soil; for comparison, the unscaled individual spectra that have been used to derive the design ones are also plotted. For rock, the lack of available information does not allow deriving V_E design spectra apart from the plateau ordinates indicated in Table 2. The spectra drawn in Figure 3 correspond to seismic zone 1 in Turkey, whose design input acceleration is 0.4 g; in the other seismic zones of Turkey and of other countries, the design spectra can be obtained by multiplying the spectral ordinates by the ratio among the actual design acceleration and 0.4 g.

5. CONCLUSIONS

This paper presents design input energy spectra in terms of velocity obtained from linear analyses of Turkish registers. The proposed spectra have three branches: for short periods the initial branch is linear starting from zero, for intermediate periods the mid branch is constant and for long periods a descending branch is proposed. Further studies will involve nonlinear analyses leading to the proposal of nonlinear spectra and of approximate criteria for estimating the ratio between the hysteretic and the input energy.

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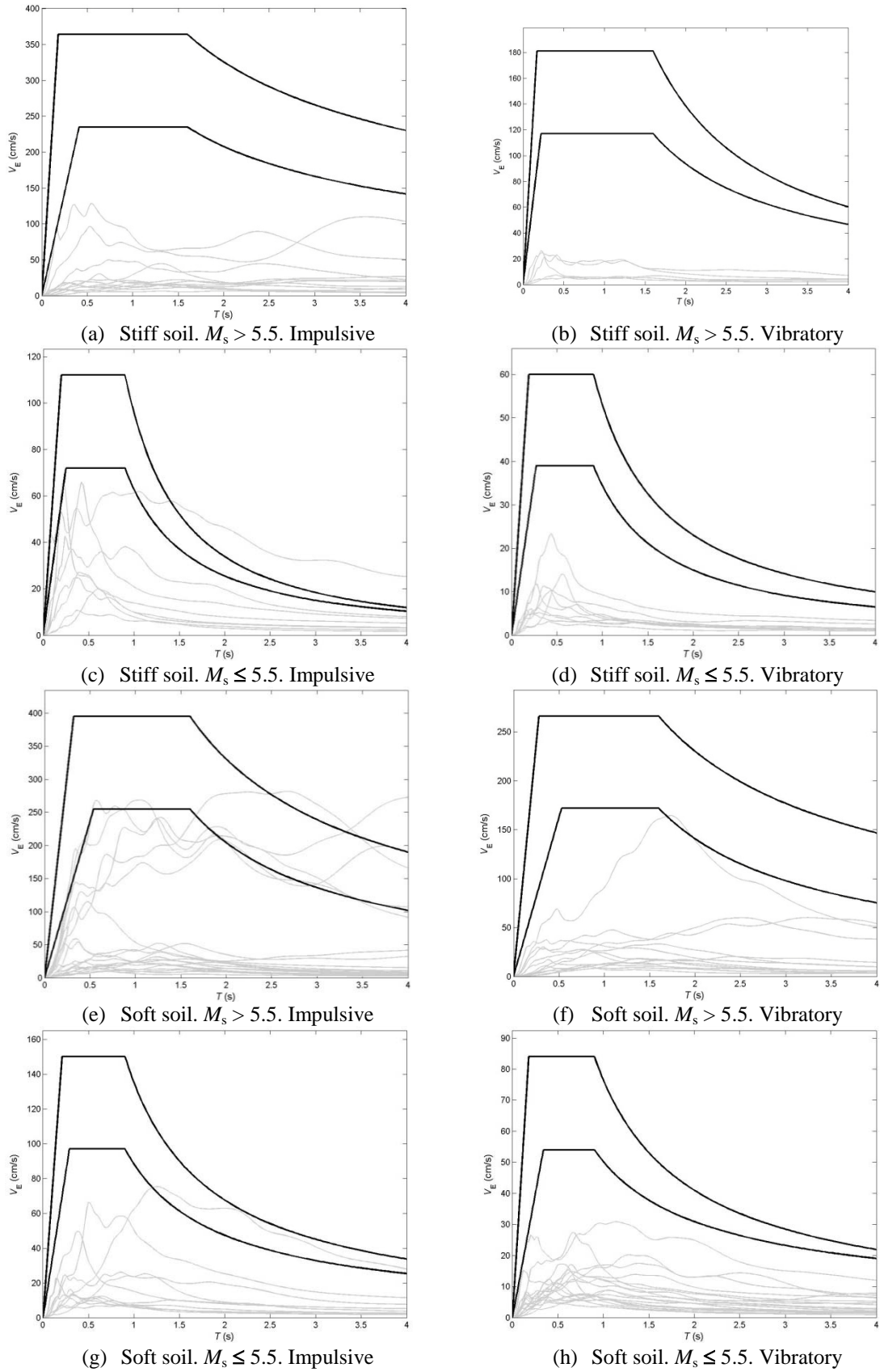
(a) Stiff soil. $M_s > 5.5$. Impulsive

(b) Stiff soil. $M_s > 5.5$. Vibratory

(c) Stiff soil. $M_s \leq 5.5$. Impulsive

(d) Stiff soil. $M_s \leq 5.5$. Vibratory

(e) Soft soil. $M_s > 5.5$. Impulsive

(f) Soft soil. $M_s > 5.5$. Vibratory

(g) Soft soil. $M_s \leq 5.5$. Impulsive

(h) Soft soil. $M_s \leq 5.5$. Vibratory

Figure 3. Linear V_E design spectra proposed for design acceleration 0.4 g