Design energy input spectra for high seismicity regions based on Turkish registers

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SUMMARY:
This work proposes design energy spectra in terms of an equivalent velocity, intended for regions with design peak acceleration 0.3 g or higher. These spectra were derived through linear and nonlinear dynamic analyses on a number of selected Turkish strong ground motion records. In the long and mid period ranges the analyses are linear, given the relative insensitivity of the spectra to structural parameters other than the fundamental period; conversely, in the short period range, the spectra are more sensitive to the structural parameters and, hence, nonlinear analyses are required. The selected records are classified in eight groups with respect to soil type (stiff or soft soil), the severity of the earthquake in terms of surface magnitude M_s ($M_s \leq 5.5$ and $M_s > 5.5$) and the relevance of the near-source effects (impulsive or vibratory). For each of these groups, median and characteristic spectra are proposed; such levels would respectively correspond to 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. Empirical criteria for estimating the hysteretic energy from the input energy are suggested. The proposed design spectra are compared with those obtained from other studies.

Keywords: energy spectra; input energy; hysteretic energy; ductility; nonlinear time history analysis; Turkey

1. Introduction

In the 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 an equivalent Single-Degree-of-Freedom (SDOF) system. This approach entails several drawbacks: (i) these equivalent forces are strongly coupled to the elastic and hysteretic characteristics of the structure, thus making seismic design cumbersome, (ii) after the onset of yielding, correlation between the design forces and the structural damage is not feasible, and (iii) the damage caused by the cumulative inelastic excursions [Fajfar, Vidic, 1994] is not accounted for. More recently, 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, in turn obtained from displacement response spectra relating the PGA to the maximum relative displacement in the top of the building. This formulation partially uncouples the input effect −in terms of displacement− from the characteristics of the structure and allows for a satisfactory correlation between the imposed displacement and the component of the structural damage that is related to the maximum displacement. Conversely, the component of damage that is related to the cumulative plastic strain energy cannot be appropriately considered. A more rational seismic design approach, which also overcomes this difficulty, is to express the dynamic input effect through energy response spectra. Interpreting the effect of earthquakes in terms of energy is gaining extensive attention [Housner, 1956; Berg, Tomaides, 1960; Kato, Akiyama, 1975; Housner, Jennings, 1977; Hall et al., 1984; Zahrah, Hall, 1984; Akiyama, 1985; Uang, Bertero, 1988 and 1990; Kuwamura et al., 1994; Bruneau, Wang, 1996; Bertero et al., 1996; Yei, Otani, 1999; Chou et al., 2000; Chou, Uang, 2003; Adang 2007; Leelataviwat et al. 2009; Jiao et al., 2011]. This approach features three major advantages: (i) the input effect in terms of energy and the structural resistance in terms of energy dissipation capacity 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 and can be directly addressed. In the energy-based methods the design criterion resides in 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 presents energy spectra for earthquake-resistant design based on accelerograms registered in high seismicity regions of Turkey. The spectra were derived through linear and nonlinear dynamic analyses of selected Turkish accelerograms. In the long and mid period ranges the analyses are linear, given the rather low sensitivity of the spectra to structural parameters other than mass and fundamental period. Conversely, in the short period range, the spectra are more sensitive to the structural parameters, for which reason the analyses must be nonlinear, and they take constant-ductility into account.

The registers studied were selected from among those available in Turkey. The chosen records were 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 Eurocode 8 classification), the magnitude of the earthquake and the relevance of near-source effects, namely the velocity pulses. The design energy spectra are envelopes of the actual spectra, in terms of equivalent velocity, corresponding to each input (pair of horizontal components); the influence of the vertical components was 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.

Empirical criteria for estimating the energy input contributable to damage (hysteretic energy) from the total input energy are also suggested. These criteria mainly take into account the damping level, the degree of plastification, and the period.

The proposed design energy input spectra are compared with those obtained from other studies.

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:

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

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

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

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:

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

E_a comprises the recoverable elastic strain energy, E_s, and the irrecoverable hysteretic energy E_H that represents the cumulative damage to the structure: $E_\mathrm{a} = E_\mathrm{s} + E_\mathrm{H}$. In turn, the sum of E_k and E_s constitutes the elastic vibrational energy of the system, ($E_\mathrm{e} = E_\mathrm{k} + E_\mathrm{s}$), so that equation (2) can be rewritten as:

$$E_\mathrm{e} + E_\zeta + E_\mathrm{H} = E_\mathrm{I} \tag{4}$$

The difference between E_I and E_ζ, was denominated by Housner [Housner 1956] as the energy input that contributes to damage E_D, that is:

$$E_D = E_I - E_\zeta = E_e + E_H \tag{5}$$

At the end of the ground motion duration E_e is almost zero; consequently, from equations (4) and (5) it follows that E_H can be taken as equal to E_D, i.e. $E_H \approx E_D$. Further, E_I and E_D can be normalized by the mass m and expressed in terms of equivalent velocities V_E and V_D defined by:

$$V_E = \sqrt{2E_I / m} \qquad\qquad V_D = \sqrt{2E_D / m} \tag{6}$$

For a given ground motion, the relationship between the input energy E_I expressed in terms of the equivalent pseudo-velocity V_E by equation (5) 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 equivalent 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):

$$V_E = \sqrt{V_{E,NS}^2 + V_{E,EW}^2} \tag{7}$$

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 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 Akiyama's approach while the second and third steps are modified. The second step features two major modifications: (i) two envelopes are proposed, corresponding to median and characteristic values, and (ii) the envelopes are not bilinear but also contain a descending branch in the long period range. In the third step, the shifting of the slope of the initial branch is not carried out by multiplying by a constant factor; rather, the factor is derived from constant-ductility nonlinear analyses, according to equation (3). The registers are classified in eight groups according to the soil type (stiff or soft soil), the severity of the earthquake in terms of surface magnitude M_s ($M_s \leq 5.5$ or $M_s > 5.5$) and the relevance of the velocity pulses in the input (impulsive or vibratory).

Once E_I is determined through design energy input spectra, the energy contributing to damage E_D can be estimated through the ratio E_D / E_I. For convenience, E_D / E_I can be expressed in terms of the equivalent velocities by V_D / V_E. Past studies [Akiyama 1985; Kuwamura, Galambos 1989; Kuwamura et al. 1994; Fajfar, Vidic 1994; Manfredi 1995; Lawson, Krawinkler 1995; Teran-Gilmore 1996; Decanini, Mollaioli 2001; Benavent et al. 2002 and 2010] show that V_D / V_E depends mainly on damping and ductility, and put forth empirical expressions of the ratio V_D / V_E in terms of damping and ductility parameters. The present contribution proposes a new criterion to estimate V_D / V_E that accounts for the characteristics of the above eight groups considered.

3. Turkish registers

A dataset from 1976 to 2006 [Erdogan 2008, Akkar et al. 2010] constitutes is the basis of this work. It covers 4203 registers from 2818 seismic events recorded at 327 stations. Of the 4203 registers, we selected 1320 corresponding to earthquakes with moment magnitude $M_w > 4$; among them, 540 high quality waveform registers from 131 earthquakes were taken, and finally, 149 registers with PGA ≥ 0.01 g corresponding to 80 earthquakes were kept for this study. The highest moment magnitude is 7.6, the Kocaeli earthquake (17/08/1999). The latest earthquakes of Kütahya-Simav (19/05/2011) and Van-Muradiye-Merkez (23/10/2011) were also included; from the Kütahya-Simav 17 registers with PGA ≥ 0.01 g and four registers from the Van-Muradiye-Merkez with PGA ≥ 0.01 g were used. Altogether, 169 registers corresponding to 82 seismic events and recorded at 90 stations are considered in this study. Every register contains horizontal (NS and EW) and vertical accelerograms; vertical components are disregarded.

Table 9 (Appendix) provides the most relevant information about the selected registers. The severity of the earthquakes is characterized by local, moment and surface magnitudes, respectively denoted by M_L, M_W, and M_S. The soil is classified as: soft soil, stiff soil or rock. When the shear wave velocity averaged in the top 30 m ($v_{s,30}$) was 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 respectively correspond to ground types C, B and A. Because there are no stations with $v_{s,30} <$ 180 m/s, this study does not cover soil types D and E. In five stations the soil classification is not based on $v_{s,30}$ and in 13 stations the soil type was not known and the corresponding 13 registers were disregarded. In view of 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. R_{jb}, R_{rup} and R_{epi} respectively correspond to Joyner-Boore, rupture and epicentral distances [Erdogan 2008]. Bracket duration (t_{br}) [Kempton, Stewart 2006] is comprised between the instants when 5% of the maximum acceleration is exceeded for the first and last time. Triffunac duration [Triffunac, Brady 1975] (t_{tf}) corresponds to the time interval in between 5% and 95% of integral $\int \ddot{z}_g^2 dt$. The Arias intensity I_A [Arias 1970] constitutes a measure of the destructive capacity of an accelerogram and is defined as

$$I_A = \frac{\pi}{2g} \int \ddot{z}_g^2 dt \tag{8}$$

The impulsivity of a given accelerogram can be detected in several ways [Baker 2007]. The dimensionless index I_D [Manfredi 2001] is a frequently used indicator defined by

$$I_D = \frac{\int \ddot{z}_g^2 dt}{\ddot{z}_g^{max} \dot{z}_g^{max}} \tag{9}$$

The integral extends to the ground motion duration. In the references [Iervolino et al. 2006, Cosenza et al. 2009] several threshold values of I_D are suggested. In this work it is assumed that $I_D < 10$ and $I_D > 10$ correspond to impulsive and to vibratory ground motions, respectively.

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 using an iterative procedure, carried out on the Fourier spectra, until the resulting velocity and displacement traces are considered visually acceptable. The low-cut frequency generally ranges between 0.05 and 0.5 Hz (2 and 20 s), while the high-cut frequency ranges from 15 to 40 Hz (0.067 and 0.025 s). This information is indicated in last two columns of Table 9. Although most of the information was taken from [Erdogan 2008], the values of the bracket and Triffunac durations, and the Arias and dimensionless indexes were determined in this study (Table 9).

Figure 1 displays the location and the soil type of the 90 stations that correspond to registers in Table 9; three of them correspond to rock, 35 to stiff soil, 42 to soft soil, and in 10 the soil type is not known. This information is superposed on the design peak ground acceleration established by the Turkish seismic design code [TSC 2007].

| Zone 1 (0.4 g) | Zone 2 (0.3 g) | Zone 3 (0.2 g) | Zone 4 (0.1 g) | Zone 5 (0.0 g) |
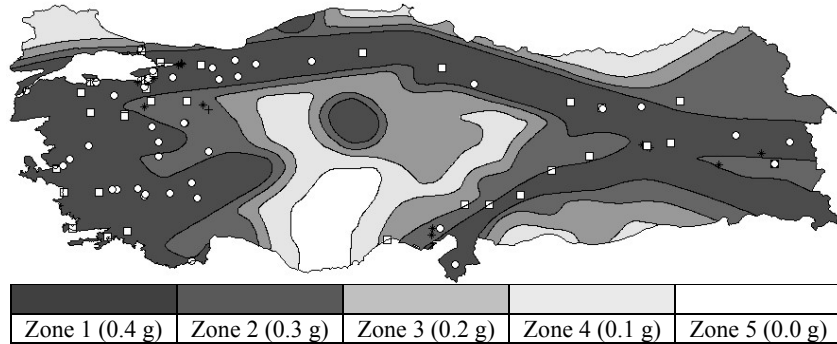
Figure 1. Location and soil type of the registering stations. Rock: "✚". Stiff soil: "☐". Soft soil: "◯". Unknown: "✳".

Figure 1 shows that most of the registering stations lie inside zone 1, i.e. the highest seismicity region of Turkey.

Figure 2 displays the location of the epicentres of the 82 earthquakes together with their magnitude.

| Zone 1 (0.4 g) | Zone 2 (0.3 g) | Zone 3 (0.2 g) | Zone 4 (0.1 g) | Zone 5 (0.0 g) |
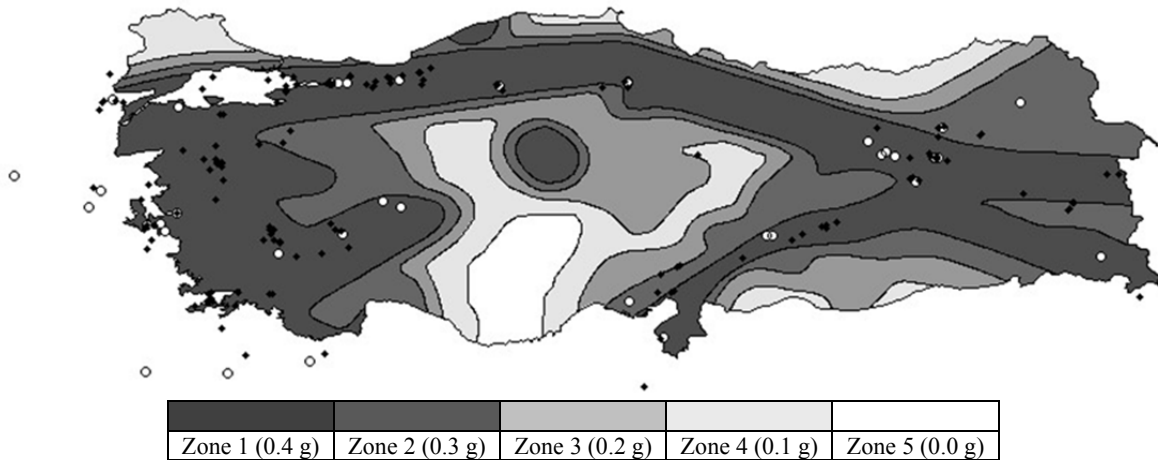
Figure 2. Locations of the epicenters and magnitudes of the earthquakes. $M_s \leq 5.5$: "◆". $M_s > 5.5$: "◯".

As seen in Figure 2, a considerable number of the epicenters are located inland, which means that important near-source effects can be expected; this is confirmed by the number of impulsive registers in Table 9.

The registers in Table 9 are classified into 12 groups in light of the following factors:

- **Soil type**. The three aforementioned soil types (rock / stiff soil / soft soil) are considered.
- **Magnitude of the earthquake**. Eurocode 8 [EN-1998 2004] proposes two different design spectra, designated as Type 1 and Type 2, corresponding to registers from earthquakes with surface magnitudes higher and smaller than 5.5, respectively. Accordingly, the registers in Table 9 are classified as produced by earthquakes with $M_s > 5.5$ or $M_s \leq 5.5$.
- **Near-fault effects**. Impulsive and vibratory registers are considered separately; as mentioned after equation (9), these categories correspond to $I_D \leq 10$ and to $I_D > 10$, respectively.

Given the scarcity of results corresponding to rock, it was decided to focus this study on stiff soil and soft soil. Therefore, eight groups of registers were finally analyzed: stiff soil / soft soil, $M_s > 5.5$ / $M_s \leq 5.5$ and impulsive / vibratory. For rock, some incomplete results about design spectra are also proposed, however, and the lack of seismic information for Turkey is partially compensated by other sources.

4. Proposal of design input energy spectra

4.1. Introductory remarks

This section describes the proposal of design input energy spectra in terms of velocity, V_E. These spectra are intended for structures with both linear and nonlinear behavior, respectively addressed in subsection 4.2 and subsection 4.3. The linear spectra are derived from linear dynamic analyses of the registers listed in Table 9. As indicated in the Introduction, in the mid and long period ranges the input energy is a rather stable quantity, primarily governed by the total mass and fundamental period T of the structure, and scarcely affected by its strength or hysteretic properties; therefore, in these period ranges the linear spectra can also be used for nonlinear design. Conversely, the energy spectral ordinates in the short period range are not as clearly independent of the resistance and hysteretic behavior, making necessary nonlinear dynamic analyses. The nonlinear spectra are proposed to be roughly equal to the linear ones in the mid and long period ranges, whereas in the short period range their ordinates are obtained by modifying those of the linear spectra with factors adequate to this end.

The linear and nonlinear spectra are proposed for each of the aforementioned eight groups (stiff soil / soft soil, impulsive / vibratory, $M_s > 5.5$ / $M_s \leq 5.5$); given the scarcity of registers out of the seismic zone 1 (see Figure 1) and their rather low intensity (see Table 9), only inputs from zone 1 are considered. For each group, median and characteristic spectra were established as the 50% and 95% percentiles, respectively. As the obtained spectra [Yazgan 2012] are not seen to fit any statistical distribution, the median and characteristic values were determined regardless of their distribution.

4.2. Linear spectra

Given the similarity between the relative velocity spectra and V_D spectra [Housner, 1956; Akiyama, 1985] and the limited sensitivity of ratio V_D / V_E to the period [Decanini, Mollaioli 2001, Benavent et al. 2010], the proposed spectra are expected to be basically shaped as the result of multiplying the design acceleration spectra according Eurocode 8 [EN-1998 2004] by the factor $T / 2\pi$. Therefore, these spectra have three branches, corresponding roughly to the short, medium and long period ranges. The first branch is linear and starts from zero, the second branch is constant, and the third branch decreases. Figure 3 offers a sketch, where T_C and T_D are the corner periods separating the three branches.
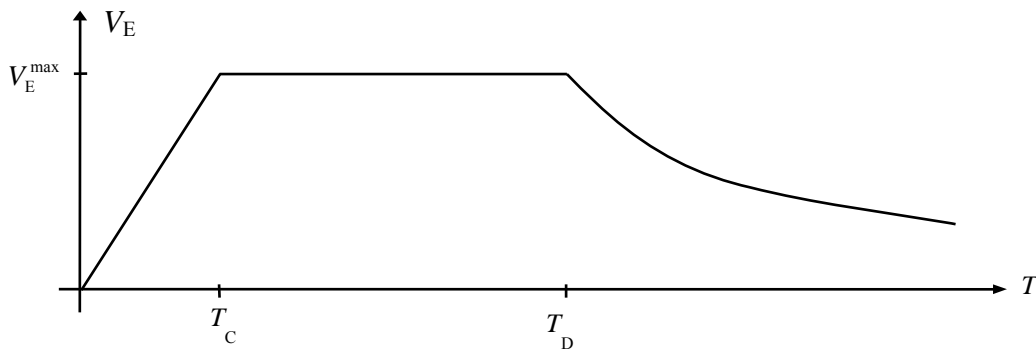

Figure 3. Proposed linear V_E design spectra

In Figure 3 the descending branch (for $T \geq T_D$) follows the equation

$$V_{\mathrm{E}} = V_{\mathrm{E}}^{\max} \left(\frac{T_{\mathrm{D}}}{T} \right)^{a} \tag{10}$$

In equation (10), $V_{\mathrm{E}}^{\max}$ is the spectral ordinate of the plateau and a is an exponent. Figure 3 and equation (10) show that every proposed linear spectrum is characterized by the periods T_{C} and T_{D}, by the plateau ordinate $V_{\mathrm{E}}^{\max}$ 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 ($V_{\mathrm{E}} / \|V_{\mathrm{E}}\|_{\mathrm{T}}$) and norms ($\|V_{\mathrm{E}}\|_{\mathrm{T}}$); the proposed V_{E} design spectra are obtained by multiplying the normalized spectra by the norms. This makes it possible to perform statistical studies on individual spectra obtained from registers of different intensities. The norm $\|V_{\mathrm{E}}\|_{\mathrm{T}}$ is defined as the integral of the V_{E} spectrum:

$$\|V_{\mathrm{E}}\|_{\mathrm{T}} = \int_{0}^{T} V_{\mathrm{E}} \, dT \tag{11}$$

The normalized spectra are obtained from the linear analyses carried out on the Turkish registers listed in Table 9. However, given the scarcity of available strong inputs, the norms are obtained from the Turkish recordings only in the group where the inputs are more demanding ("Soft Soil / $M_{\mathrm{s}} > 5.5$ / Impulsive"). For the other groups, the available registers are too small, and this lack of seismic information is offset with information from previous studies [Decanini, Mollaioli 1998] and major design codes [EN-1998 2004; BSL 2009; UBC 1997]. The linear analyses consisted of determining the value of E_{I} in equation (3) for SDOF systems with damping factor $\zeta = 0.10$ and for natural T periods between 0.02 and 8 s.

Below we specify the criteria for estimating, for each of the eight groups (section 3), the values of parameters T_{C}, T_{D}, $V_{\mathrm{E}}^{\max} / \|V_{\mathrm{E}}\|_{\mathrm{T}}$ and a that characterize every normalized spectrum. The spectra with the smallest norms, corresponded to minor registers, were disregarded.

- **Period T_{C}.** For each of the eight groups, the procedure to estimate the median and characteristic values of the corner period T_{C} involved the following consecutive steps: (i) for each individual normalized spectrum, T_{C} is initially defined as the intersection between the initial envelope (linear envelope starting from the origin) and the horizontal (maximum) envelope; (ii) for all the individual normalized spectra considered in this group, the median and characteristic values of such T_{C} periods are determined. The initial median and characteristic branches are finally obtained by joining the origin and the points of the above maximum linear envelopes corresponding to the median and characteristic values of T_{C}, respectively.
- **Period T_{D}.** Eurocode 8 proposes separate design spectra for registers corresponding to $M_{\mathrm{s}} > 5.5$ (Type 1) and to $M_{\mathrm{s}} \leq 5.5$ (Type 2), though T_{D} does not depend on the soil type in eithr case. In this study, the same value for T_{D} is used for all types of soil. Eurocode 8 specifies $T_{\mathrm{D}} = 2$ s and $T_{\mathrm{D}} = 1.2$ s for Type 1 and Type 2 spectra, respectively, whereas for our purposes values $T_{\mathrm{D}} = 1.6$ s and $T_{\mathrm{D}} = 0.9$ s provided better fits and were adopted for registers corresponding to $M_{\mathrm{s}} > 5.5$ and to $M_{\mathrm{s}} \leq 5.5$, respectively. These values are taken regardless of the soil type and the near-source effects, and no distinction is made between median and characteristic spectra.
- **Plateau ordinate $V_{\mathrm{E}}^{\max} / \|V_{\mathrm{E}}\|_{\mathrm{T}}$.** For each of the eight groups, the median and characteristic maximum normalized spectral ordinates $V_{\mathrm{E}}^{\max} / \|V_{\mathrm{E}}\|_{\mathrm{T}}$ are respectively estimated as the average, in the range $T_{\mathrm{C}} - T_{\mathrm{D}}$, of the median and characteristic values of the normalized spectra. The individual spectra having the smallest norms were disregarded in this operation.
- **Exponent a.** For each group, the exponent a is determined as providing the best fit, in the range $T_{\mathrm{D}} - T$.

Since most civil engineering constructions correspond to periods not exceeding 4 s, in this study $T = 4$ s, that is, the proposed design spectra are limited to the range $0 - 4$ seconds. However, the linear dynamic analyses were carried out in the interval $0 - 8$ seconds. When relevant peaks were detected for periods $4 < T < 8$ seconds, this information was considered for modifying the descending branch. For each of the eight groups, Table 1 gives the actual number of registers (n) and the values of parameters T_C, T_D, $V_E^{max} / \left\| V_E \right\|_T$ and a, for the median / characteristic $V_E / \left\| V_E \right\|_4$ normalized spectra. Figure 4 displays the spectra. Each of the eight groups of plots inside Figure 4 contains the individual normalized spectra (thin gray lines), the median and characteristic ones (bold gray lines) and the proposed (smoothed) median and characteristic normalized spectra (black bold lines).

Table 1. Parameters for the median / characteristic normalized spectra $V_E / \left\| V_E \right\|_4$							
Soil type	Magnitude	Pulses	n	T_C (s)	T_D (s)	$V_E^{max} / \left\| V_E \right\|_4$ (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

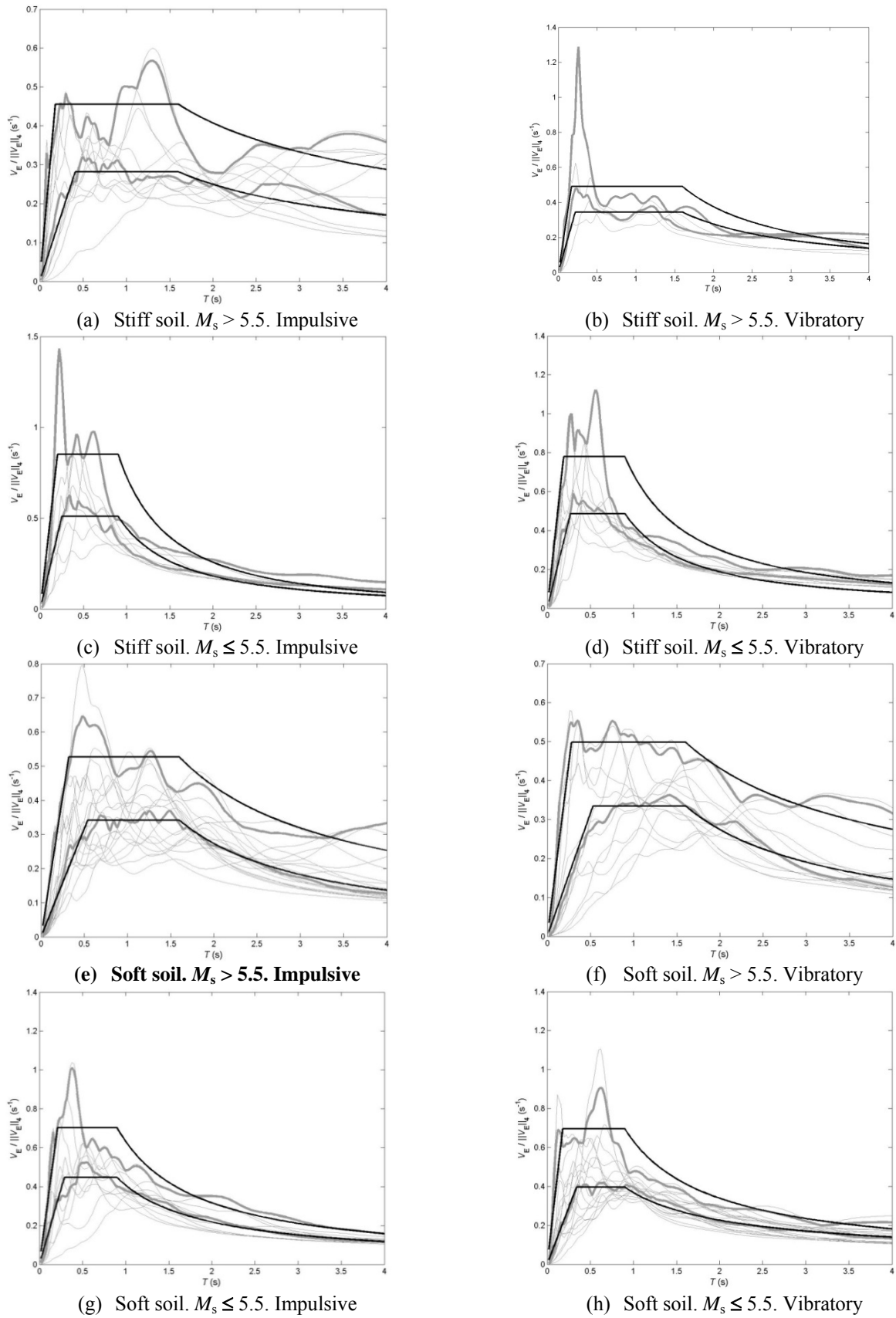(*) These values were modified to fit the peaks inside the range from 4 to 8 s.

Figure 4. Proposed normalized $V_E / \|V_E\|_4$ design spectra

As stated previously, the proposed V_E design linear spectra are determined by multiplying the smoothed (three-branched) normalized spectra shown in Figure 4 by norm $\|V_E\|_4$. Table 2 aims to highlight this process

by displaying the values of $\|V_E\|_4$ and of the ordinate values for the constant-velocity branches of several V_E spectra, i.e. their plateau ordinates V_E^{max}; the left / right figures represent median / characteristic values, respectively. The fourth column of Table 2 shows the values of norm $\|V_E\|_4$ obtained in this study as the average of the largest registers in each group [Yazgan 2012]. The fifth column contains the spectral values described in the reference [Decanini, Mollaioli 1998] and the sixth, seventh and eighth columns contain the design quantities according to the Eurocode 8 [EN-1998 2004], the Japanese code [BSL 2009] and the UBC-97 [UBC 1997]. In all these codes, the design ground acceleration is 0.4 g. Further details are given below.

- **Decanini, Mollaioli 1998**. These researchers described design spectra in terms of input energy normalized with respect to the mass (E_I / m); the corresponding V_E value in Table 2 was determined using equation (6). The design spectra were based on linear analyses of numerous seismic strong motions world-wide, classified by soil conditions, earthquake magnitude and source-to-site distance. The values shown in Table 2 were selected to represent similar conditions. Decanini and Mollaioli specified S1, S2 and S3 soil types; the "rock" and "stiff soil" in this work match their S1 while "soft soil" matches S2. Since the values proposed for soil S1 stand for the most demanding situation in this category, we assigned these values to "stiff soil" rather than "rock". The values for earthquake magnitude, as shown in Table 2, were $M_s > 5.5$ for the interval $6.5 - 7.1$ and $M_s \leq 5.5$ for the interval $4.2 - 5.2$. The values indicated for impulsive and vibratory registers are consistent with source-to-site distances smaller than 5 km, and between 12 and 30 km, respectively. In Table 2, left figures are mean values and the right ones give the mean + standard deviation.
- **Eurocode 8**. Since Eurocode 8 does not directly establish energy input spectra, V_E values were estimated by identifying the V_D spectra with the pseudo-velocity design spectra (S_v); their ordinates were determined by multiplying those of the acceleration design spectra S_a by $T / 2\pi$. Input energy in terms of velocity (V_E) was derived from V_D by means of the left-hand equation (14) [Akiyama 1985]. Magnitudes higher than 5.5 correspond to Type 1 spectra and those smaller than 5.5 are consistent with Type 2 spectra. Since Eurocode 8 does not contain any specific indication about directivity effects or the probability of exceeding the spectral ordinate, the obtained quantities were assigned to vibratory registers and to characteristic values.
- **BSL 2009**. The Japanese code provides energy input spectra directly in terms of V_D; the V_E spectra were obtained from V_D spectra as in Eurocode 8. The soil is classified in types 1, 2 and 3. Type 1 is considered to be equivalent to "rock" and type 2 matches the conditions of both "stiff soil" and "soft soil"; since the values for type 2 should correspond to the most demanding situation inside this category, they have been assigned to "soft soil".
- **UBC 1997**. Like Eurocode 8, the UBC-1997 code proposes energy input spectra indirectly, through absolute acceleration S_a response spectra. The input energy in terms of equivalent velocity (V_E) was accordingly determined along the lines of Eurocode 8. Soil is classified in six types, S_A to S_F; S_B is equivalent to "rock", S_C is "stiff soil" and S_D matches the conditions of "soft soil". Registers generated by earthquakes with $M_s > 5.5$ and with $M_s \leq 5.5$ are respectively identified with types A and C. For earthquakes with $M_s > 5.5$, the values for impulsive registers can be obtained by multiplying those of the vibratory ones by a factor N_v; under UBC-1997, it is assumed that $N_v = 1.6$.

Soil type	Magnitude	Velocity pulses	$\|V_E\|_4$ (cm)	Decanini, Mollaioli (1998)	Eurocode 8	Japanese code	UBC-97	This study	Proposal
Table 2. Mean / characteristic ordinates of the constant-velocity branches of the V_E spectra									
				(V_E^{max}) (cm/s)					
Rock	$M_s > 5.5$	Impulsive	–	– / –	– / –	– / –	– / 142	– / –	168 / 260
		Vibratory	–	– / –	– / 89	– / 234	– / 88	– / –	84 / 129
	$M_s \leq 5.5$	Impulsive	–	– / –	– / –	– / –	– / 88	– / –	51 / 80
		Vibratory	–	– / –	– / 56	– / 234	– / 88	– / –	28 / 43
Stiff Soil	$M_s > 5.5$	Impulsive	200	312 / 361	– / –	– / –	– / 199	56 / 93	235 / 364
		Vibratory	47	155 / 179	– / 133	– / –	– / 123	17 / 22	117 / 181
	$M_s \leq 5.5$	Impulsive	71	95 / 110	– / –	– / –	– / 123	37 / 60	72 / 112
		Vibratory	22	52 / 60	– / 75	– / –	– / 123	11 / 17	39 / 60
Soft Soil	$M_s > 5.5$	Impulsive	746	338 / 419	– / –	– / –	– / 227	**255 / 395**	255 / 395
		Vibratory	208	228 / 283	– / 153	– / 312	– / 142	69 / 104	172 / 266
	$M_s \leq 5.5$	Impulsive	59	129 / 160	– / –	– / –	– / 142	27 / 41	97 / 150
		Vibratory	50	72 / 89	– / 83	– / 312	– / 142	21 / 34	54 / 84

The ninth column of Table 2 contains the constant-velocity spectral ordinates V_E^{max} obtained in this study for seismic zone 1 in Turkey (design ground acceleration 0.4 g) obtained by multiplying the normalized ordinates $V_E^{max} / \|V_E\|_4$ given in the seventh column of Table 1 by norm $\|V_E\|_4$ in the fourth column of Table 2. Comparison of the obtained quantities and the figures in the previous four columns shows that only the group "Soft Soil / $M_s > 5.5$ / Impulsive" contains sufficient strong registers for highly demanding results; in the other groups, the obtained spectral ordinates are too small to represent the actual seismicity of Turkey. This lack of data calls for complementary information from the previous four columns, mainly the first one. Accordingly, the final column in Table 2 displays the constant-velocity spectral ordinates V_E^{max} proposed in this study for seismic zone 1 in Turkey. The proposed median values were determined taking into account columns five through eight, while the characteristic values were derived from the median ones by assuming that the median / characteristic ratios are the same as in the group "Soft Soil / $M_s > 5.5$ / Impulsive" that is, 255 / 395 = 0.646. This assumption stems from the consideration that the statistical properties are basically independent of soil type, earthquake magnitude and source-to-site distance. For stiff and soft soil, the median values were determined using the mean values of Decanini and Mollaioli and adopting the proportion of group "Soft Soil / $M_s > 5.5$ / Impulsive", which is 255 / 338 = 0.754. In contrast, for rock, we arrived at the median and characteristic values by dividing those proposed for stiff soil by 1.4, as indicated under UBC-97 (seventh column) for earthquakes with $M_s > 5.5$.

The proposed V_E design linear spectra are shaped like the normalized spectra shown in Figure 4, but the plateau ordinates V_E^{max} are taken from Table 2. Figure 5 displays the proposed V_E linear spectra corresponding to stiff soil and to soft soil; the unscaled individual spectra used to derive the design ones are also plotted for comparison. In the case of rock, available information did not allow for deriving V_E design spectra aside from the plateau ordinates indicated in Table 2.

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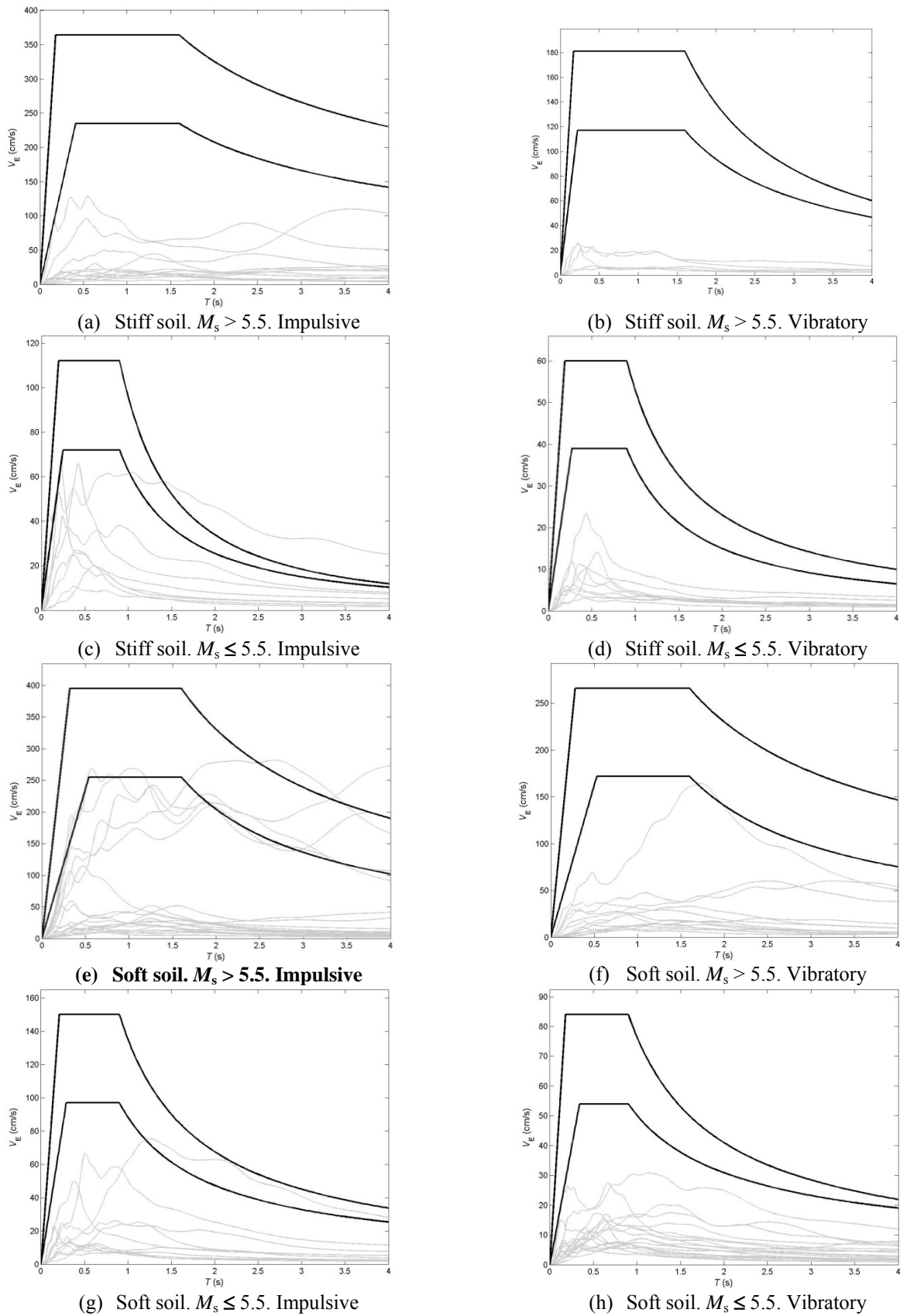
(h) Soft soil. $M_s \leq 5.5$. Vibratory

Figure 5. Linear V_E design spectra proposed for design acceleration 0.4 g

The spectra drawn in Figure 5 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 between the actual design acceleration and 0.4 g.

4.3. Nonlinear spectra

As discussed in section 2, the proposed V_E nonlinear spectra are similar to the linear ones except in the short period range, where the energy input in a nonlinear SDOF system with initial period T is larger than that of the counterpart elastic system with the same period of vibration, due to the elongation of the fundamental period of the structure generated by the nonlinear behavior. This causes a shortening of the corner period T_C that results in an increase of the slope of the initial branch. Akiyama [1985] suggested deriving the slope of the initial branch of the nonlinear spectra by multiplying the slope of the linear spectra by 1.2, a factor derived from a limited number of records; the authors believe a more precise evaluation is required because many low-to-medium rise buildings have fundamental periods in the range $0 - T_C$. The nonlinear time history analyses consist of determining the value of E_I given by equation (3) in the range $0 - 4$ seconds for the inputs listed in Table 9. The considered nonlinear SDOF systems have an elastic-perfectly plastic behavior and are therefore characterized by their damping ratio ζ, by their initial (elastic) natural period T, and by the displacement ductility μ. In this study, three values of ζ are considered (0.02, 0.05, 0.10) and six values of μ are considered (2, 3, 5, 10, 15, 20). Obtaining the spectrum of each acceleration record for a given fixed value of μ calls for performing iterative analyses in which the yield strength of the SDOF system, Q_y, is varied until the resulting μ reaches the prescribed target value with 10% tolerance. Since the accelerograms corresponding to NS and EW directions are considered separately, the total number of spectra obtained is $338 \times 3 \times 6 = 6084$. As discussed in the next section, these spectra are also used for estimating the ratio V_D / V_E.

For each nonlinear analysis the slope of the initial smoothed branch is obtained as the best linear fit in the range $0 - T_C$, and this slope is termed m_μ. Figure 6 displays, in thin dashed lines, some values of the ratio m_μ / m_1 that correspond to $\zeta = 0.05$; m_1 is the linear slope, i.e. corresponding to $\mu = 1$. The work [Yazgan 2012] shows the omitted plots and similar results for $\zeta = 0.02$ and 0.10. Given the high scattering of the values shown in Figure 6, these ratios cannot be used to modify the linear spectra; rather, they must be averaged and smoothed. The thick dashed lines in Figure 6 represent the median values, i.e. corresponding to the 50% percentile. Since these lines are too abrupt, they can be smoothed by means of the following equation [Benavent et al. 2010]:

$$\frac{m_\mu}{m_1} = p\,(\mu - 1) + \frac{(1 + r)\mu^s}{r + \mu^s} \tag{12}$$

In this study, parameter r is taken to be $r = 0.3$, while parameters p and s are determined the ones providing the best fit with the median values (thick dashed lines in Figure 6); the resulting values are indicated in Table 3. The smoothed ratios m_μ / m_1 are drawn with thick solid lines in Figure 6. Table 4 displays the smoothed factors m_μ / m_1 that will modify the slopes of the initial branches of the linear V_E spectra.

| (a) Stiff soil. $M_s > 5.5$. Impulsive | (b) Stiff soil. $M_s > 5.5$. Vibratory |

Figure 6. Factor modifying the slope of the initial branch of the linear V_E spectra. $\zeta = 0.05$
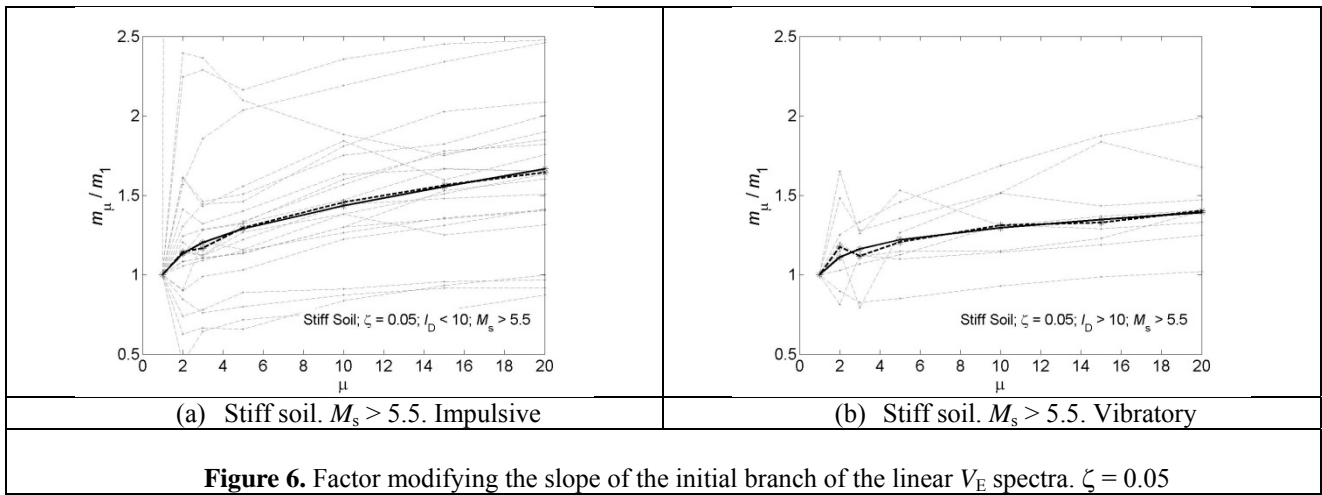
Table 3. Coefficients p and s for the correction of the slopes of the initial branches of the linear V_E spectra. $r = 0.3$

Soil type	Magnitude	Velocity pulses	$\zeta = 0.02$		$\zeta = 0.05$		$\zeta = 0.10$	
			p	s	p	s	p	s
Stiff Soil	$M_s > 5.5$	Impulsive	0.026	0.58	0.020	0.82	0.020	0.34
		Vibratory	0.010	0.687	0.007	0.741	0.012	0.204
	$M_s \leq 5.5$	Impulsive	0.025	0.88	0.030	0.41	0.037	0.088
		Vibratory	0.014	1.052	0.017	0.58	0.014	0.60
Soft Soil	$M_s > 5.5$	Impulsive	0.033	1.273	0.028	1.124	0.029	0.60
		Vibratory	0.019	0.70	0.016	0.43	0.018	0.23
	$M_s \leq 5.5$	Impulsive	0.015	1.59	0.015	1.052	0.015	0.70
		Vibratory	0.013	0.70	0.011	0.62	0.015	0.23

Table 4. Factors m_μ / m_1 correcting the slopes of the initial branches of the linear V_E spectra

Damping	Soil type	Magnitude	Pulses	$\mu = 2$	$\mu = 3$	$\mu = 5$	$\mu = 10$	$\mu = 15$	$\mu = 20$
$\zeta = 0.02$	Stiff Soil	$M_s > 5.5$	Impulsive	1.13	1.14	1.25	1.46	1.63	1.70
			Vibratory	1.34	1.27	1.43	1.51	1.43	1.46
		$M_s \leq 5.5$	Impulsive	1.18	1.24	1.26	1.46	1.66	1.75
			Vibratory	1.17	1.22	1.27	1.39	1.50	1.54
	Soft Soil	$M_s > 5.5$	Impulsive	1.24	1.25	1.35	1.60	1.77	1.91
			Vibratory	1.12	1.18	1.27	1.34	1.58	1.59
		$M_s \leq 5.5$	Impulsive	1.24	1.29	1.24	1.41	1.48	1.62
			Vibratory	1.11	1.16	1.22	1.31	1.38	1.44
$\zeta = 0.05$	Stiff Soil	$M_s > 5.5$	Impulsive	1.14	1.17	1.29	1.46	1.56	1.64
			Vibratory	1.23	1.19	1.36	1.31	1.37	1.41
		$M_s \leq 5.5$	Impulsive	1.14	1.16	1.22	1.44	1.59	1.80
			Vibratory	1.11	1.13	1.25	1.37	1.45	1.57
	Soft Soil	$M_s > 5.5$	Impulsive	1.21	1.23	1.30	1.57	1.70	1.78
			Vibratory	1.15	1.15	1.20	1.26	1.41	1.56
		$M_s \leq 5.5$	Impulsive	1.13	1.23	1.31	1.41	1.46	1.59
			Vibratory	1.11	1.16	1.22	1.30	1.35	1.39
$\zeta = 0.10$	Stiff Soil	$M_s > 5.5$	Impulsive	1.15	1.10	1.17	1.30	1.50	1.55
			Vibratory	1.19	1.14	1.24	1.25	1.32	1.37
		$M_s \leq 5.5$	Impulsive	1.08	1.11	1.16	1.37	1.57	1.77
			Vibratory	1.18	1.09	1.22	1.34	1.43	1.51
	Soft Soil	$M_s > 5.5$	Impulsive	1.17	1.16	1.27	1.45	1.67	1.80
			Vibratory	1.04	1.14	1.14	1.23	1.41	1.47
		$M_s \leq 5.5$	Impulsive	1.17	1.21	1.18	1.36	1.47	1.56
			Vibratory	1.04	1.07	1.12	1.20	1.28	1.35

Table 4 shows that the m_μ / m_1 ratios are greater for higher values of μ, and that for mid and large values of μ, the ratios m_μ / m_1 tend to be higher for impulsive registers than for vibratory ones. Comparison of the constant value 1.2 suggested by Akiyama and the factors displayed in Table 4 reveals that for displacement ductility larger than about 5, the value proposed by Akiyama may be unconservative.

The proposed design nonlinear V_E spectra are based on modifying the slopes of the initial branches of the linear spectra (shown in Figure 4) with the factors listed in Table 4; the same factors are used to multiply the median and characteristic branches.

5. Comparison with other studies

In this section, the design energy input spectra proposed in this study for high seismicity regions based on Turkish ground motions are compared with those proposed by Decanini and Mollaioli [1998, 2001] and with those proposed based on registers from Colombia [Benavent et al. 2010], Iran [Amiri el al. 2008] and Greece [Tselentis et al. 2010]. Furthermore, the proposed spectra are compared with those put forth under the current Japanese seismic code [BSL 2009] and by Akiyama [Akiyama 1985]. Figure 7 shows, in solid lines, the characteristic energy input spectra proposed in this study for impulsive and vibratory earthquakes with $M_s >$ 5.5 and $\mu = 1$ (see Figure 4, Table 1 and Table 2) and, with thin lines, these spectra proposed by the aforementioned authors and codes. Descriptions of these comparisons are included next.

- **Spectra from Colombian registers**. Figure 7.a shows the design energy input spectra proposed in [Benavent-Climent el al., 2010] based on 144 Colombian registers associated with design PGA equal to 0.4 g. These authors considered three soil types: rock (shear wave velocity $v_s > 750$ m/s), stiff soil (375 ≤ v_s ≤ 750 m/s) and intermediate soil (175 ≤ v_s ≤ 375 m/s). As seen in the figure, the levels of input energy proposed in this study are approximately bounded by the levels adopted from Colombian records for soils type I and II.

- **Spectra from the Japanese code**. Figure 7.b shows with thin lines the design energy input spectra V_E prescribed by the current Japanese seismic code BSL [2009] to be used in conjunction with earthquake-resistant structural calculation based on energy balance. The BSL code classifies the surface geology in three types: (i) soil 1 is rock, stiff sand gravel, and pre-Tertiary deposits; (ii) soil 3 includes alluvial layers mainly consisting of humus and mud whose depth is over 30 m, or filled land more than 3 meters deep and worked within the past 30 years; (iii) soil 2 comprises layers other than types 1 and 3. The BSL code directly gives the V_D spectra. For comparison with the spectra proposed in this study, V_E was estimated from V_D using the proposed equation (17) particularized for a vibratory earthquake with $M_s >$ 5.5, and assuming $\zeta = 0.05$ and $\eta = 15$ (Table 5). The levels of V_E prescribed by BSL and those proposed in this study are similar in the medium period range (i.e. in the region where V_E is constant). However, in the short and large period ranges the levels prescribed by BSL are smaller and larger, respectively, than those proposed in this study. The levels put forth here for impulsive earthquakes are clearly larger than those proposed by the BLS code.

- **Spectra from [Akiyama 1999]**. Figure 7.c shows in thin lines the design energy input spectra proposed by Akiyama [1999] for Japan, considering four types of surface geology. Soil type I corresponds to hard rock or very hard conglomerates (shear wave velocity $v_s > 750$ m/s); type II corresponds to hard conglomerates, compact sand and gravel with 375 ≤ v_s ≤ 750 m/s; type III corresponds to intermediate soils such as semi-compact sands and gravels with 175 ≤ v_s ≤ 375 m/s; and type IV corresponds to soft soils with v_s ≤ 175 m/s. In the medium period range (i.e. the range where V_E is constant) the spectra proposed in this study are close to those proposed by Akiyama.

- **Spectra from Iranian registers**. Figure 7.d shows the design energy input spectra proposed by Amiri el al. [2008] based on 110 Iranian earthquakes. These authors consider four types of soil (I, II, III and IV), corresponding to rock, stiff, medium and soft soil, respectively. It can be seen that the spectra proposed in this study for vibratory registers are approximately 30% larger in stiff soil and about 45% larger in soft soil, than those suggested by Amiri et al. For impulsive earthquakes the levels proposed in this study are roughly two times greater than those proposed by Amiri et al. It is worth noting that both regions (Iran and Turkey) have similar seismicity and the maximum design PGA in the Turkish seismic code (0.4 g) is similar to that of the Iranian code (0.35 g). The biggest discrepancy with the spectra proposed

by Amiri et al. corresponds to the impulsive registers. Such disagreement might be due to the scarcity of near-fault registers in their study. Further discrepancies may be attributed to statistical criteria: this work establishes the design spectra corresponding to the top 95% percentile, while Amiri et al. take the average plus one standard deviation; if normality is assumed, this level would correspond to the 84% percentile.

- **Spectra from Greek registers**. Figure 7.e shows the V_E spectra proposed by Tselentis et al. [2010] for six cities in Greece by means of a methodology unlike ours. These authors adopt the probabilistic approach originally developed by Cornell [1968] and extended later by Esteva [1970]. Each city has a different design PGA (0.16 g for Athens and Thessaloniki; 0.24 g for Patras, Korinthos and Chania; and 0.36 g for Argostolion), which varies in approximately the same range as the Turkish seismic code (i.e. from 0.15 g to 0.4 g). As observed in the figure, the spectra proposed by Tselentis et al. [2010] for these cities would match the spectra developed in this study for vibratory records and for stiff and soft soil quite well.

- **Decanini, Mollaioli 1998 and 2001**. Decanini and Mollaioli [1998] proposed general shapes for design energy input spectra, normalized by the Seismic Hazard Factor AE_I. These authors proposed different values for AE_I depending on the surface geology conditions, the interval of surface-wave magnitude M_S and the epicentral distance R_{epi}. For 12 km $< R_{epi} <$ 30 km and $6.5 \leq M_S \leq 7.1$, Decanini and Mollaioli proposed $AE_I = 16000$ cm^2/s for soil type S1 and $AE_I = 50000$ cm^2/s for soil type S2; this is identified as the vibratory register. For $R_{epi} <$ 5 km and $6.5 \leq M_S \leq 7.1$, Decanini and Mollaioli proposed $AE_I = 65000$ cm^2/s for soil type S1 and $AE_I = 110000$ cm^2/s for soil type S2; this is identified as the impulsive register. The design energy input spectra obtained by substituting these values of AE_I in the normalized spectra considered by Decanini and Mollaioli [1998] for $\mu = 1$ are drawn in Figure 7.f. In the medium period range (i.e. constant input energy range) the levels of V_E proposed in this study are seen to be similar to those of Decanini and Mollaioli; although the descending branches begin earlier in their case, the rate of stabilization of the slope is higher.

Figure 7. Comparison among the proposed spectra and those from other studies
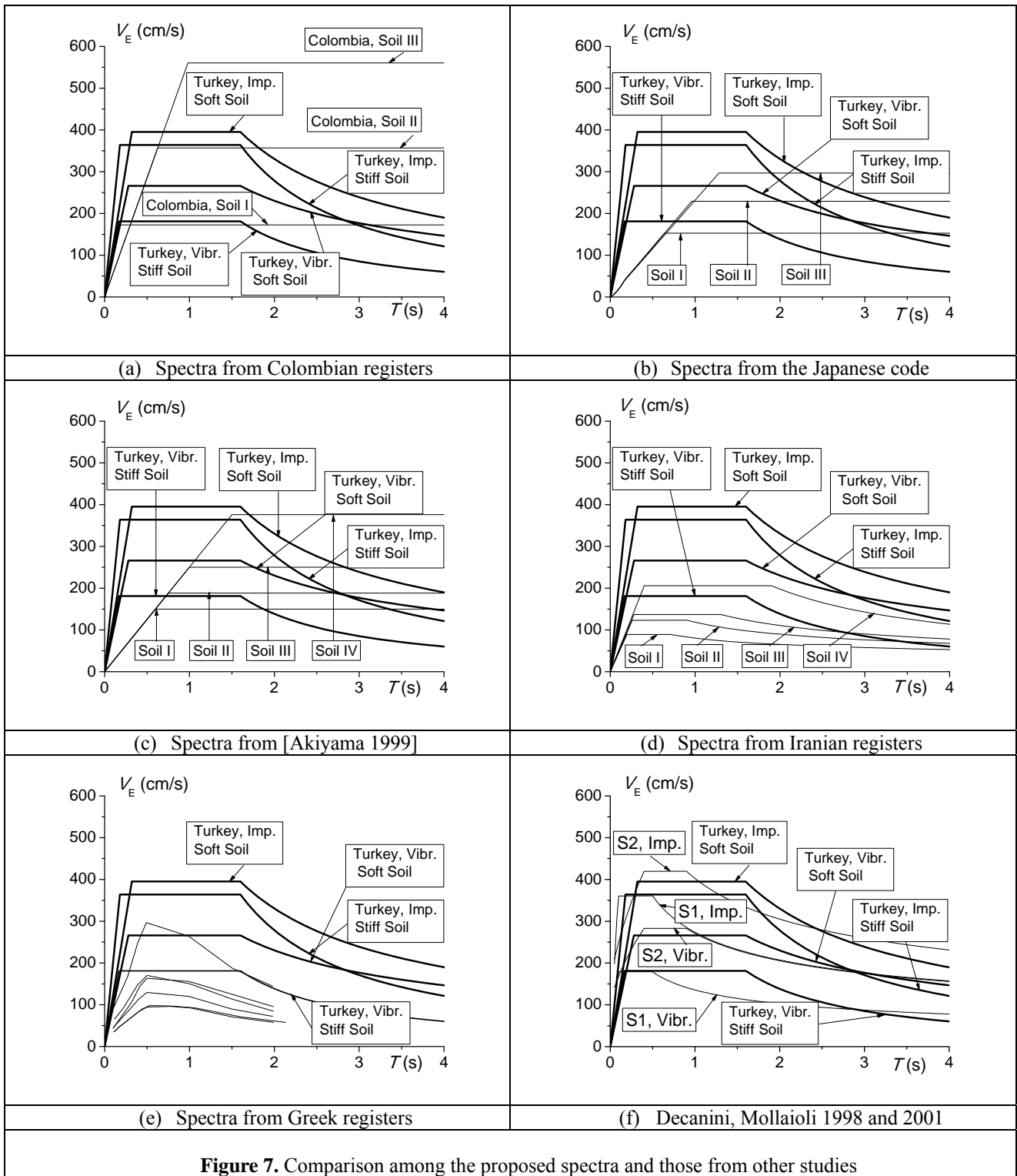
6. Design hysteretic energy to input energy ratio V_D / V_E

6.1. Introductory remarks

The evaluation of the input energy E_I is an acceptable starting point to develop and apply the seismic energy-based design methods. However, only hysteretic energy E_H (alike E_D, according to equation (5)) is directly related to seismic structural damage, and must be evaluated [Manfredi 2001]. Since V_D and E_H are directly

related by equation (6), estimation of the ratio V_D / V_E, in view of the non-linear analyses presented in subsection 4.3, is described below.

6.2. Previous studies

As discussed in section 2, V_D / V_E depends mainly on the structural damping and on the demanded ductility; the latter can be formulated in terms of the displacement ductility μ, or in terms of the cumulative ductility η:

$$\mu = \frac{y_{max}}{y_y} \qquad\qquad \eta = \frac{E_H}{Q_y \, y_y} \qquad\qquad (13)$$

In equation (13), y_{max} is the maximum displacement and Q_y and y_y are the restoring force and the displacement at yielding, respectively. Several empirical equations have been proposed in the literature to estimate V_D / V_E. Based on analyses of SDOF systems with elastic-perfectly-plastic restoring force characteristics, Akiyama [1985] and Kuwamura and Galambos [1989] respectively presented the following equations:

$$\frac{V_D}{V_E} = \frac{1}{1 + 3\zeta + 1.2\sqrt{\zeta}} \qquad\qquad \frac{V_D}{V_E} = \frac{\dfrac{\eta}{\eta + 0.15}}{1 + \dfrac{20(3\zeta + 1.2\sqrt{\zeta})}{\eta + 10}} \qquad\qquad (14)$$

In turn, Benavent et al. [2002, 2010] suggested, respectively, the following modifications of the (left) Akiyama equation (14) to account for the level of plastification:

$$\frac{V_D}{V_E} = \frac{1.15\eta}{(0.75 + \eta)(1 + 3\zeta + 1.2\sqrt{\zeta})} \qquad\qquad \frac{V_D}{V_E} = \frac{1}{\sqrt{1 + 4\pi\zeta n}} \frac{\eta^c}{(8.75\zeta + k^c + \eta^c)} \qquad (15)$$

In the last equation (15), n, k and c are dimensionless coefficients whose values are $n = 0.9$, $k = 0.33$ and $c = 0.57$ for rock, and $n = 0.15$, $k = 0.02$ and $c = 0.37$ for soil.

From parametric studies with non-linear elastic-perfectly-plastic SDOF systems, Fajfar and Vidic [1994] proposed an expression valid for systems with $\zeta = 0.05$:

$$\frac{V_D}{V_E} = \sqrt{\frac{0.9(\mu - 1)^{0.95}}{\mu}} \qquad\qquad (16)$$

Lawson and Krawinkler [1995] confirmed that V_D / V_E constitutes a highly stable parameter, and proposed adopting $V_D / V_E = 0.63$ for $\mu = 2$ and $V_D / V_E = 0.77$ for $4 \leq \mu \leq 8$, except for the shortest periods. Decanini and Mollaioli [2001] investigated the ratio $E_H / E_{I,abs}$ in relation with the period T, the type of soil, and the ductility μ for elastic-perfectly-plastic SDOF systems with $\zeta = 5\%$; Although Akiyama used the relative input energy and Decanini and Mollaioli the absolute input energy, the design values of the ratio of hysteretic energy to total input energy proposed by both approaches are comparable. Decanini and Mollaioli moreover investigated the effects of the hysteretic model, the vibration period, and the soil type.

6.3. Influence of damping and ductility

In this study, the registers were classified into eight groups, depending on the soil type, the earthquake magnitude and the relevance of the velocity pulses (section 3). Mainly for this reason, we develop a new empirical approximation of V_D / V_E whose parameters take such diversity into account. This expression is intended to be used together with the spectra proposed in section 4. The agreement between the obtained

points and previously suggested fits is reasonable [Yazgan 2012], particularly a recent study by Benavent et al. [2010]. However, the fit can be further improved and, moreover, no previous study looked into the influence of soil type, earthquake magnitude, velocity pulses and period to such an extent. For this reason, another fitting criterion is proposed here. To derive such criteria, Figure 8 shows the obtained points for damping 5%; the reference [Yazgan 2012] contains similar results for damping 2% and 10%. These points are plotted together with the best fit curve using a two-term exponential expression:

$$\frac{V_{\mathrm{D}}}{V_{\mathrm{E}}} = a\, e^{b\eta} + c\, e^{d\eta} \tag{17}$$

This expression is chosen given its suitability to the clouds of points to be fitted. In the second term of equation (17), coefficients c ("amplitude") and d ("exponent") are intended to be negative and provide the trend of the fitting curves to be horizontal for $\eta > 100$; in the first term amplitude a is positive and exponent b can be either negative or positive. The absolute values of the exponent b are significantly smaller than those of d, while this trend is inverted for the amplitudes. Roughly, the first term governs the behavior for small values of η whereas the second term controls the values for higher values of η.

Table 5 shows the values of the coefficients a, b, c and d that provide the best fit in the sense of the least value of the sum of the squares of the differences between the ordinates of the obtained points and those of the fitting curves.

(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
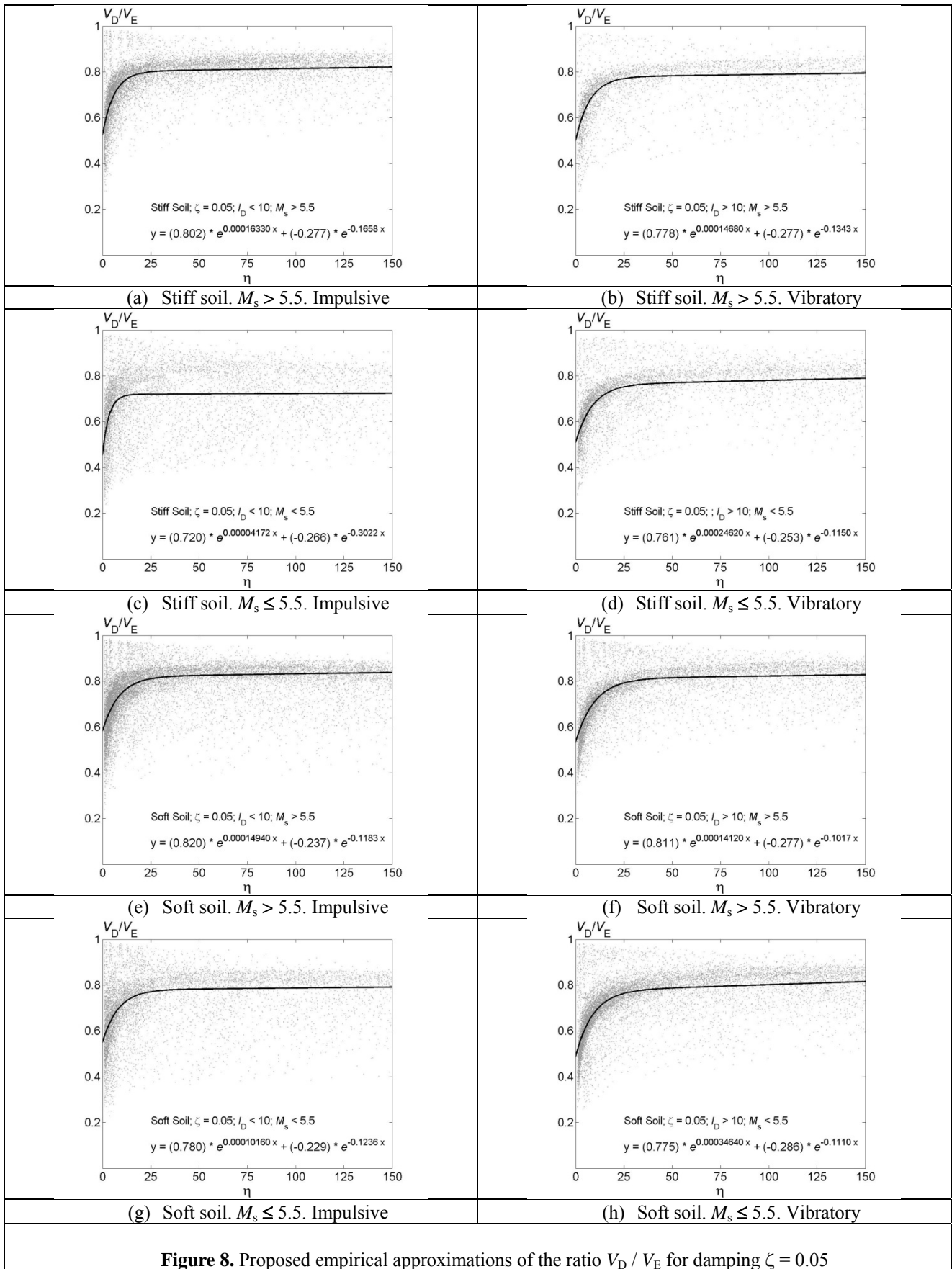
Figure 8. Proposed empirical approximations of the ratio V_D / V_E for damping $\zeta = 0.05$

20

Table 5. Coefficients of the best exponential fit curve of the V_D / V_E ratio for each group							
Damping	Soil type	Magnitude	Pulses	a	b	c	d
$\zeta = 0.02$	Stiff Soil	$M_s > 5.5$	Imp.	0.893	0.0001885	− 0.243	− 0.180
			Vibr.	0.877	0.0001867	− 0.236	− 0.156
		$M_s \leq 5.5$	Imp.	0.879	− 0.0000235	− 0.291	− 0.262
			Vibr.	0.866	0.0002698	− 0.219	− 0.142
	Soft Soil	$M_s > 5.5$	Imp.	0.904	− 0.000000757	− 0.219	− 0.146
			Vibr.	0.898	0.0001648	− 0.229	− 0.118
		$M_s \leq 5.5$	Imp.	0.880	0.0000201	− 0.206	− 0.140
			Vibr.	0.878	0.0002496	− 0.247	− 0.131
$\zeta = 0.05$	Stiff Soil	$M_s > 5.5$	Imp.	0.802	0.0001633	− 0.277	− 0.166
			Vibr.	0.777	0.0001467	− 0.277	− 0.134
		$M_s \leq 5.5$	Imp.	0.720	0.0000417	− 0.266	− 0.302
			Vibr.	0.761	0.0002462	− 0.252	− 0.115
	Soft Soil	$M_s > 5.5$	Imp.	0.820	− 0.0001494	− 0.273	− 0.118
			Vibr.	0.811	0.0001412	− 0.277	− 0.102
		$M_s \leq 5.5$	Imp.	0.780	− 0.0001016	− 0.229	− 0.124
			Vibr.	0.775	0.0003464	− 0.286	− 0.111
$\zeta = 0.10$	Stiff Soil	$M_s > 5.5$	Imp.	0.704	0.00004824	− 0.276	− 0.152
			Vibr.	0.673	0.00004073	− 0.266	− 0.109
		$M_s \leq 5.5$	Imp.	0.607	− 0.0001398	− 0.231	− 0.272
			Vibr.	0.665	0.0000176	− 0.252	− 0.086
	Soft Soil	$M_s > 5.5$	Imp.	0.732	− 0.0000412	− 0.239	− 0.098
			Vibr.	0.702	0.00001194	− 0.284	− 0.089
		$M_s \leq 5.5$	Imp.	0.710	− 0.0003608	− 0.259	− 0.096
			Vibr.	0.665	0.0004298	− 0.281	− 0.099

Table 5 shows the following general trends: (i) V_D / V_E increases with the increase of η, but this dependency tends to disappear as the parameter grows; (ii) V_D / V_E decreases with the increase of ζ; (iii) for a given value of η, the dispersion of V_D / V_E increases with ζ and, for a given value of ζ, the dispersion of V_D / V_E decreases with η; (iv) the overall behavior of V_D / V_E for impulsive and vibratory registers is quite similar, although for smaller η the values of V_D / V_E are slightly higher for impulsive registers than for vibratory ones; (v) the results for $M_s > 5.5$ and for $M_s \leq 5.5$ are roughly equivalent; and (vi) V_D / V_E is similar in stiff soil and in soft soil. These last three conclusions show that the ratio V_D / V_E is analogous in the eight groups analyzed (section 3); therefore, the proposal of approximate expressions for estimating V_D / V_E can be made irrespectively of soil type, impulsivity of the register and magnitude of the earthquake. Figure 9 displays the clouds of points corresponding to all the considered registers (Table 9) for damping factors $\zeta = 0.02$, 0.05 and 0.10 together with the best fit curves according to the two-term exponential expression (17). Figure 9.a, Figure 9.b and Figure 9.c show the cases for $\zeta = 0.02$, 0.05 and 0.10, respectively, while Figure 9.d shows jointly the three exponential fitting curves alone (e.g. without the fitted points). In addition, Table 6 displays the values of the coefficients a, b, c and d that provide the best fit for $\zeta = 0.02$, 0.05 and 0.10.
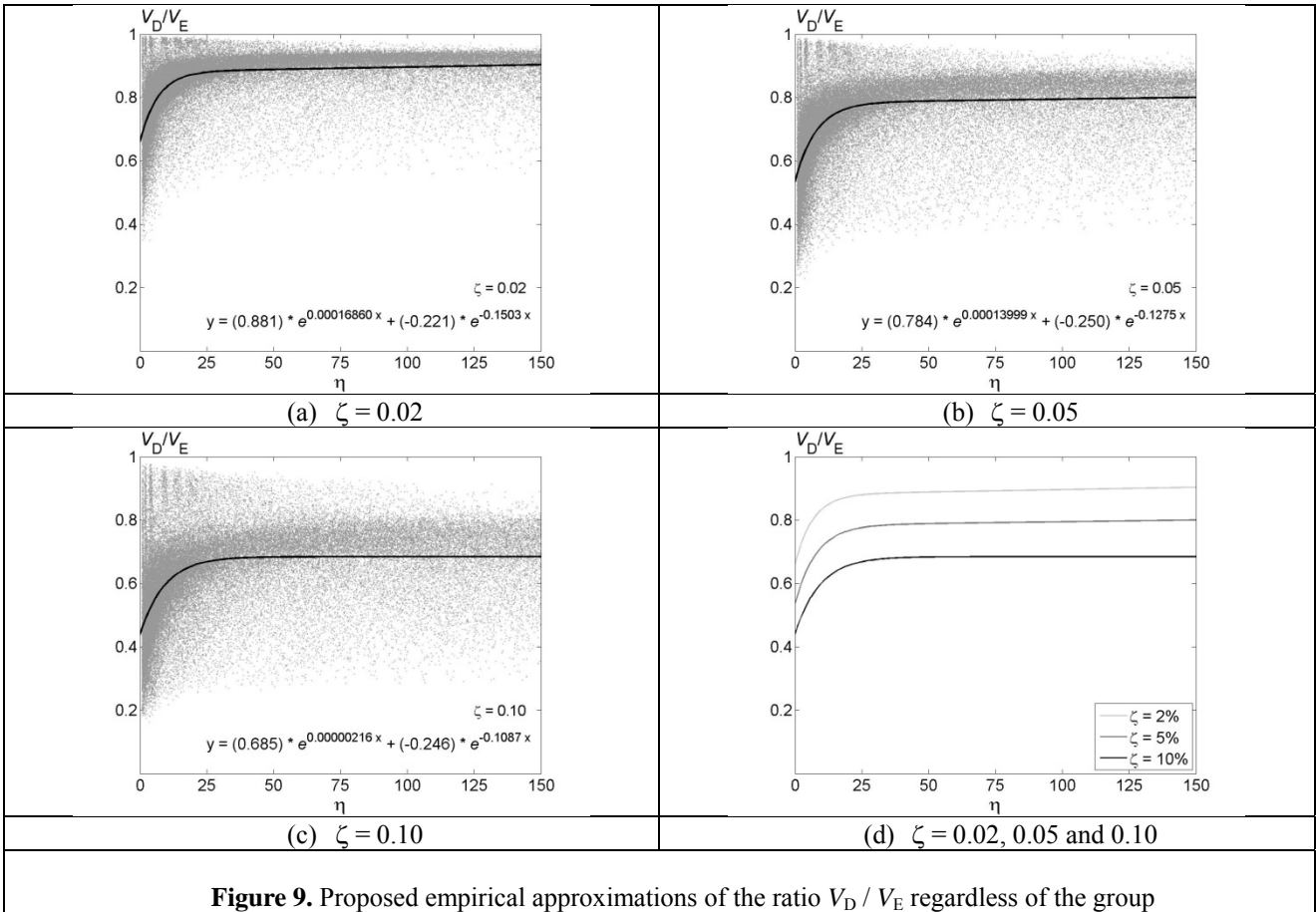
Figure 9. Proposed empirical approximations of the ratio V_D / V_E regardless of the group

Table 6. Coefficients of the best exponential fit curve of the V_D / V_E ratio for all the groups

Damping	a	b	c	d
$\zeta = 0.02$	0.881	0.00016860	-0.221	-0.1503
$\zeta = 0.05$	0.784	-0.00013999	-0.250	-0.1275
$\zeta = 0.10$	0.685	0.00000216	-0.246	-0.1087

6.4. Influence of period

To assess the variation of ratio V_D / V_E with period T, Figure 10 shows the spectra of V_D / V_E for different values of the damping factor ($\zeta = 0.02$, 0.05 and 0.10) and of displacement ductility ($\mu = 2$, 3, 5, 10, 15 and 20). Since the previous study about the influence of ζ and η on the V_D / V_E ratio (subsection 6.3) points to little influence of the soil type, the impulsive / vibratory character and the earthquake magnitude, the V_D / V_E spectra are presented herein regardless of these aspects; in other words, each set of plots in Figure 10 corresponds to all the registers in Table 9. Figure 10.a through Figure 10.r illustrate the individual spectra, the median and a linear fit of the median spectrum. Remarkably, a bilinear approximation (where the initial branch starts from $V_D / V_E = 1$ for $T = 0$) would provide a better match; however, since that branch corresponds only to extremely short periods (e.g. shorter than 0.06 s), it is neglected in this study. Table 7 displays the parameters of the chosen linear fit: the slope, the spectral ordinate corresponding to $T = 4$ s, and the average spectral ordinate, e.g. the one that corresponds to $T = 2$ s.

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(a) $\zeta = 0.02$; $\mu = 2$	(b) $\zeta = 0.05$; $\mu = 2$	(c) $\zeta = 0.10$; $\mu = 2$
(d) $\zeta = 0.02$; $\mu = 3$	(e) $\zeta = 0.05$; $\mu = 3$	(f) $\zeta = 0.10$; $\mu = 3$
(g) $\zeta = 0.02$; $\mu = 5$	(h) $\zeta = 0.05$; $\mu = 5$	(i) $\zeta = 0.10$; $\mu = 5$
(j) $\zeta = 0.02$; $\mu = 10$	(k) $\zeta = 0.05$; $\mu = 10$	(l) $\zeta = 0.10$; $\mu = 10$
(m) $\zeta = 0.02$; $\mu = 15$	(n) $\zeta = 0.05$; $\mu = 15$	(o) $\zeta = 0.10$; $\mu = 15$
(p) $\zeta = 0.02$; $\mu = 20$	(q) $\zeta = 0.05$; $\mu = 20$	(r) $\zeta = 0.10$; $\mu = 20$
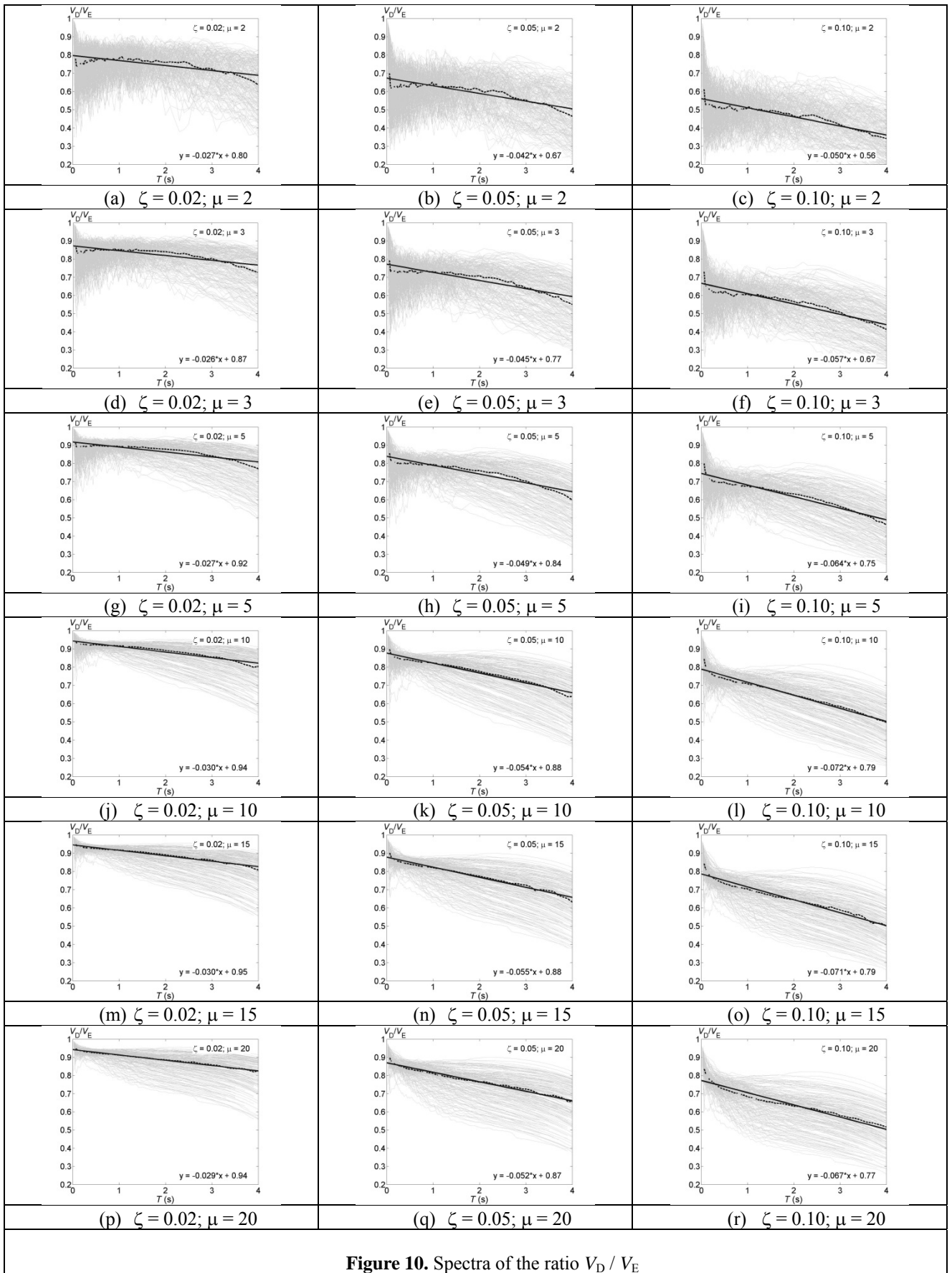
Figure 10. Spectra of the ratio V_D / V_E

Table 7. Parameters for the linear fit of the V_D / V_E spectra				
ζ	μ	Slope (s^{-1})	Spectral ordinate ($T = 4$ s)	Average spectral ordinate ($T = 2$ s)
0.02	2	− 0.027	0.692	0.746
	3	− 0.026	0.766	0.818
	5	− 0.027	0.812	0.866
	10	− 0.030	0.820	0.880
	15	− 0.030	0.830	0.890
	20	− 0.029	0.824	0.882
0.05	2	− 0.042	0.502	0.586
	3	− 0.045	0.590	0.680
	5	− 0.049	0.644	0.742
	10	− 0.054	0.664	0.772
	15	− 0.055	0.660	0.770
	20	− 0.052	0.662	0.766
0.10	2	− 0.050	0.360	0.460
	3	− 0.057	0.442	0.556
	5	− 0.064	0.494	0.622
	10	− 0.072	0.502	0.646
	15	− 0.071	0.506	0.648
	20	− 0.067	0.502	0.636

Taken together, the plots from Figure 10 and data from Table 7 reflect the overall trends of damping and of ductility influence outlined earlier (the V_D / V_E ratio decreases with increasing damping and increases with increasing ductility). The results in Table 7 moreover show that the slope increases with damping, and the dependency of the slope on ductility also increases with damping; roughly, it grows as ductility does. The spectral ordinates corresponding to periods 2 and 4 s are seen to increase with ductility while decreasing with damping.

As shown next, the fits of Figure 10 and those of Decanini and Mollaioli [2001] generally agrees, except in the short period range. This difference stems from the conception of absolute energy. Decanini and Mollaioli propose a trilinear E_H / E_I spectrum characterized, among other parameters, by e, f and T_3, with e as the maximum spectral ordinate, f the ordinate at $T = 4$ s, and T_3 the period that determines the onset of the horizontal branch. Parameters e and f (see Fig. 16 and Table 11 in [Decanini, Mollaioli 2001]) can be compared, for $\zeta = 0.05$, to the squares of the spectral ordinates corresponding to T_3 (ranging between 0.225 and 0.55 s) and to 4 s, respectively (Figure 10 and Table 7). Meanwhile, Table 8 offers a comparison of the values of the square roots of e and f and those of the aforementioned spectral ordinates. The second and fourth columns of Table 8 ($\sqrt{e}$ and spectral ordinate for period T_3) show satisfactory agreement, yet the third and fifth columns ($\sqrt{f}$ and spectral ordinate for 4 s) show poorer agreement, the proposed fit being more conservative.

Table 8. Comparison among the parameters for the proposed linear fit of the V_D / V_E spectra (for $\zeta = 0.05$) and the one by Decanini and Mollaioli [2001]				
μ	$\sqrt{e}$ (stiff soil / soft soil)	$\sqrt{f}$ (stiff soil / soft soil)	Spectral ordinate (T_3) (stiff soil / soft soil)	Spectral ordinate ($T = 4$ s)
2	0.693 / 0.707	0.632 / 0.686	0.657 / 0.645	0.502
3	0.742 / 0.758	0.671 / 0.731	0.758 / 0.745	0.590
5	0.800 / 0.822	0.714 / 0.781	0.829 / 0.817	0.644

The common assumption that V_D / V_E is roughly independent of period is no longer sustainable in view of Figure 10 and Table 7. In contrast, the approximation given by equation (17) (with the values of the coefficients a, b, c and d listed in Table 6) corresponds to the average ordinate of the fits shown in Figure 10 and listed in Table 7.

6.5. Proposed criteria for estimating V_D / V_E

The previous two subsections describe criteria for estimating the V_D / V_E ratio in terms of period T, ductility μ or η, and damping ζ. Subsection 6.4 provides criteria that depend on T, μ and ζ; while the study expounded in subsection 6.3 illustrates the influence of η and ζ but must be complemented with subsection 6.4 to incorporate the effect of T. Accordingly, the first proposed criterion consists of the linear decreasing spectra drawn in Figure 10 (the values of the parameters of the linear fit are listed in Table 7 in terms of μ and ζ). The second proposed criterion consists of the two-term exponential curves plotted in Figure 9.d and described in Table 6, multiplied by the ratio between the ordinate corresponding to the considered period and the average spectral ordinate (Figure 10 and Table 7). Since there is no direct relation between μ and η, the two proposed criteria are not equivalent.

The V_D spectra can be obtained by multiplying the V_D / V_E spectra put forth in this subsection by the three-branched V_E spectra (linear spectra depicted in Figure 5 and nonlinear modification of the initial branches described in Table 4).

The suitability of each criterion described here depends mainly on whether the energy dissipation capacity is characterized in terms of displacement ductility μ or cumulated ductility η. The second criterion would be preferable in the particular case of designing structures with hysteretic dampers.

7. Conclusions

This work proposes design input energy spectra formulated in terms of velocity (V_E), especially appropriate for regions with design peak ground acceleration equal or higher than 0.3 g. They were obtained from a number of Turkish records from zones with PGAs of this magnitude.

The proposed spectra are derived through linear and nonlinear dynamic analyses for selected Turkish registers. In the long and mid period ranges, due to the relative insensitivity of the spectra to the structural parameters other than the fundamental period, the analyses are linear. Contrariwise, in the short period range, the spectra are more sensitive to the structural parameters and call for nonlinear analyses. The selected Turkish records, classified in eight groups with respect to the soil type (stiff and soft soil), the magnitude of the earthquake ($M_s \leq 5.5$ and $M_s > 5.5$) and the relevance of the near-source effects (impulsive and vibratory registers), give rise to median and characteristic spectra for each group, with levels intended to correspond to the 50% and 95% percentiles, respectively. The proposed 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. For nonlinear design, in each of the eight groups, empirical criteria are proposed to modify the slope of the initial branch according to the displacement ductility; the same criteria are considered for the median and characteristic spectra.

Empirical criteria for estimating the ratio between hysteretic energy in terms of velocity (V_D) and input energy (V_E) are presented. Although these criteria depend on period, damping and ductility; displacement and cumulated ductility are considered as well. It should be stressed that the influence of period is considered relevant, yet the influence of the parameters that characterize each group (soil type, earthquake magnitude and impulsivity) is negligible.

When compared with those obtained from other studies, the proposed design spectra are in some cases greater while in other cases they are smaller. Overall, no noteworthy differences are observed.

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Register Index	Date	Earthquake	Hypo central depth (km)	Magnitude			Station Code	$V_{s,30}$ (m/s)	Soil Type	Seismic Zone	Distance			Duration (NS)		Duration (EW)		Arias Intensity		ID		Filtering range f_1 / f_2 (Hz)	
				M_L	M_w	M_s					R_{jb} (km)	R_{rup} (km)	R_{epi} (km)	t_{br} (s)	t_{tf} (s)	t_{br} (s)	t_{tf} (s)	NS	EW	I_{D-NS}	I_{D-EW}	NS	EW
1	19/08/1976	Denizli	19.8	6.1	6.1	6.03	2001	346	Soft	1	6.4	17.9	9.9	13.6	5.2	14.6	5.9	72.3	52.4	5.1	7.2	0.5/40	0.7/35
2	16/12/1977	Izmir-Guzelyali	24.2	5.6	5.6	5.41	3506	771	Stiff	1	9.5	-	9.5	2.2	0.8	9.0	2.1	36.9	6.6	4.5	6.6	0.4/25	0.5/25
3	18/07/1979	Balikesir	7.0	5.3	5.3	4.93	1010	496	Stiff	1	5.1	7.1	6.5	11.8	3.3	9.7	2.5	20.2	21.0	6.0	5.7	0.3/30	0.35/30
4	05/07/1983	Balikesir	6.9	6.1	6.1	6	1012	520	Stiff	1	47.6	47.8	55.4	17.2	8.1	17.3	10.5	3.9	2.3	9.0	13.4	0.25/25	0.4/25
5							1014	397	Stiff	1	37.8	38	44.1	14.6	11.4	14.7	9.0	2.3	2.9	7.7	17.1	0.2/30	0.3/22
6	05/05/1986	Adiyaman	4.4	6.0	6.0	5.90	203	-	Stiff	1	23.9	24	29.2	19.5	10.5	19.6	10.8	15.7	4.7	5.8	6.8	0.15/20	0.2/20
7	06/06/1986	Adiyaman	10.6	5.8	5.8	5.66	203	-	Stiff	1	30.3	31.1	34.4	14.8	7.7	14.9	8.5	5.1	1.5	5.5	6.6	0.3/20	0.4/20
8	13/03/1992	Erzincan	22.6	6.6	6.6	6.6	2402	-	Soft	1	3.3	16.8	12.8	25.1	9.1	23.5	9.8	163.7	177.6	2.3	3.0	0.1/30	0.1/35
9							2403	433	Stiff	1	63	65.5	76.4	16.8	12.0	16.9	10.3	5.2	5.8	11.5	12.3	0.3/25	0.2/20
10	15/03/1992	Erzincan	28.5	5.9	5.9	5.78	2402	-	Stiff	1	41.7	48.6	45.4	31.3	16.9	31.6	19.3	1.7	2.1	10.0	7.3	0.15/20	0.1/22
11	06/11/1992	Aydin	17.2	6.0	6.0	5.90	905	369	Stiff	1	38.1	40.3	38.7	22.5	9.5	22.7	10.6	6.4	9.4	11.1	24.6	0.35/35	0.35/35
12	13/11/1994	Mugla	10.0	5.3	5.3	4.93	4804	372	Stiff	1	30.1	32.2	33.2	9.6	4.3	9.5	4.7	3.9	4.9	9.1	8.8	0.35/30	0.4/20
13	29/01/1995	Erzincan	28.2	5.2	5.2	4.76	2405	320	Soft	1	19.6	33.3	21.7	16.4	10.2	16.6	10.1	3.0	3.3	17.8	11.6	0.35/25	0.2/20
14	01/10/1995	Afyon-Dinar	5.0	6.4	6.4	6.4	1501	335	Soft	1	29	29	39.1	25.1	17.3	25.2	17.8	3.9	4.2	15.5	15.7	0.3/15	0.3/15
15							2006	-	Soft	1	43.9	43.9	49.6	27.7	13.6	27.7	13.9	7.7	7.2	24.7	19.1	0.3/15	0.3/15
16							302	198	Soft	1	0	2.9	0.5	27.1	16.9	26.9	15.6	165.5	203.3	12.7	9.0	0.2/30	0.15/30
17							2002	356	Soft	1	86.9	86.9	95.4	131.4	61.4	123.6	62.8	1.6	1.4	20.0	16.3	0.07/20	0.1/20
18	05/12/1995	Erzincan	25.5	5.8	5.8	5.66	2401	314	Soft	1	58.9	65	61.6	65.0	21.5	65.8	30.5	1.9	1.5	19.9	32.4	0.1/25	0.1/25
19	14/08/1996	Amasya	11.9	5.7	5.7	5.54	502	443	Stiff	1	43.5	44.4	47.8	36.9	10.0	20.5	5.8	1.0	2.8	18.4	14.3	0.1/30	0.2/20
20	14/08/1996	Amasya	11.9	5.7	5.7	5.54	6002	-	Soft	1	115	115	119	48.2	13.2	47.3	23.4	0.3	0.2	16.2	20.4	0.25/15	0.25/15
21	14/08/1996	Amasya	2.7	5.6	5.6	5.4	502	443	Stiff	1	44.3	44.3	47.9	39.7	11.4	26.6	8.1	0.5	0.8	14.4	10.8	0.25/20	0.2/20
22							6002	-	Soft	1	116	116	120	46.7	13.3	47.3	22.9	0.5	0.3	14.7	15.0	0.3/15	0.2/15
23	22/01/1997	Hatay	45.4	5.7	5.7	5.54	3102	-	Soft	1	19.2	46.8	19.8	31.9	13.4	26.9	15.1	18.7	16.2	15.8	11.1	0.1/35	0.1/30
24	28/02/1997	Amasya	4.9	5.2	5.2	4.76	502	443	Stiff	1	39.8	39.9	42.1	30.3	9.2	30.8	9.2	0.4	0.4	9.7	16.9	0.2/20	0.2/25
25	14/11/1997	Canakkale	2.3	5.8	5.8	5.66	1701	192	Stiff	1	150	150	154	34.8	23.1	34.6	24.1	0.4	0.4	17.0	17.8	0.15/20	0.2/25
26	04/04/1998	Afyon-Dinar	19.3	5.2	5.2	4.8	2006	-	Soft	1	50	54.2	51.8	14.2	7.0	14.1	7.3	0.7	0.7	25.6	27.0	0.4/30	0.5/25
27							302	198	Soft	1	2	18	4.4	20.5	9.8	22.2	9.1	10.9	14.2	8.1	5.6	0.25/20	0.2/25
28	13/04/1998	Bingol	15.3	5.2	5.2	4.76	1208	485	Stiff	1	36.9	39.2	37.6	35.9	13.4	30.5	9.9	0.1	0.2	9.8	6.0	0.15/20	0.15/20
29	09/05/1998	Elazig	26.5	5.1	5.1	4.58	2301	407	Stiff	2	47.7	53.9	49.2	26.1	12.3	39.1	16.1	0.5	0.4	6.0	15.5	0.15/25	0.15/20
30	27/06/1998	Adana-Ceyhan	46.6	6.2	6.2	6.1	105	264	Soft	2	40	58.2	48.2	27.4	13.0	27.1	13.2	94.2	105.8	8.8	10.6	0.1/22	0.1/30
31							3301	366	Stiff	3	57.5	71.2	64.9	20.8	11.3	20.9	10.3	8.2	8.9	3.2	5.4	0.2/15	0.3/15
32							3102	-	Soft	1	101	111	103	31.9	15.7	31.9	16.2	1.6	1.6	14.8	9.4	0.1/35	0.2/30
33	04/07/1998	Adana	54.6	5.4	5.4	5.1	107	-	-	2	39.2	65.5	42.2	50.5	25.0	59.9	27.2	0.9	0.7	11.1	20.2	0.05/40	0.05/30
34							108	-	-	2	30.9	61.1	33.8	33.9	13.7	40.8	13.8	0.8	0.6	20.8	19.2	0.1/35	0.1/40
35	24/07/1999	Balikesir	10.0	5.0	5.0	4.41	1001	662	Stiff	1	37.9	39.5	39.8	68.9	52.5	66.3	52.8	0.1	0.1	8.1	7.7	0.15/30	0.07/35

Table 9. Considered Turkish registers

Table 9. Considered Turkish registers

Register Index	EARTHQUAKE INFORMATION						STATION INFORMATION							REGISTER INFORMATION								
	Date	Earthquake	Hypo central depth (km)	M_L	M_w	M_s	Station Code	$V_{s,30}$ (m/s)	Soil Type	Seismic Zone	R_{jb} (km)	R_{rup} (km)	R_{epi} (km)	t_{br} (s)	t_{tf} (s)	t_{br} (s)	t_{tf} (s)	NS	EW	I_{D-NS}	I_{D-EW}	NS	EW
36	25/07/1999	Balikesir	15.2	5.2	5.2	4.76	1001	662	Stiff	1	35.1	37.4	37.3	36.8	16.5	37.3	10.9	0.2	0.2	9.4	10.1	0.15/30	0.07/35
37							1604	-	-	1	61.8	63.2	94.7	80.4	79.1	98.2	79.0	7.9	7.3	9.9	12.7	0.05/25	0.05/25
38							8101	282	Soft	1	46	46.2	101	22.5	11.9	24.8	11.9	139.9	113.2	4.1	3.8	0.05/22	0.05/25
39	17/08/1999	Kocaeli	17.0	7.6	7.6	7.9	4106	701	Stiff	1	4.9	6.2	42.8	35.4	29.6	44.2	28.9	56.7	33.5	6.3	12.3	0.2/30	0.2/30
40							1404	348	Soft	1	44.2	45.7	80.7	25.5	11.5	25.4	11.6	20.4	26.3	7.9	10.5	0.05/25	0.07/25
41							3401	595	Stiff	1	43.4	43.5	86.5	71.1	38.1	78.7	37.4	4.1	4.8	4.7	9.5	0.05/40	0.05/40
42							1612	197	Soft	1	33.2	34.8	40.3	52.2	33.3	52.1	32.5	30.9	53.6	10.6	10.2	0.05/20	0.05/25
43							4101	826	Rock	1	0.6	3.9	3.4	50.7	34.1	49.1	34.4	74.1	98.2	12.5	7.1	0.1/35	0.1/30
44							4501	340	Soft	1	286	287	325	140.9	61.4	144.3	62.6	0.6	0.4	10.0	16.8	0.05/15	0.05/15
45							301	226	Soft	2	221	222	225	156.5	62.9	146.9	55.5	1.2	1.6	16.2	13.0	0.05/15	0.05/15
46	17/08/1999	Kocaeli	17.0	7.6	7.6	7.9	1001	662	Stiff	1	171	172	217	93.4	52.4	93.3	37.9	1.1	1.0	8.5	7.0	0.07/25	0.07/25
47							1701	192	Soft	1	255	255	309	129.7	53.7	131.2	61.1	4.1	3.9	12.4	14.5	0.07/20	0.07.20
48							4302	243	Soft	2	148	149	148	155.2	104.0	154.8	106.4	0.0	0.0	25.6	14.4	0.03/20	0.03/25
49							3701	362	Stiff	1	290	290	345	102.6	85.0	104.1	79.0	0.7	0.6	7.1	10.1	0.05/15	0.05/15
50							6401	285	Soft	2	228	229	236	101.9	54.7	99.7	44.7	0.7	0.7	21.7	7.2	0.07/20	0.07/20
51	31/08/1999	Sakarya	4.0	5.1	5.1	4.58	5401	412	Stiff	1	35.8	36.1	37.7	23.9	9.5	31.2	11.4	0.2	0.3	3.4	12.9	0.1/25	0.1/25
52							3401	595	Stiff	2	91.3	92.3	96.4	49.5	15.8	53.5	13.5	0.2	0.2	9.9	10.3	0.07/40	0.07/30
53	13/09/1999	Sakarya	10.4	5.8	5.8	5.7	1612	197	Soft	1	41.2	41.9	46	27.7	13.5	27.8	9.9	2.8	3.8	6.3	3.4	0.2/25	0.2/23
54							4302	243	Soft	2	146	146	148	88.0	34.7	89.2	33.2	0.5	0.7	15.5	12.0	0.05/20	0.05/20
55							5401	412	Stiff	1	20.5	21.8	25.5	30.1	10.1	29.8	10.4	1.2	2.4	7.4	14.8	0.05/35	0.05/30
56	29/09/1999	Sakarya	12.2	5.2	5.2	4.76	5401	412	Stiff	1	86	87.2	88.6	46.3	10.4	38.4	8.7	0.1	0.2	8.2	16.3	0.15/25	0.15/25
57	11/11/1999	Sakarya	7.5	5.6	5.6	5.4	4302	243	Soft	2	145	145	149	63.7	27.3	64.0	29.3	0.2	0.2	11.6	21.0	0.1/20	0.1/20
58							5401	412	Stiff	1	10.4	11.3	11.2	13.4	3.4	10.8	2.3	19.8	44.6	4.3	8.2	0.25/22	0.2/25
59							1401	294	Soft	1	8	8.6	36.1	17.2	8.6	24.0	9.0	386.3	252.6	5.8	2.9	0.05/25	0.05/40
60							8101	282	Soft	1	0	9.7	5.3	23.7	10.9	25.2	11.2	304.8	282.4	4.5	6.4	0.05/40	0.07/35
61	12/11/1999	Duzce	10.4	7.1	7.1	7.3	4302	243	Soft	2	164	164	184	116.6	57.8	116.6	44.0	1.9	4.6	13.6	13.9	0.05/15	0.07/15
62							1406	355	Soft	1	32.1	32.3	37.5	28.8	16.8	28.5	15.5	9.5	21.2	6.0	10.6	0.07/20	0.07/25
63							5401	412	Stiff	1	40.5	40.8	68.6	82.0	30.0	74.4	24.8	0.9	1.7	7.4	8.6	0.07/30	0.07/30
64	13/11/1999	Bolu	5.2	5.0	5.0	4.41	1401	294	Soft	1	47.6	47.8	49.7	23.1	4.7	23.0	8.3	0.2	0.1	10.6	11.5	0.25/22	0.25/23
65	14/02/2000	Duzce	10.0	5.3	5.3	4.93	8101	282	Soft	1	51.7	52.4	54	43.4	10.9	40.6	10.8	0.8	1.0	9.4	10.6	0.25/25	0.25/25
66	02/04/2000	Sakarya	8.8	4.5	4.5	3.53	5401	412	Stiff	1	15.3	17.3	15.6	7.2	2.1	6.6	1.2	0.6	1.9	6.4	5.3	0.20/25	0.07/30
67	21/04/2000	Sakarya	19.9	5.4	5.4	5.11	2002	356	Soft	1	22.6	28.5	23.4	68.0	42.6	81.3	43.5	1.4	1.3	12.4	20.5	0.1/35	0.1/35
68	06/06/2000	Cankiri-Cerkes	10.0	6.0	6.0	5.9	1801	348	Soft	1	8.2	11.1	15.2	63.5	33.6	65.8	39.7	11.4	9.3	14.2	14.7	0.07/25	0.07/40
69							3701	362	Stiff	1	90.9	91.8	95.5	60.6	29.3	61.2	31.0	0.3	0.2	18.6	14.7	0.15/25	0.15/25
70	08/06/2000	Cankiri-Cerkes	32.6	4.9	4.9	4.23	1801	348	Soft	1	9.5	32.9	11.2	43.5	20.4	42.1	17.7	0.5	0.4	15.8	15.8	0.07/40	0.07/40
71	09/06/2000	Cankiri-Cerkes	3.9	5.0	5.0	4.41	1801	348	Soft	1	9	9.3	10.7	44.8	24.5	43.6	21.8	0.5	0.6	19.8	13.7	0.1/40	0.07/40
72	23/08/2000	Sakarya	10.5	5.3	5.3	4.9	5402	272	Soft	1	14.2	16.6	17	31.5	11.1	23.5	13.9	6.9	10.0	3.3	3.4	0.07/25	0.1/25
73							8101	282	Soft	1	30.9	32.1	33.5	25.2	13.3	25.1	13.8	0.4	0.4	8.9	14.0	0.1/30	0.07/40
74							1612	197	Soft	1	93.6	93.9	96	39.8	14.7	44.2	20.0	1.1	0.7	11.3	12.8	0.07/25	0.1/25

Table 9. Considered Turkish registers

Register Index	EARTHQUAKE INFORMATION						STATION INFORMATION															REGISTER INFORMATION	
	Date	Earthquake	Hypo central depth (km)	Magnitude			Station Code	$V_{s,30}$ (m/s)	Soil Type	Seismic Zone	Distance			Duration (NS)		Duration (EW)		Arias Intensity		ID		Filtering range f_1 / f_2 (Hz)	
				M_L	M_w	M_s					R_{jb} (km)	R_{rup} (km)	R_{epi} (km)	t_{br} (s)	t_{tf} (s)	t_{br} (s)	t_{tf} (s)	NS	EW	I_{D-NS}	I_{D-EW}	NS	EW
75							5401	412	Stiff	1	29.8	31.6	32.5	28.4	11.9	26.6	10.0	0.3	0.6	11.4	17.4	0.1/15	0.2/15
76	04/10/2000	Denizli	2.8	5.0	5.0	4.41	2002	356	Soft	1	9.9	10.1	11.9	23.2	18.1	22.5	16.2	3.3	4.2	31.2	33.1	0.35/30	0.25/30
77	15/11/2000	Van	48.4	5.5	5.5	5.28	6501	363	Stiff	2	36.8	59.4	40.6	66.2	33.1	66.2	33.4	0.3	0.4	18.5	27.1	0.15/25	0.2/30
78	16/01/2001	Istanbul	13.8	4.0	4.0	2.65	3401	595	Stiff	2	17.6	21.8	18	18.4	6.9	9.8	4.5	0.0	0.0	6.3	4.8	0.4/15	0.4/15
79	22/03/2001	Cankiri	10.8	4.7	4.7	3.88	1801	348	Soft	1	22.6	24.6	24	41.5	12.7	41.6	12.5	0.3	0.3	9.4	19.8	0.6/30	0.6/35
80	29/05/2001	Erzurum	20.3	4.9	4.9	4.23	2501	375	Stiff	2	33.9	38.6	35.3	31.1	11.5	36.3	13.6	0.5	0.4	8.8	11.7	0.1/30	0.1/30
81	22/06/2001	Balikesir	7.0	5.2	5.2	4.76	1001	662	Soft	1	33.8	34.2	34.8	26.5	8.9	27.1	9.7	0.1	0.1	9.1	11.9	0.07/25	0.1/25
82	25/06/2001	Kahramanmaras	10.0	5.4	5.4	5.11	4603	466	Rock	2	73.7	74.7	75.8	74.0	24.6	73.1	23.9	0.3	0.4	21.3	20.8	0.1/25	0.1/20
83	10/07/2001	Erzurum	22.5	5.4	5.4	5.11	2501	375	Stiff	2	31.2	37.1	34.1	36.2	11.2	34.9	11.4	0.7	0.9	8.9	12.8	0.07/30	0.07/25
84	26/08/2001	Bolu	8.8	5.2	5.2	4.76	1401	294	Soft	1	22.8	23.8	24.2	4.5	1.6	5.6	2.3	6.5	3.0	6.5	7.8	0.6/35	0.6/35
85	02/12/2001	Van	19.6	4.8	4.8	4.06	6501	363	Stiff	2	12.8	22.7	14.2	26.1	10.9	27.9	13.9	0.7	0.5	7.8	12.8	0.1/30	0.2/35
86	03/02/2002	Afyon	22.1	6.5	6.5	6.5	301	226	Soft	2	51.7	57.7	64.7	30.3	14.2	31.9	16.7	13.7	17.1	5.8	13.5	0.07/17	0.1/17
87							4302	243	Soft	2	133	135	144	42.1	25.9	41.9	24.8	1.7	1.7	13.7	13.7	0.1/22	0.07/15
88	03/02/2002	Afyon	24.9	5.8	5.8	5.66	301	226	Soft	2	30.8	37.9	34	55.6	28.6	45.8	20.1	3.5	5.4	17.2	12.4	0.1/20	0.1/20
89	30/07/2002	Denizli	6.0	4.7	4.7	3.88	2002	356	Soft	1	24	25.1	25.4	39.5	21.3	38.8	17.1	0.3	0.4	23.1	18.8	0.1/45	0.2/35
90	19/11/2002	Malatya	10.0	4.8	4.8	4.06	4401	481	Stiff	1	35.2	37.1	35.9	20.6	6.7	17.0	4.9	0.1	0.2	11.2	6.0	0.2/30	0.15/35
91	14/12/2002	Kahramanmaras	29.2	4.8	4.8	4.06	4604	611	Stiff	2	17.3	32.9	19.1	8.1	3.1	9.7	3.8	1.3	0.9	6.0	8.4	0.2/25	0.2/30
92	10/04/2003	Izmir	11.3	5.7	5.7	5.5	3502	270	Soft	1	33.2	34.6	37.5	25.2	11.0	37.4	13.3	4.2	2.5	5.4	10.8	0.07/35	0.05/27
93							908	269	Soft	1	129	129	133	50.0	31.5	50.0	33.6	0.3	0.2	17.0	21.6	0.2/30	0.15/25
94	01/05/2003	Bingol	10.0	6.3	6.3	6.27	1201	529	Stiff	1	2.2	5.8	11.8	23.9	4.6	23.9	6.8	200.3	82.7	7.4	8.0	0.2/25	0.1/25
95							1202	-	-	1	13.3	15	14	36.0	15.9	29.2	15.7	0.8	0.4	14.4	12.7	0.05/30	0.1/30
96							1201	529	Stiff	1	11.6	13.4	12.9	25.2	11.1	23.7	11.2	0.2	0.3	12.3	4.9	0.15/20	0.1/20
97	08/05/2003	Bingol	8.6	4.9	4.9	4.2	1205	529	Stiff	1	11.6	13.4	12.9	33.3	16.7	28.4	14.7	0.6	0.9	17.7	8.0	0.1/45	0.07/45
98							1203	-	-	1	16.4	17.8	18	28.7	14.9	25.9	13.3	0.5	0.6	8.9	7.5	0.1/17	0.1/25
99							1204	-	-	1	12.9	14.6	14.3	27.9	13.6	31.3	13.3	0.1	0.0	10.4	8.4	0.1/40	0.1/22
100	10/05/2003	Bingol	10.0	4.8	4.8	4.06	1205	529	Stiff	1	19.5	21.2	20.8	30.2	14.1	32.8	17.4	0.5	0.2	10.7	14.4	0.15/22	0.1/22
101	21/05/2003	Duzce	5.0	4.4	4.4	3.36	8101	282	Soft	1	15.7	16.1	16.4	31.7	13.6	21.8	12.7	0.3	0.4	13.4	8.8	0.1/30	0.3/30
102	09/06/2003	Bandirma	9.1	4.8	4.8	4.06	1007	417	Stiff	1	17	19.9	18.2	16.3	4.0	17.0	5.2	0.7	0.4	5.6	7.1	03/35	0.2/35
103	06/07/2003	Canakkale	17.1	5.7	5.7	5.54	1701	192	Soft	1	44.1	46.8	45.9	58.2	31.9	58.7	28.1	1.3	1.1	13.2	22.2	0.1/30	0.07/25
104	13/07/2003	Malatya	12.9	5.5	5.5	5.28	4401	481	Stiff	1	55	55.9	56.3	39.6	15.3	38.9	17.9	0.2	0.2	8.1	11.4	0.07/30	0.1/30
105	23/07/2003	Denizli	28.3	5.3	5.3	4.9	2007	232	Soft	1	10.9	28.3	13.3	90.0	12.0	21.3	11.3	5.6	7.3	7.7	7.8	0.07/30	0.07/30
106							907	301	Soft	1	37.4	45.7	39.9	26.5	10.7	35.3	10.5	0.5	0.5	9.5	13.7	0.05/40	0.05/30
107							908	269	Soft	1	47.4	54.1	49.9	49.3	23.9	51.1	18.6	0.8	1.0	15.3	16.4	0.07/30	0.1/35
108							2002	356	Soft	1	30.2	39.9	32.9	42.0	23.4	33.0	16.7	0.6	1.1	19.4	12.3	0.15/35	0.1/40
109	26/07/2003	Denizli	5.0	4.9	4.9	4.2	2007	232	Soft	1	18.8	19.1	20	22.7	11.3	38.6	15.1	1.2	0.9	12.9	12.8	0.07/30	0.1/30
110							907	301	Soft	1	42.8	43	43.2	35.6	11.3	30.1	10.5	0.1	0.1	8.6	11.6	0.07/40	0.1/30
111							908	269	Soft	1	52.1	52.2	52.6	48.6	20.6	41.6	18.4	0.2	0.3	24.3	18.1	0.15/40	0.2/40
112	26/07/2003	Denizli	21.3	5.4	5.4	5.1	2007	232	Soft	1	11.2	22	13.8	37.4	15.5	36.8	18.3	10.8	10.4	11.6	12.9	0.05/30	0.05/30
113							2002	356	Soft	1	29.2	34.8	32.2	50.9	32.9	50.4	32.2	0.9	1.3	15.8	20.1	0.1/15	0.1/15

	Table 9. Considered Turkish registers																					
	EARTHQUAKE INFORMATION						STATION INFORMATION							REGISTER INFORMATION								
Register Index	Date	Earthquake	Hypo central depth (km)	Magnitude			Station Code	$V_{s,30}$ (m/s)	Soil Type	Seismic Zone	Distance			Duration (NS)		Duration (EW)		Arias Intensity		ID		Filtering range f_1 / f_2 (Hz)	
				M_L	M_w	M_s					R_{jb} (km)	R_{rup} (km)	R_{epi} (km)	t_{br} (s)	t_{tf} (s)	t_{br} (s)	t_{tf} (s)	NS	EW	I_{D-NS}	I_{D-EW}	NS	EW
114							907	301	Soft	1	40	44.3	42.5	36.1	11.6	36.2	10.7	0.8	0.7	8.9	18.6	0.05/30	0.1/30
115							908	269	Soft	1	49.9	53.4	52.5	62.4	20.8	59.9	19.6	1.1	1.4	16.8	19.7	0.1/30	0.1/35
116							904	371	Stiff	1	76.3	78.7	79	37.3	11.4	53.5	12.6	0.1	0.1	11.2	11.5	0.1/30	0.1/30
117	26/07/2003	Denizli	7.3	4.9	4.9	4.2	2007	232	Soft	1	16.8	17.8	18.5	65.0	32.0	51.7	27.8	0.3	0.3	16.6	12.0	0.15/35	0.1/35
118							908	269	Soft	1	48.2	48.5	49.9	49.5	20.5	47.6	23.2	0.3	0.3	12.4	9.8	0.1/40	0.2/40
119	26/02/2004	Malatya	5.0	4.9	4.9	4.23	4401	481	Stiff	1	44.1	44.6	45.6	17.7	9.9	29.8	11.8	0.1	0.1	7.2	18.5	0.3/40	0.3/40
120	03/03/2004	Malatya	7.2	4.6	4.6	3.71	1201	529	Stiff	1	17.8	18.8	18.7	17.5	8.8	28.5	12.6	0.1	0.1	4.0	11.6	0.2/40	0.25/30
121	13/04/2004	Bolu	5.0	4.4	4.4	3.36	1401	294	Soft	1	7.3	8.3	7.4	34.8	5.6	28.7	5.3	1.7	1.9	4.8	14.4	0.2/25	0.35/22
122	04/08/2004	Mugla	10.0	5.5	5.5	5.3	4802	747	Stiff	1	33.1	35.2	36.5	32.2	6.2	31.2	6.5	0.3	0.4	6.1	4.9	0.15/30	0.2/35
123							4802	747	Stiff	1	34.2	36.2	37	14.2	3.7	15.9	4.0	0.3	0.3	3.6	8.4	0.07/30	0.1/30
124	11/08/2004	Elazig	7.4	5.6	5.6	5.41	2301	407	Stiff	2	33.4	33.8	37	44.9	15.2	43.5	15.7	0.6	1.0	8.1	8.2	0.1/20	0.1/15
125	20/12/2004	Mugla	12.5	5.3	5.3	4.9	4804	372	Stiff	1	33.8	35.5	36.7	21.8	9.0	33.5	13.2	0.4	0.2	10.3	15.9	0.07/30	0.2/30
126							4805	393	Stiff	1	16.2	19.4	18.7	50.4	14.3	35.6	12.7	1.7	2.8	19.4	26.4	0.07/12	0.15/12
127	10/01/2005	Mugla	15.8	5.4	5.4	5.11	4805	393	Stiff	1	40.2	42.5	43.3	54.2	16.1	42.0	16.8	0.5	0.5	13.1	19.7	0.07/12	0.1/12
128	11/01/2005	Mugla	14.9	5.0	5.0	4.41	4802	747	Stiff	1	25.5	29.7	27.4	27.5	8.7	26.9	8.2	0.0	0.1	15.6	16.3	0.1/30	0.1/12
129	23/01/2005	Antalya	12.1	5.8	5.8	5.66	703	299	Soft	1	75.2	75.9	80	58.8	19.9	65.2	28.3	1.5	1.2	11.0	9.6	0.07/20	0.1/22
130	06/06/2005	Bingol	10.5	5.6	5.6	5.41	1208	485	Stiff	1	45.4	46	48.5	39.9	12.4	33.3	9.8	0.3	0.3	15.4	15.9	0.15/25	0.1/25
131	17/10/2005	Izmir	20.5	5.5	5.5	5.28	3502	270	Soft	1	53	56	56.2	37.6	14.0	36.6	13.6	0.4	0.3	14.6	10.0	0.3/30	0.3/30
132	17/10/2005	Izmir	18.6	5.8	5.8	5.66	3502	270	Soft	1	51.3	53.5	56.1	37.1	12.9	35.4	14.7	0.6	0.6	10.3	14.0	0.15/25	0.07/25
133	17/10/2005	Izmir	11.0	5.2	5.2	4.76	3502	270	Soft	1	56.1	57.1	58.3	37.1	14.3	37.0	15.6	0.2	0.2	9.8	15.1	0.1/30	0.1/30
134	20/10/2005	Izmir	15.4	5.8	5.8	5.7	3502	270	Soft	1	54.1	55.4	59	45.7	15.1	42.4	15.7	1.3	1.2	16.1	8.7	0.0730	0.07/35
135							4501	340	Soft	1	75.4	76.4	80.3	61.4	17.0	38.9	15.1	0.3	0.4	18.2	7.3	0.1/25	0.1/25
136	26/11/2005	Malatya	19.1	5.1	5.1	4.58	4401	481	Stiff	1	47.6	50.6	49.2	28.2	12.6	33.7	15.6	0.1	0.1	8.8	13.6	0.1/35	0.1/35
137							2007	232	Soft	1	14.2	18.3	15.8	34.8	10.2	35.6	13.6	0.6	0.4	8.2	14.3	0.1/25	0.1/40
138	05/06/2006	Denizli	11.1	4.8	4.8	4.1	907	301	Soft	1	22.8	25	24.5	12.7	5.6	10.4	4.2	0.9	1.1	12.3	6.1	0.2/25	0.2/25
139							908	269	Soft	1	33.5	35	35.2	40.9	16.9	47.5	12.0	0.4	0.5	22.9	21.9	0.2/25	0.2/30
140							1603	459	Stiff	1	27	28.4	29	16.3	2.7	21.5	5.4	0.6	0.3	7.8	8.3	0.2/25	0.2/20
141							1601	249	Soft	1	20.9	22.6	22.9	20.7	13.3	25.7	11.4	1.8	0.9	3.4	9.0	0.15/40	0.15/40
142							1606	274	Soft	1	10.7	12.2	12.7	13.4	4.9	11.4	4.8	13.2	15.0	7.2	8.7	0.1/20	0.2/30
143							1607	370	Stiff	1	7.3	9.3	9.4	19.2	7.5	15.1	8.2	14.4	10.8	5.8	3.2	0.1/20	0.2/30
144	24/10/2006	Bursa	7.9	5.2	5.2	4.8	1608	366	Stiff	1	13.7	14.9	15.8	15.7	6.3	14.4	4.6	3.0	4.3	7.6	4.8	0.15/20	0.1/25
145							1609	228	Soft	1	12.7	13.9	14.7	26.7	10.7	19.9	10.4	5.0	5.8	14.4	7.4	0.1/20	0.1/25
146							1615	-	-	1	23.2	23.9	25.2	35.3	9.7	22.0	11.0	1.2	1.1	13.9	5.6	0.15/30	0.1/30
147							7701	375	Stiff	1	29.4	29.9	30.8	21.0	12.9	26.9	11.4	0.5	0.7	11.9	10.3	0.2/15	0.15/15
148							7702	359	Soft	1	28.5	29.1	29.7	18.1	3.3	18.5	7.3	0.9	0.6	7.4	10.5	0.2/25	0.25/20
149							1613	401	Stiff	2	57.8	58.7	59.8	48.3	21.7	48.8	23.9	0.1	0.1	28.5	31.7	0.2/25	0.2/25
150							302	198	Soft	1	-	-	151	95.0	42.7	95.5	50.1	0.5	0.3	14.9	21.8	0.1/20	0.1/20
151	19/05/2011	Kutahya-Simav	24.5	5.7	5.9	5.7	1006	321	Soft	1	-	-	162	84.9	20.1	85.5	19.4	0.4	0.5	8.1	11.5	0.1/20	0.1/20
152							1009	561	Stiff	1	-	-	62.8	128.5	25.2	128.2	25.5	0.4	0.3	10.1	13.0	0.1/20	0.1/20

				Table 9. Considered Turkish registers																		
Register Index	EARTHQUAKE INFORMATION						STATION INFORMATION							REGISTER INFORMATION								
	Date	Earthquake	Hypo central depth (km)	Magnitude			Station Code	$V_{s,30}$ (m/s)	Soil Type	Seismic Zone	Distance			Duration (NS)		Duration (EW)		Arias Intensity		ID		Filtering range f_1/f_2 (Hz)	
				M_L	M_w	M_s					R_{jb} (km)	R_{rup} (km)	R_{epi} (km)	t_{br} (s)	t_{tf} (s)	t_{br} (s)	t_{tf} (s)	NS	EW	$I_{D\text{-}NS}$	$I_{D\text{-}EW}$	NS	EW
153							1102	407	Stiff	2	-	-	119	54.9	25.9	59.5	25.7	0.2	0.2	10.1	11.6	0.1/20	0.1/20
154							1613	401	Stiff	2	-	-	87.8	92.7	26.0	95.3	30.1	1.2	0.7	17.7	19.2	0.1/20	0.1/20
155							1614	265	Soft	1	-	-	116	48.9	16.7	40.2	9.6	1.1	2.6	9.9	7.4	0.1/20	0.1/20
156							1618	-	-	1	-	-	136	95.9	25.6	95.8	23.5	0.4	0.3	15.1	16.1	0.1/20	0.1/20
157							2605	801	Rock	2	-	-	141	52.7	24.9	115.4	29.1	0.2	0.3	10.6	14.2	0.1/20	0.1/20
158							2610	-	-	2	-	-	138	113.0	30.7	97.6	32.6	0.4	0.3	12.9	13.1	0.1/20	0.1/20
159							2613	-	-	2	-	-	73.4	100.7	32.3	99.5	40.9	0.2	0.2	11.0	14.3	0.1/20	0.1/20
160							4108	-	-	1	-	-	195	164.0	67.2	160.9	75.3	0.9	1.0	30.0	15.2	0.1/20	0.1/20
161							4116	-	-	1	-	-	188	161.3	77.9	155.4	87.4	0.4	0.4	12.0	12.7	0.1/20	0.1/20
162							4301	267	Soft	2	-	-	85	90.8	19.7	92.9	26.3	1.8	1.4	17.9	18.3	0.1/20	0.1/20
163							4304	343	Soft	1	-	-	31.5	81.0	18.4	80.5	16.1	4.9	7.6	9.6	13.0	0.1/20	0.1/20
164	19/05/2011	Kutahya-Simav	24.5	5.7	5.9	5.7	4306	304	Soft	1	-	-	26.8	36.3	13.7	38.7	15.2	8.3	6.4	8.6	8.8	0.1/20	0.1/20
165							4502	292	Soft	1	-	-	11.8	95.8	33.1	94.7	35.2	0.8	0.8	10.7	9.2	0.1/20	0.1/20
166							6401	285	Soft	2	-	-	58.4	35.1	10.8	35.6	10.3	2.9	2.7	10.0	8.8	0.1/20	0.1/20
167							6503	293	Soft	1	-	-	42.2	57.0	19.2	57.1	22.3	78.5	50.9	10.5	12.8	0.1/20	0.1/20
168	23/10/2011	Van-Muradiye-Merkez	19.02	6.6	6.7	6.8	1302	-	-	2	-	-	117	116.7	12.6	117.8	16.1	10.4	14.9	8.3	11.8	0.1/20	0.1/20
169							4902	311	Soft	1	-	-	95.5	46.0	36.8	45.6	27.7	9.3	7.3	11.1	7.7	0.1/20	0.1/20