Adaptation of Energy Principles in Seismic Design of Turkish RC Frame Structures. Part I: Input Energy Spectrum

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SUMMARY:
In new generation seismic codes, traditional force-based design principles give way to more sophisticated displacement and energy based approaches. This study is a contribution to such attempts, for which the main goal is to develop design energy input spectra (DEIS) by scaling selected ground motions recorded during earthquakes in Turkey. To achieve this, the elastic design acceleration spectrum in the latest version of the Turkish Earthquake Code is taken as reference. There exist 16 different variants of design acceleration spectrum in terms of seismic zone and site class. Ground motion scaling approach is used in order to obtain input energy equivalent counter-part of each of these variants. Then, these scaled records are employed for the construction of the DEIS. At the end of the study, DEIS for 16 different cases are proposed as a substitute for the corresponding elastic design acceleration spectra in Turkish Earthquake Code (TEC).

Keywords: Energy-based seismic design, input energy, energy equivalent velocity, ground motion scaling

1. INTRODUCTION

The earthquake-resistant design has been traditionally based on strength of structures where a certain amount of static lateral seismic force, combined with the gravity load, is applied to a structure as the strength demand. The members are selected based on the principle that the strength supply from the structure should not be less than the strength demand on it. Engineers have been seeking for more rational seismic design alternatives so that the earthquake resistant structure could be designed based on how it performs during an earthquake. One of these design alternatives is the energy-based design approach. The concept of energy seems to best explain the structural response to a strong ground motion. The earthquake effect on the structure can be considered as energy input, a function of the structural properties and characteristics of the earthquake ground motion. The structural capacity is defined by the energy dissipation capacity, the total area enclosed in the force-deformation curves under cyclic loading. Therefore, seismic design becomes the balance of the energy demand and capacity of the structure.

Quantification of input energy is the first step in energy based approach. Before identifying the sources of energy dissipation, it must be clear how much energy is input to structure during an earthquake. This study is conducted to examine the effect of magnitude and site class on the energy spectrum and to develop design energy input spectra (DEIS) for the corresponding variants in terms of seismic zone and site class as defined in the latest version of the Turkish Earthquake Code (TEC, 2007). Hence it constitutes the first part in the development of an energy-based seismic design methodology for Turkish RC frame structures. It only deals with the amount of energy input to these structures. The dissipation of this energy through structural components is the subject of the second part of the study and it will not be discussed in this paper.

2. PREVIOUS STUDIES

Starting from the early work of Housner (1956), there exists research on the energy-based concepts for structural systems (Zahrah and Hall, 1984; Akiyama, 1985; McCabe and Hall, 1989; Uang and Bertero, 1990; Fajfar *et al*., 1992; Sucuoğlu and Nurtuğ, 1995; Decanini and Mollaoli, 1998; Ye and Otani, 1999; Riddell and Garcia, 2001, Sucuoğlu and Erberik, 2004). Previous studies have been mainly focused on single degree of freedom (SDOF) systems and concluded that the energy input is much more sensitive to the ground motion parameters than the structural properties (such as the period, ductility and strength), particularly in the medium and long period structures. Empirical formulas have been proposed to estimate the energy input for the SDOF system mainly based on ground motion characteristics.

Uang and Bertero (1990) derived relative and absolute energy equations in their study. They showed that relative input energy represents the work done by equivalent lateral force and absolute input energy covers both the relative displacement of the mass and the rigid body translation (displacement of the base). Therefore, relative input energy is more sensitive to small periods where absolute energy is sensitive to larger periods. At the intermediate periods they give almost the same results.

According to Akiyama (1985) and Uang and Bertero (1990), relative input energy of an SDOF system can provide a good estimate of the input energy for multi storey buildings. In their study, Uang and Bertero (1990) conducted a shaking table test of 6 story steel frame structure subjected to a specific ground motion record and the correlation between experimentally measured energy equivalent velocity for the multi storey structure and the calculated energy equivalent velocity for an SDOF system was found to be very good. Similarly, Tso et al (1993) stated that there is a good correlation of input energy between low rise ductile moment resisting frames and equivalent SDOF systems. However, for high rise frames, the contributions of higher modal responses become significant and the use of equivalent SDOF systems may underestimate the energy demand on the building.

According to Zahrah and Hall (1984), for an SDOF system subjected to ground motion, increase in the amount of damping reduces the maximum responses but it has a little or no effect on amount of energy imparted to that system. Furthermore, they suggested that spectral velocity of an SDOF system for zero damping is a good estimate for equivalent velocity of the same system for 5% damping.

In the last two decades, studies concerning the development of DEIS for different earthquake-prone regions of the world have gained importance. Decanini *et al*. (1998) studied on the formulation of earthquake input energy spectra and they used 296 records taken from 37 seismic events and they classified these records according to their site classes, distance to fault and magnitude. They normalized the energy spectra with a factor, by calculating the area under each spectrum between the periods 0 and 4. Similarly, Benavent-Climent *et al*. (2002) derived elastic input energy spectra by using the records from 48 earthquakes that have occurred in Spain. Records are classified according to two soil types; soft and stiff. Amiri *et al*. (2008) proposed DEIS based on Iranian earthquakes. 110 records were selected and through dynamic response analyses, DEIS for four site classes were obtained. Recently, Benavent-Climent *et al*. (2010) constructed energy input spectra applicable to the seismic design of structures in moderate-to-high seismicity regions. They used 144 ground motions recorded in Colombia. In a similar manner, Tselentis *et al*. (2010) assessed the seismic hazard for Greece in terms of response spectra acceleration and elastic input energy.

3. CHARACTERISTICS OF DEIS

One of the major properties of DEIS is its idealized shape. In literature, two piece-wise linear shapes have been used to represent DEIS. The first one is the bilinear shape with linearly increasing and constant regions and the second one is the trilinear shape with linearly increasing, constant and descending regions. Akiyama (1985), Kuwamura *et al.*(1989) and Benavent Climent *et al.* (2002) used bilinear shape in their studies while Decanini and Mollaioli (1998) and Amiri *et al.* (2008) used trilinear shape for DEIS. Bilinear shape seems more appealing than trilinear shape for some reasons. First of all, a design spectrum should have a simple shape and also should be conservative. Besides, constant spectral input energy in the medium and long period range is intended to include the energy contained in the higher modes of flexible structures, since the spectral input energy in multi degree of freedom (MDOF) systems is given by a direct summation of the input energy for all modes in the structure (Kuwamura *et al.,* 1989 and Chai *et al.,* 1998). In other words, the descending branch of a trilinear design energy spectrum shape may underestimate the actual energy amount due to the effect of higher modes. As a result, shape of the energy spectra is selected as bilinear in this study. Bilinear DEIS has two important parameters; corner period (T_C) and maximum input energy equivalent velocity (V_{EM}) which are shown in Fig. 3.1. Input energy is expressed in terms of input energy equivalent velocity, V_E

$$V_E = \sqrt{\frac{2E_I}{M}} \tag{3.1}$$

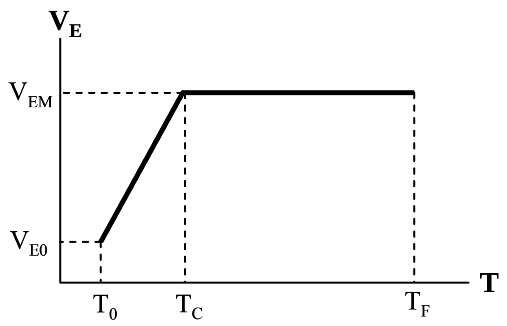

Figure 3.1. Representation of bilinear DEIS

In Eqn. 3.1, M stands for the total mass of the structure. In Fig. 3.1, V_{E0} and T_0 are the initial energy equivalent velocity and period, respectively. Parameter T_F stands for the final period to be considered for the design of building structures. In this study, parameters T_0 and T_F are set to 0.1 and 4.0 seconds, respectively.

4. TOWARD AN ENERGY-BASED DESIGN APPROACH

This section is devoted to the adaptation of energy-based principles to earthquake resistant design philosophy in Turkey, which is currently a force-based approach. The section starts with the introduction of the current earthquake code and the related force-based design parameters. Next, DEIS is constructed as a substitute for the elastic acceleration spectrum, keeping the same seismic zonation and site classification of the current code. This is achieved by grouping the acceleration traces recorded in Turkey for the last four decades and using them to obtain the statistical variation of DEIS. During the process, ground motion scaling techniques are used. Final step is to present the energy based design parameters for different seismic zones and site classes.

4.1. Examination of the Current Force-Based Design Approach in Turkish Earthquake Code

Just like most of the existing earthquake codes, the current version of TEC depends on a force-based approach, in which the design base shear force is calculated through 5% damped elastic design acceleration spectrum. Design acceleration spectrum in the TEC mainly depends on three parameters which are effective ground acceleration coefficient (A_o), building importance factor (I) and elastic acceleration spectrum, S(T) as given in Eqn. 4.1.

$$A(T) = A_o\ I\ S(T) \tag{4.1}$$

Parameter A_o depends on the seismic zone and parameter I stands for the importance of the building. There are four seismic zones (I-IV) and the parameter takes values between 0.1 (zone IV, the least critical) and 0.4 (zone I, the most critical), respectively. Parameter I is based on the occupancy classes and post-earthquake usage of the building. For reinforced concrete buildings used for residential purposes, parameter I can be taken as 1. Acceleration spectrum S(T) (see Fig. 4.1) is composed of three regions and it is a function of the period of the structure. The corner periods T_A and T_B are determined from local site classes (Z1-Z4 in TEC). Z1 is for stiff site conditions whereas Z4 is for very soft site conditions. Further information about the design parameters can be obtained from TEC (2007).

$$S(T)=\begin{cases} 1+1.5\left(\dfrac{T}{T_A}\right) & T \le T_A \\ 2.5 & T_A < T \le T_B \\ 2.5\left(\dfrac{T_B}{T}\right)^{0.8} & T > T_B \end{cases} \tag{4.2}$$

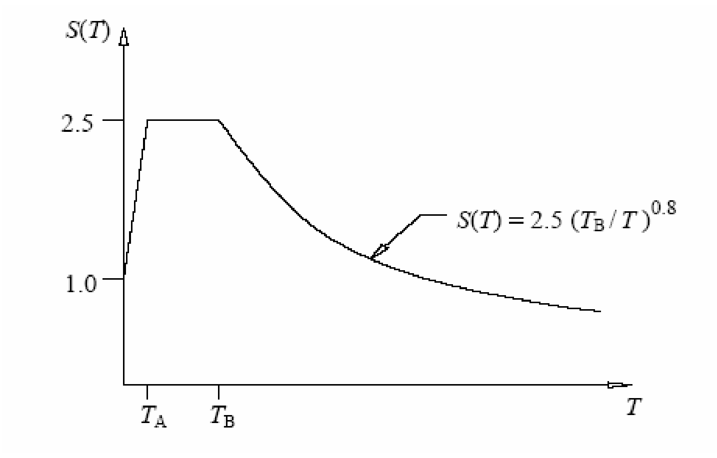

Figure 4.1. Shape of the elastic acceleration design spectrum proposed by TEC (2007)

Different design acceleration spectrum is obtained for each seismic zone-site class combination, which is defined as a "variant" in this study. Since there are four groups of seismic zone and site class, there exist 16 variants for the design acceleration spectrum. In order to cover all range of magnitudes and site classes in the energy-based approach, a different DEIS should be obtained for each variant, as explained in the following sections in a detailed manner.

4.2. Selection and Scaling of Ground Motion Records

According to the previous studies, major parameters that play significant role in the construction of DEIS are magnitude, distance from the seismic source and site class (Decanini and Mollaioli, 1998; Benavent-Climent *et al.*, 2002; Benavent-Climent *et al.*, 2010). Other researchers tried to include effective duration also as an additional parameter since it directly affects the amount of energy input to the structure (Chai and Fajfar, 2000; Amiri *et al.*, 2008). Hence it is necessary to modify the parameters used for an energy-based design approach. The most important parameter among the others is the magnitude. Especially, moment magnitude is directly related with the amount of energy released during the earthquake. So this parameter should be explicitly included in the design approach. This is achieved by defining the seismic zones proposed by TEC in terms of some magnitude ranges. Examining the magnitudes of the past earthquakes in Turkey that occurred in different seismic zones and using some engineering judgment, the magnitude ranges of seismic zones are considered as shown in Table 4.1. To determine the site classes belonging to the ground motion records, mean shear-wave velocity of uppermost 30 m of soil/rock profile ($V_{s,30}$) of each local site are considered (Sandıkkaya *et al*., 2010). The relationship between site class and the parameter $V_{s,30}$ is given in Table 4.2.

Table 4.1. Seismic zones in TEC and the corresponding magnitude ranges

Seismic Zone (TEC, 2007)	Magnitude range
I	$M \geq 7$
II	$6 \leq M < 7$
III	$5.5 \leq M < 6.5$
IV	$5 \leq M < 6$

Table 4.2. The relationship between site classes of TEC and the parameter $V_{s,30}$

Site Class	Mean $V_{s,30}$ (m/s)
Z1	≤ 700
Z2	400 – 700
Z3	200 – 400
Z4	≥ 200

Since the aim of this study is to propose an alternative design approach to be used for Turkish RC frame buildings, the ground motion records are taken from the previous earthquakes in Turkey. However, for some site classes (for Z1 and Z4 classes) and magnitude ranges (M>7 and 6<M<7), the number of ground motion records is not sufficient to carry out the scaling process. To solve this issue, ground motions recorded during the earthquakes caused by the San Andreas Fault in California are included into the database since this fault emerges as a close analogue of the North Anatolian Fault (NAF), with the two continental transforms sharing similar slip rates, total length, and straightness relative to their poles of rotation (Stein *et al*., 1997). In other words, the source mechanism of the earthquakes created by this fault is close to the ones created by the NAF. Hence, some records taken from the 1989 Loma Prieta earthquake (caused by the San Andreas Fault) are included in the groups that contain the ground motions with M>7 and recorded on site classes Z1 and Z4. However, there still exists lack of data in the number of records for the groups that contain ground motions with 6<M<7 and recorded on site classes Z1 and Z4 and for these groups there are no available records that can be taken from the earthquakes caused by the San Andreas Fault Zone (although records exist, they were not recorded on the required site classes Z1 and Z4). Hence, an alternative solution proposed by Ay and Akkar (2012) is employed for the required data. Their method is based on modifying each strong-motion record by using known fundamental seismological parameters together with the estimations of ground-motion prediction equations (GMPE) for a given target hazard level. In other words, it is possible to transfer ground motion records from a group with abundant of data to a group with missing data since during scaling, seismological parameters of the records (i.e. magnitude, distance to fault and even site class) also change. Therefore the method can be used in this study to develop DEIS for the variants that involve missing data (ground motion groups with 6<M<7 and recorded on site classes Z1 and Z4). By also considering the limitations of the method stated by Ay and Akkar (2012), the scaling and transfer of ground motion data is achieved from neighbor groups (i.e. M>7 and 5<M<6 with the same site classes Z1 and Z4). After the application of the method, all ground motion groups that correspond to a magnitude range-site class pair have sufficient data (i.e. at least 10 records) to be used for the construction of DEIS.

4.3 Construction of DEIS

For the construction of DEIS, first the ground motion records in each group are scaled such that the mean scaled spectrum matches with the target design acceleration spectrum of the considered group for a specific range of periods. Then the ground motions with the appropriate scale factors are used to construct the mean V_E spectra. These spectra are used to determine the parameters V_{EM} and T_C, therefore the idealized (bilinear) DEIS for each group that represents a pair of magnitude range and site class.

There are different techniques in ground motion scaling: frequency domain methods, time domain methods, wavelet matching, spectrum compatible artificial record generation, etc (Naeim *et al*., 2004;

Fajhan, 2008). In this study, scaling in the time domain is performed in a specific period range. For any group of ground motion record data, scaling procedure basically involves these following steps in order to construct target V_E spectra:

- Select a target design acceleration spectrum from TEC for a specific pair of seismic zone (magnitude range) and site class.
- Scale each ground motion in the considered group so that sum of scaled acceleration spectra fit the target acceleration spectrum with minimum error.

$$\sum_{i=1}^{n} A_i(T)\, w_i \cong A_{target}(T) \tag{4.3}$$

- Scale V_E spectrum of each record so that sum of these spectra is equal to the target V_E of the considered group.

$$V_{E,target}(T) = \sum_{i=1}^{n} V_{E,i}(T)\, w_i \tag{4.4}$$

The results of the scaling process are shown in Fig. 4.2 for seismic zone II (6<M<7) and site class Z2. For this case, the scaling process is applied for the complete range of periods (0.01-4.0 seconds) and nearly a perfect match is obtained for the target acceleration spectrum. However this is not always true since in some groups (especially for the ones with lower magnitude events and soft site conditions), a good match cannot be achieved by scaling throughout the whole range of periods for some reasons. First, it is difficult to match the target and scaled spectra with a single scaling factor through the whole range of periods including acceleration, velocity and displacement sensitive regions. Second, the power term in the descending branch of the design acceleration spectrum enforced by TEC is 0.8 (see Eqn. 4.2), which is a conservative value when compared to the counterparts in other earthquake codes and standards. In most of the codes, this power term is taken as 1.0, which is more consistent with the natural decay in spectral acceleration of actual ground motion records. Hence in such cases, the scaling process is repeated by considering bracketed interval of periods to isolate different regions of the design spectra. Since the matching problems generally occur in the descending branch of the spectrum, the scaling is conducted for two different period interval definitions; between T_B and 4 seconds, where T_B is the corner period in the design spectrum between velocity and displacement sensitive regions and between 2-4 seconds. The results of such a scaling process that has been carried out for seismic zone III (5<M<6) and site class Z3 is demonstrated in Fig 4.3. The figure clearly shows how the match is improved when a bracketed interval is used. In such cases, DEIS is constructed as the envelope of all the spectral energy curves obtained for different period ranges.

The next step is the determination of energy parameters T_C and V_{EM} and construction of the bilinear DEIS. This is not a very difficult task since the actual trend for the energy spectra is close to the idealized bilinear shape as seen in Fig. 4.2.b. Both energy parameters can be obtained by using the initial slope in the short period range and a constant line which envelopes the V_E values in the medium and long period ranges.

There are other studies based on the determination of these energy parameters since the pioneer study of Akiyama (1985). Chai and Fajfar (2000) stated that parameter T_C can be estimated by

$$T_C = 2\pi \frac{c_v}{c_a} \frac{PGV}{PGA} \tag{4.5}$$

where c_v is the ratio of spectral elastic response velocity to peak ground velocity in the medium period range c_a is the ratio of spectral elastic response acceleration to peak ground acceleration in the short period range, PGA is the peak ground acceleration and PGV is the peak ground velocity. The values of c_v and c_a recommended by the authors are 2.0 and 2.5, respectively. They also concluded that c_v>2.0

for ground motions for soft soil sites. According to Newmark and Hall (1985), the following formulation holds for c_v and c_a as a function of the damping ratio (ξ)

$$c_a = 3.21 - 0.68\ \ln\xi \tag{4.6}$$

$$c_v = 2.31 - 0.41\ \ln\xi \tag{4.7}$$

These relationships had been obtained after a large number of analyses with an ensemble of ground motion records on firm ground. Vidic *et al* (1994) used c_a=2.4 and c_v=1.9 in their study.

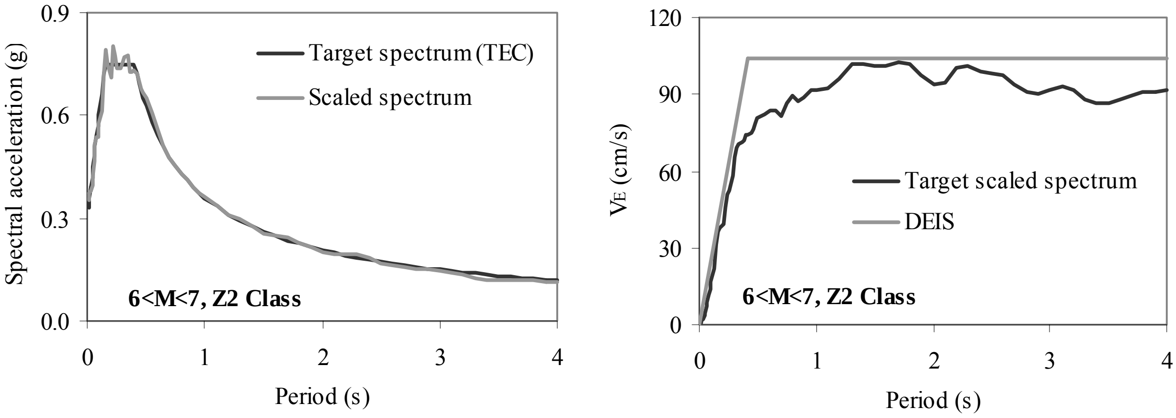

Figure 4.2. The group with 6<M<7 and site class Z2. **a)** acceleration spectra: design and scaled, **b)** input energy equivalent velocity spectra: scaled and DEIS

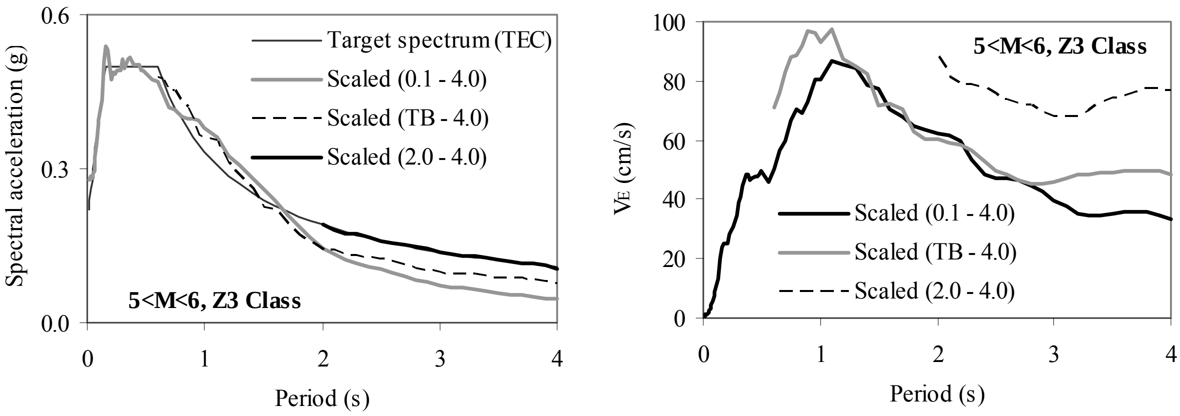

Figure 4.3. The group with 5<M<6 and site class Z3. **a)** acceleration spectra: design and scaled with different period intervals, **b)** input energy equivalent velocity spectra: scaled with different intervals

For the quantification of the parameter V_{EM}, Chai *et al.* (1998) derived the following formulation

$$V_{EM} = 0.69\left(PGA \times t_{eff}\right)^{3/8}\left(PGV\right)^{5/8} \tag{4.8}$$

where t_{eff} is the effective duration according to the definition of Trifunac and Brady (1975). Chai and Fajfar (2000) proposed another relationship for the parameter V_{EM}

$$V_{EM} = \frac{PGA}{Z}\sqrt{t_{eff}T_c}\sqrt{\frac{\lambda + 1/2}{2\lambda + 2}} \tag{4.9}$$

where Z is peak factor that estimates the most probable PGA for a given root mean square (RMS) value of ground acceleration and λ is the spectral shape constant when $T > T_C$. According to Chai and Fajfar (2000), $\lambda = 0$ for a bilinear shape. Therefore, Eqn. 4.9 becomes:

$$V_{EM} = \frac{PGA}{2Z}\sqrt{t_{eff} T_c} \tag{4.10}$$

Considering all the above discussions, DEIS are obtained for 16 considered variants are presented in Fig. 4.4. It is observed that parameter V_{EM} increases by shifting from hard (Z1) to soft (Z4) sites and from small magnitude to large magnitude events. Parameter T_C is rather stable for cases with similar site classes but starts to increase (i.e. it elongates) shifting toward soft site conditions. These trends seem to be quite reasonable when compared to DEIS obtained in other studies (Decanini *et al.* 1998, Benavent-Climent *et al.* 2002, Amiri *et al.* 2008, Benavent-Climent *et al.* 2010). Hence by using the curves in Fig 4.4, a structural designer can quickly determine the amount of energy input to be used as the demand parameter in design process of an ordinary RC frame building.

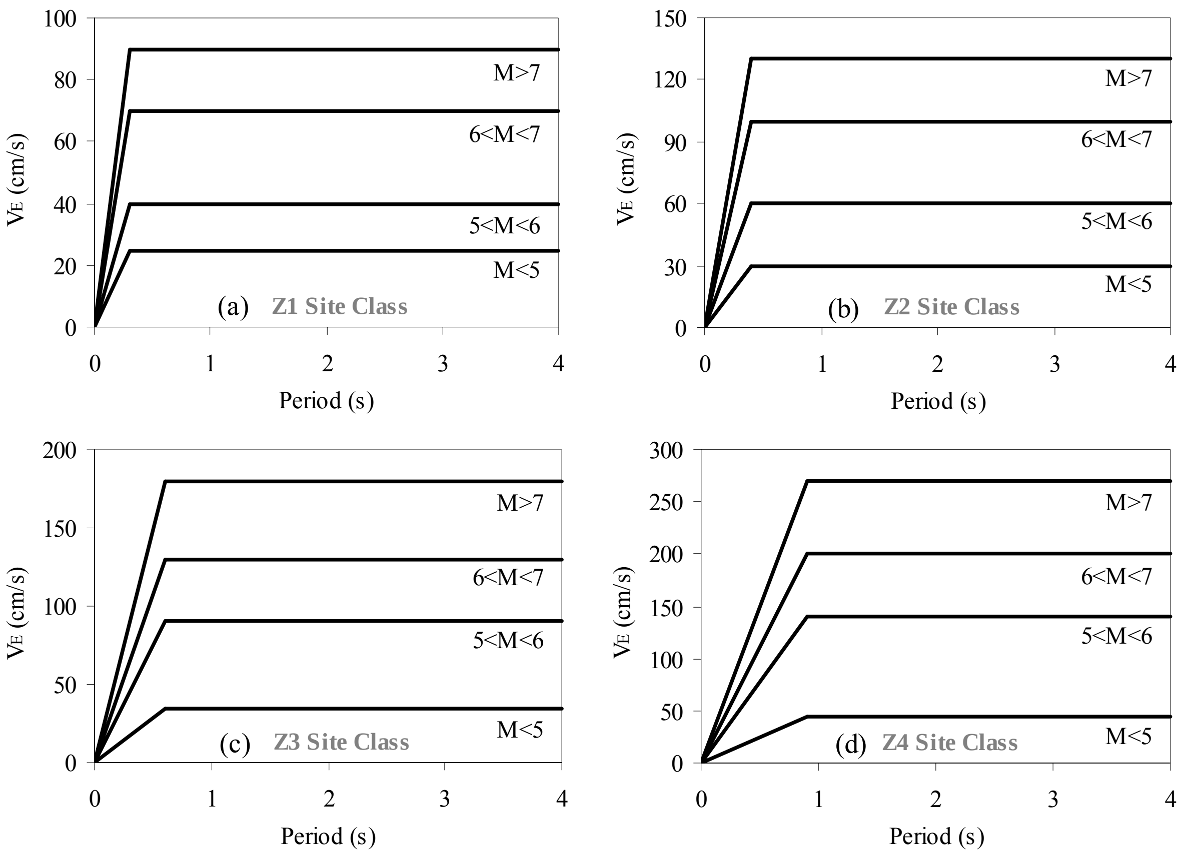

Fig 4.4 DEIS for all variants of seismic zone (magnitude range)-site class that are constructed as a substitute for elastic design spectra in TEC

5. SUMMARY AND CONCLUSIONS

This paper summarizes the first phase of an extensive study, which is being conducted with the purpose of developing energy-based design methodologies for Turkish construction practice. The study is especially focused on residential RC frame buildings that constitute the major percentage of Turkish building stock. In the first phase of the study, the aim is to develop design energy input spectra (DEIS) to be used during the design process by the structural engineers in order to calculate the energy demand. For this purpose, 16 variants of DEIS are developed for different magnitude intervals (seismic zones) and site classes, which is a compatible classification with the current force-based code procedure in Turkey. If available, ground motions which have been recorded in Turkey are employed to construct the variants of DEIS. In the cases of missing data, different solution methods are used as explained above. The results are presented in the form of bilinear DEIS with two parameters (TC, VEM) as a function of magnitude ranges (or seismic zones according to TEC) and site classes. The energy equivalent velocity data obtained in this study can be used as an input in order to design structural members of RC frame buildings in the second phase of the study.

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