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EVALUATING THE EFFECTS OF GROUND MOTION PARAMETERS ON RESPONSE SPECTRA OF IRANIAN EARTHQUAKES

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ABSTRACT

In this study, the effects of important ground motion parameters and site conditions on linear and nonlinear, pseudo-acceleration and input energy response spectra are evaluated. These parameters include magnitude, epicentral distance of recording station, strong motion duration, soil conditions, damping and ductility. A total of 620 Iran's earthquake time-histories (1240 horizontal and 619 vertical components) recorded by ISMN (Iranian Strong Motion Network) were selected for this study. The accelerographs are classified based on parameters of earthquake ground motion and site conditions. Statistical investigations are made on the response spectra of the accelerographs of these groups and it is shown that these parameters significantly affect the shape and magnitude of pseudo acceleration and input energy response spectra. Finally, based on these studies, some pseudo acceleration and yield acceleration design spectra are proposed for the region of Iran.

Keywords: response spectra, ground motion parameters, Iranian earthquakes, pseduo acceleration, yield acceleration

1. INTRODUCTION

Since Iran is situated on the Alpine-Himalayan earthquake belt, the structures built in Iran are often subjected to strong ground motions in their life. Hence, the earthquake-resistant design of buildings is of major importance in the high seismic zones of Iran.

Response spectrum is an important tool in the seismic analysis and design of structures and equipment. Unlike the power spectral density which presents information about input energy and frequency content of ground motion, the response spectrum presents the maximum response of a structure to a given earthquake ground motion. The response spectrum introduced by Biot and Housner [16-18] describes the maximum response of a damped single-degree-of-freedom (SDOF) oscillator at different frequencies or periods.

While response spectra for a specified earthquake record may be used to obtain the

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response of a structure to an earthquake ground motion with similar characteristics, they cannot be used for design because the response of the same structure to another earthquake record will undoubtedly be different. Nevertheless, the recorded ground motion and computed response spectra of past earthquakes exhibit certain similarities. For example, studies have shown that the response spectra from accelerograms recorded on similar soil conditions reflect similarities in shape and amplifications. For this reason, response spectra from records with common characteristics are averaged and then smoothed before they are used in design [1].

The design spectra have been used for several years in the seismic design of structures. Besides, recent studies have led to major improvements in the construction and use of the design spectra. Trifunac and Todorovska [13] presented a review of the advances in strong motion recording since the early 1930s, based mostly on the experiences in the United States. A particular emphasis was placed on the amplitude and spatial resolution of recording, which both must be “adequate” to capture the nature of strong earthquake ground motion and response of structures. They compared the effectiveness of dynamic range of instruments in recording and the spatial resolution of recording network and concluded that the current spatial resolution of recording in the U.S. should be increased by at least two orders of magnitude.

Tan [14] proposed two alternative methods of construction of design response spectrum, for determination of the design spectra for the region of Taiwan. In that study, the evolutionary power spectra and frequency-dependent normalization factors were utilized to construct the design response spectra. They concluded that their methods, namely the multifilter and subprocess techniques, provide better physical interpretation than does the conventional method.

In recent years, displacement-based design spectra are widely considered in the design of structures. Displacement-based design has attracted growing interest among engineers, because it is recognized that under seismic actions, displacements describe in a more explicit way the structural response, and hence the damage, compared to forces, which can be obtained from acceleration design spectra. In 1998, Bommer and Elnashai [12] derived the attenuation relationships for horizontal displacement response spectral ordinates, by using a processed dataset of European strong motion records. The authors formulated a simple parametric presentation that allows the straightforward construction of displacement design spectra for rock, stiff soil and soft soil sites at distances of up to 50 km from earthquakes with magnitudes between 5.5 and 7.5, for six damping levels and up to response periods of 3.0 seconds.

Tolis and Faccioli [10] studied several high-quality digital recordings from the 1995 Hyogoken-Nanbu (Kobe) earthquake to identify the possible trends in long-period spectral displacements. Based on their studies on recent attenuation relationships, they proposed possible modifications for the design spectrum to take into account in future revision of Eurocode 8.

Although the limitations and drawbacks of the force-based design by using the acceleration design spectra are well recognized, this approach is still widely used because of its practical convenience. Currently the design spectra of the Iranian Seismic Design Code [5] are not based on Iranian earthquakes, and the design spectra of UBC-94 are used instead.

However, the recent studies based on the Iranian earthquakes have showed important imparities between these design spectra and the response spectra of the earthquakes occurring in Iran.

Some studies have been carried out on the response spectra of Iranian earthquakes. Tehranizadeh and Hamedi [2] studied the effects of source parameters on the response spectra of earthquakes occurred in Iran and compared the deterministic design spectra and stochastic ones. Mir-Ahsani [15] proposed some design spectra by studying some important earthquake records of Iran. Nonetheless, these studies were not based on all important earthquakes in Iran and the number of records used in the construction of the design spectra were low. Furthermore, they did not provide design spectra for all site conditions.

In this study, the linear pseudo-acceleration response spectra of 620 carefully corrected earthquake records were calculated for normalized accelerographs with 1.0g, for damping ratios of 0%, 2%, 5%, 10% and 20%. These spectra were classified based on important earthquake source parameters and site conditions of the recording station, and the effects of these parameters on the response spectra were studied.

The nonlinear design spectra are being developed in recent years. Some algorithms for computation of the constant-ductility and constant-damage spectra are presented in [8 and 9], where the accuracy of these method are evaluated and verified. To compute the nonlinear design spectra for Iran region, the elastic-perfectly plastic response spectra for each normalized accelerograph were also calculated for damping ratio of 5% and ductility ratios of 1.0, 1.5, 2.0, 4.0 and 8.0. Ductility is known as the ratio of maximum displacement of the elastic-perfectly plastic system to the yield displacement of the system. With the use of the nonlinear capacity the structures, the design base shear decreases in the expense of additional displacements beyond their proportional limit.

Although the linear and nonlinear response spectra have been used for decades to compute design displacements and accelerations as well as base shears, they do not include the influences of the number of response cycles and yield excursions, stiffness and strength degradation, or damage potential to structures. Particularly, with the use of innovative protective systems such as seismic isolation and passive energy dissipation devices, there is a need to revise the present design procedures.

Housner first recommended the energy approach for earthquake resistant design. He pointed out that the earthquake transmits energy into the structure and approximated the input energy as one-half of the product of the mass and the pseudo-velocity $m(PS_v)^2/2$. His study provided the impetus for later developments of energy concept. The idea of energy-based design is appealing where the focus is not so much on the lateral resistance of the structure but rather on the need to dissipate and/or reflect seismic energy imparted to the structure.

For a nonlinear SDOF system with pre-yield frequency and damping ratio of ω and ξ the energy balance equation per unit mass is as follows:

$$E_I = E_K + E_D + E_S + E_H \tag{1}$$

where:

Input energy: $$E_I = \int_0^t \ddot{u}_g(t)\dot{u}dt \qquad (2a)$$

Kinetic energy: $$E_K = \frac{\dot{u}^2}{2} \qquad (2b)$$

Dissipative damping energy:

$$E_D = 2\xi\omega\int_0^t \dot{u}^2 dt \qquad (2c)$$

Recoverable elastic strain energy:

$$E_S = \frac{F_s^2}{2\omega^2} \qquad (2d)$$

Dissipative plastic strain energy:

$$E_H = \int_0^t F_s \dot{u}dt - E_S \qquad (2e)$$

in which F_s represents the nonlinear restoring force per unit mass.

Different researchers have introduced several energy spectra. The first definition in this regard was the maximum value of the sum of the kinetic and elastic strain energies plotted versus natural period or frequency [3]. Afterwards, Zahrah and Hall introduced an energy spectrum as a plot of the numerical value of the input energy E_I at the end of motion as a function of period or frequency.

According to Uang and Bertero [11], the energy equations (1) and (2) should be considered as relative energy equations, since the integrations are performed for equation of motion using the relative displacements. They introduced the absolute energy equations by integrating the equation of motion using the absolute displacements. For the absolute energy terms, E_D, E_S, and E_H are the same as their relative counterparts, while the absolute input and kinetic energy are given as:

$$E_{I,ABS} = \int_0^t \ddot{u}_{g,ABS}(t)\dot{u}dt \qquad (3a)$$

$$E_{K,ABS} = \frac{\dot{u}_{ABS}^2}{2} \qquad (3b)$$

They indicated that the relative and absolute input energies are very close for the mid-range periods. For longer and shorter periods however, the difference becomes significant. The absolute and relative equivalent velocities defined as $V_I = \sqrt{2E_I}$ converge to the peak ground velocity at very short and very long periods, respectively. Subsequently they concluded that the absolute input energy could be used as a damage index for short period structures, while the relative input energy is more suitable for long period structures. Alternative definitions of energy response spectrum for a given period (1.0 second here) are presented on the energy time history of Naghan record in Figure 1.

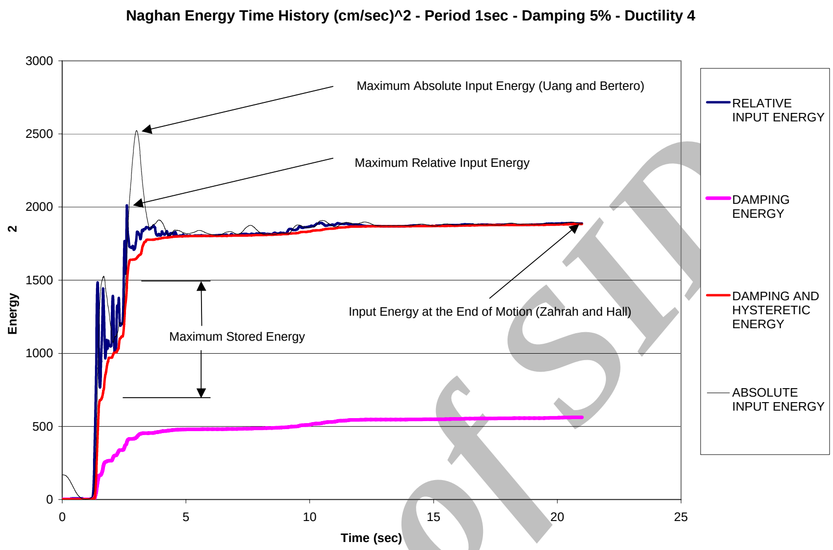

Figure 1. Naghan record energy time-history and alternative definitions of energy response spectrum

The most important shortcoming in the energy approach is that the damage is dependent to the load path, while the energy does not yield any judgment about this concept. Hence, the damage cannot be easily determined by considering the dissipated energy via plastic strain. On the other hand, the energy concept becomes of high importance in structures having passive dampers, where the main concern is energy dissipation rather than lateral resistance.

In this study, the maximum value of relative or absolute input energies at every period is selected as the energy spectrum. Since the relative and absolute input energies show higher values in very long and very short periods respectively, the resulting spectrum can be used to determine the input energy demand for structures with known natural period of vibration.

Statistical calculations were made to compute the average, maximum and average plus standard deviation response spectra. Comparisons among the spectra were performed using the average response spectra of each class.

1.1 Ground Motion Records

The selected earthquake accelerographs were recorded between March 7th 1976 and January 6th 2002 whose epicenters and M_w magnitudes are shown in Figure 2. Most of the accelerographs were recorded within 100 km of epicenter, have a magnitude between 4.0 and 5.5, and horizontal peak ground accelerations less than 200 cm/s^2. The accelerographs having a horizontal peak ground acceleration of at lease 40 cm/s^2 were selected for this study.

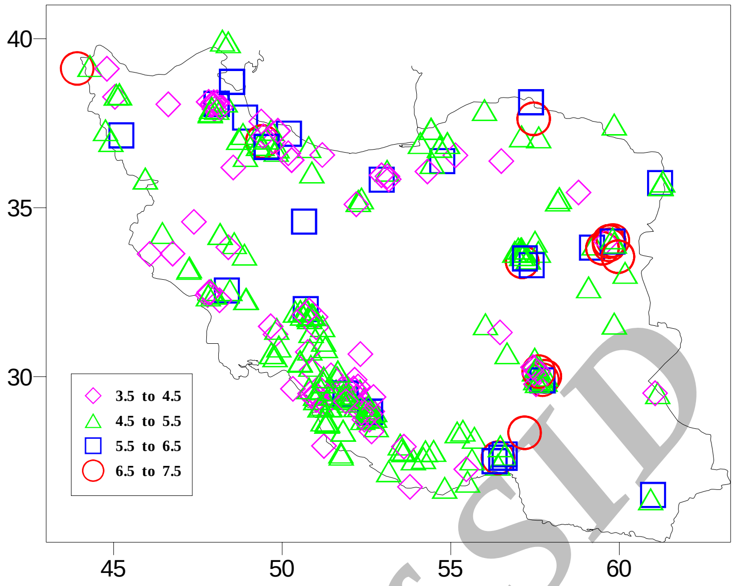

Figure 2. Magnitude of earthquakes and their epicenter

1.2 Record Classifications

The accelerographs were categorized based on soil type at the recording station, its epicentral distance, magnitude and strong motion duration. Based on the soil type, the records were divided into 4 groups, whose soil conditions are showed in Table 1.

Table 1. Soil classifications [5]

Type	Description	Shear wave velocity (m/s)
I	Hard rocks, very hard conglomerate layers, very compact sediments with a depth less than 30 m	$\overline{V}_S > 750$
II	Soft rocks, stiff soils with a depth more than 30 m	$750 \geq \overline{V}_S > 375$
III	Crushed rocks, semi-compact soils	$375 \geq \overline{V}_S > 175$
IV	Soft sediments, any other kind of soft soil having a plastic index of 20 or greater and a water content of at least 40%	$175 > \overline{V}_S$

The average shear wave velocity $\overline{V}_s$ for a soil profile consisting of layers having shear wave velocities of V_{Si} and thicknesses of d_i located between ground surface and the depth of 30 m, is given by:

$$\overline{V}_s = \frac{\Sigma d_i}{\Sigma\left(\frac{d_i}{V_{si}}\right)} \tag{5}$$

Other classifications are shown in Table 2, where the numbers of records in each group are given as well. The strong motion duration is defined as the interval between 5% and 95% of input energy. As shown in the table, the only available information for all records was the strong motion duration, and other information was available for some of these records.

Since the soil type is the most important parameter in the design spectra, other classifications were applied to each soil type separately and their effects were evaluated for each sub soil class.

In this paper, the response spectra of horizontal components computed for 5% damping and ductility of 4.0 are illustrated and others are omitted.

Table 2. Classifications and number of classified records

Soil Type	**Records**	**Epicentral Distance (km)**	**Records**	**Strong Motion Duration (sec)**	**Records**	**Magnitude (M_w)**	**Records**
I	93	Less than 10	85	Less than 2	95	Less than 4	26
II	139	10 to 20	115	2 to 4	175	4 to 5	245
III	97	20 to 50	176	4 to 6	115	5 to 6	99
IV	7	More than 50	100	6 to 10	111	More than 6	68
				More than 10	124		
Total	336	Total	476	Total	620	Total	438

1.3 Effect of Soil Conditions

As the earthquake waves cross the different layers of soil, the frequencies near to layer ones will be amplified and others reduced. Hence, it is expected that the earthquakes recorded in soft soils have a higher content of lower frequencies. The average linear response spectra, which are classified based on soil type, are shown in Figure 3. It is seen that softer soils produce larger amplification factors in periods longer than about 0.4 sec. In periods less than 0.2 sec however, the amplification factors for hard soils are greater than those for soft soils. The average response spectra of soil types I and II are very close. On the other hand, the average spectrum of soil IV shows a significant difference to other types of soil. It should be noted that the average response spectrum of soil IV are computed using seven records (14 horizontal components) only, and this results in sharper variations in the response.

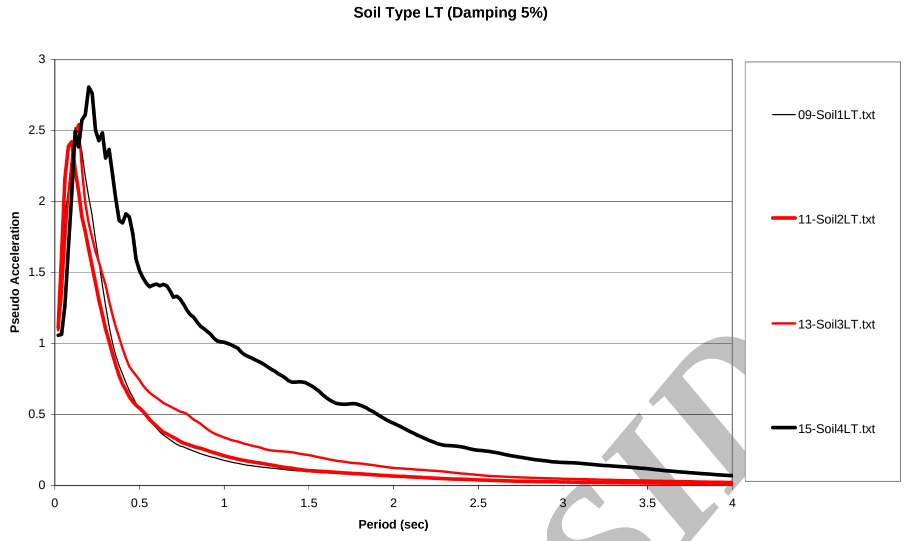

Figure 3. Average linear response spectra for different soil types (Damping 5%)

The specific characteristics of the response spectra resulted from Iranian earthquakes are their very short dominant periods (about 0.2 to 0.4 sec) and their high spectral accelerations for short period structures, which can be clearly seen in Figure 3. This results in severe damages to low rise structures, which are very common in Iran.

The average nonlinear yield acceleration response spectra for different soil types are shown in Figure 4. The effect of soil type is similar to that of linear spectra, except that the response spectra of relatively hard soils (types I, II and III) are very close in periods shorter than 0.2 sec. As shown, in soil types II, III, and IV the nonlinear response increases in softer soils.

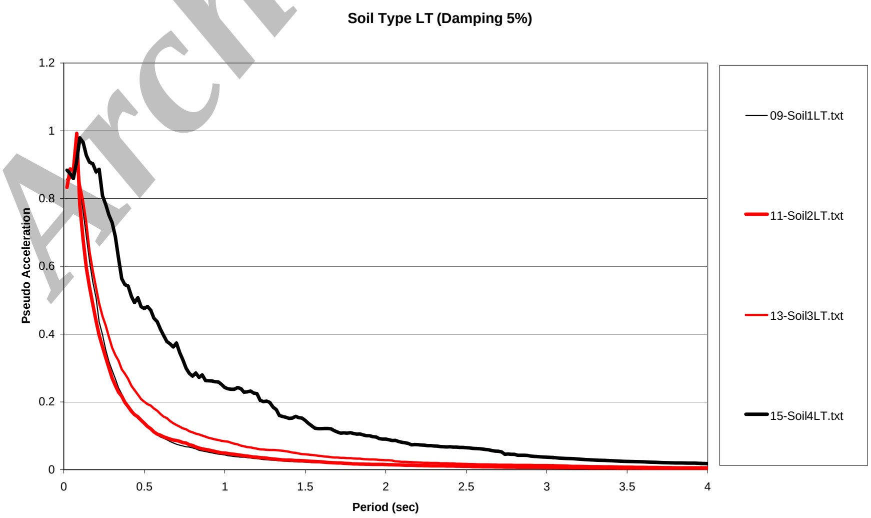

Figure 4. Average nonlinear response spectra for different soil types (Damping 5%, Ductility 4.0)

Average energy response spectra for different soil types are shown in Figure 5. As mentioned earlier, these spectra are maximum values of relative and absolute energies at their peak. It can be seen that the spectra show greater values in softer soils. Furthermore, the period at which the peak energy response occurs, shifts to longer values in softer soils.

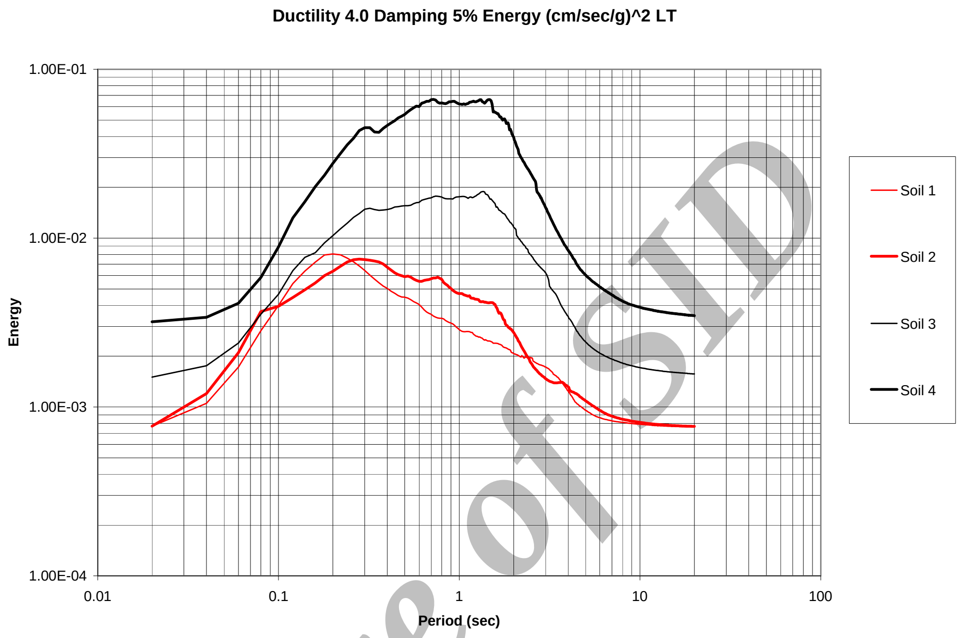

Figure 5. Average energy response spectra for different soil types

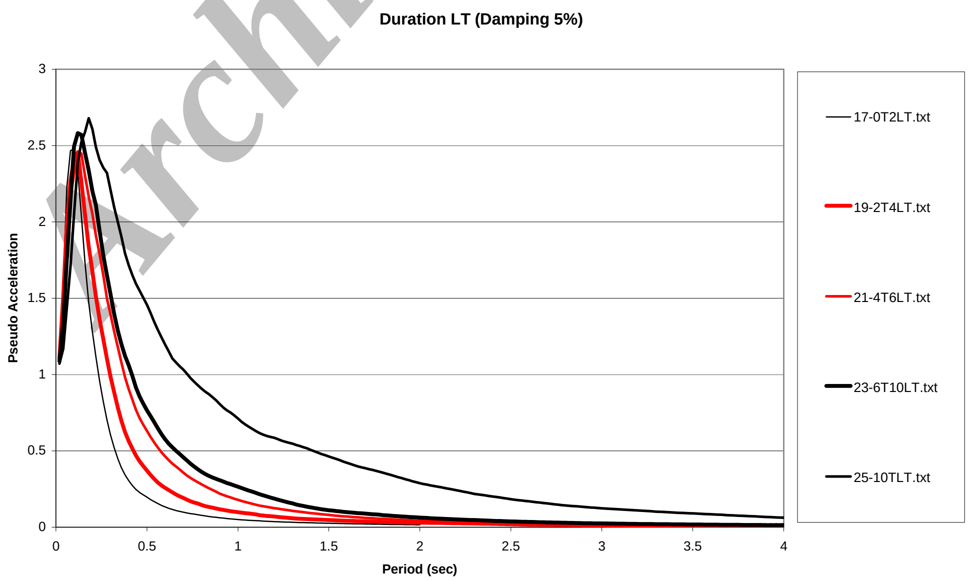

Figure 6. Average linear response spectra for different strong motion durations

1.4 Effect of Strong Motion Duration

The average response spectra of classes divided based on strong motion duration are shown in Figure 6. As illustrated, longer strong motion duration, results in larger spectral values for periods longer than about 0.2 sec. In shorter periods however, accelerographs with shorter strong motion duration show larger spectral values. This manner can be seen in specific soil types similarly (Figure 7, soil type II).

Figure 8 shows that the nonlinear spectral value increases, when the strong motion duration becomes longer. Opposite to the linear spectrum, the change of effect of strong motion duration for periods less than 0.2 sec is not clear. For periods shorter than 0.1 sec however, the yield acceleration spectra show values close to each other.

In the Iranian Seismic Design Code (Standard no. 2800) the minimum strong motion duration for design earthquakes are proposed to be 10 sec. This seems to be somewhat overestimate for relatively tall structures and underestimate for small structures.

The effect of strong motion duration on energy response spectra are studied as illustrated in Figure 9. It is clear that with longer strong motion duration, the energy transferred to the structure increases significantly, and the maximum input energy increases in longer period structures. Hence, from energy point of view, the design earthquake for all structures (including short- or long-period ones) should be selected from records having longer strong motion durations.

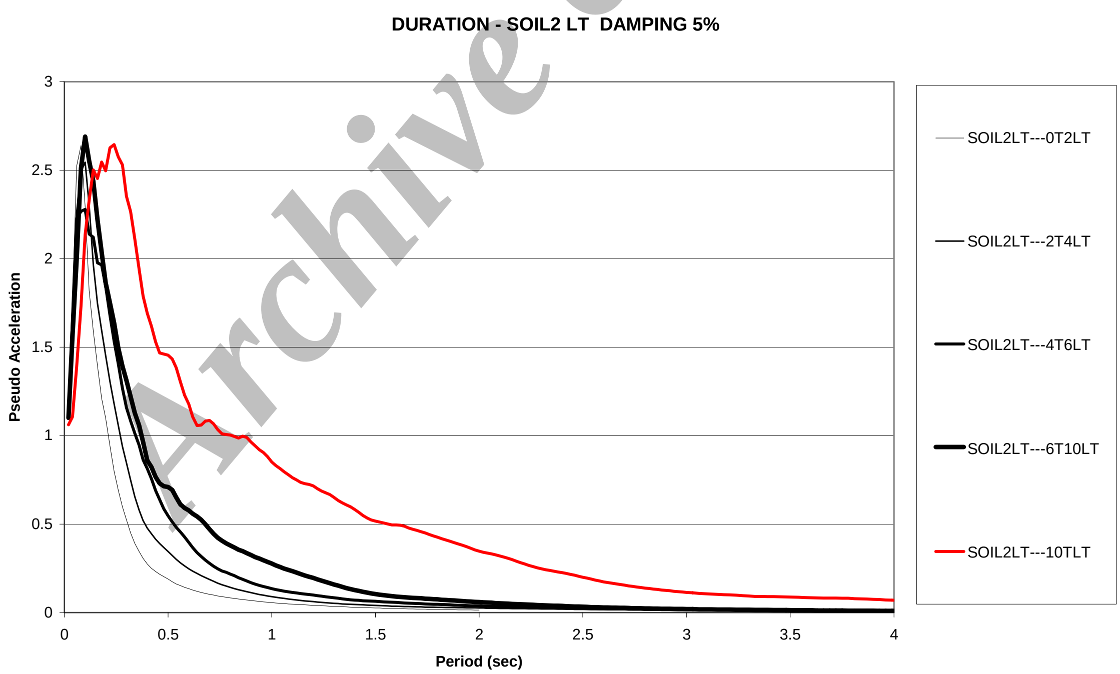

Figure 7. Average linear response spectra for different strong motion durations (soil type II)

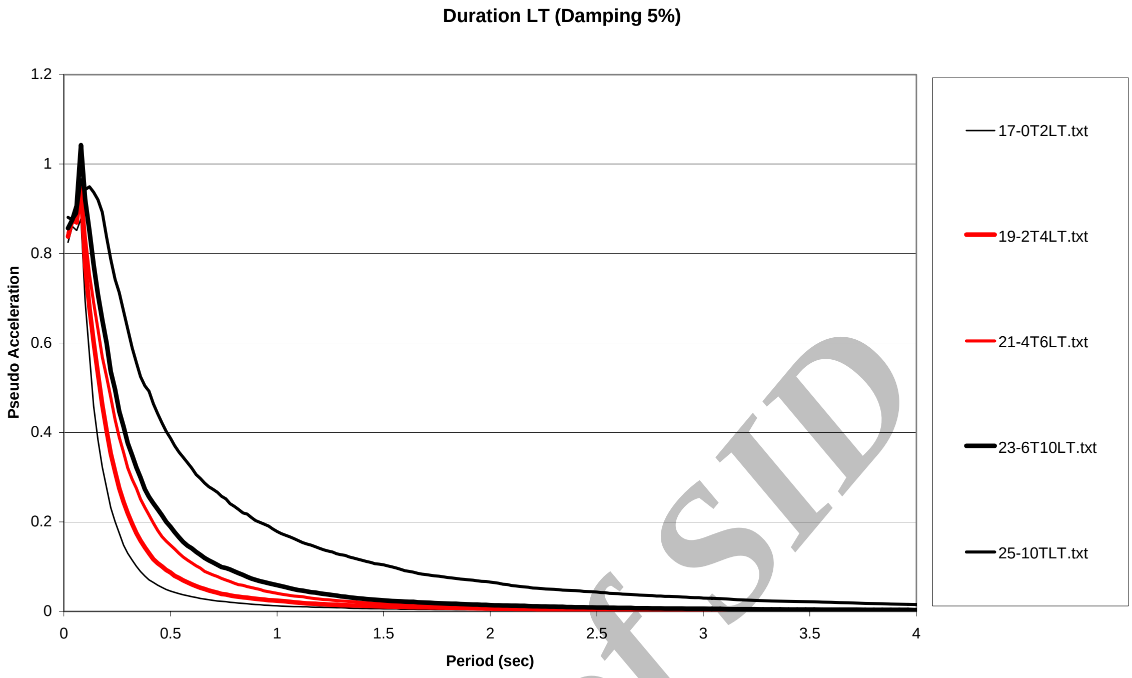

Figure 8. Average nonlinear response spectra for different strong motion durations

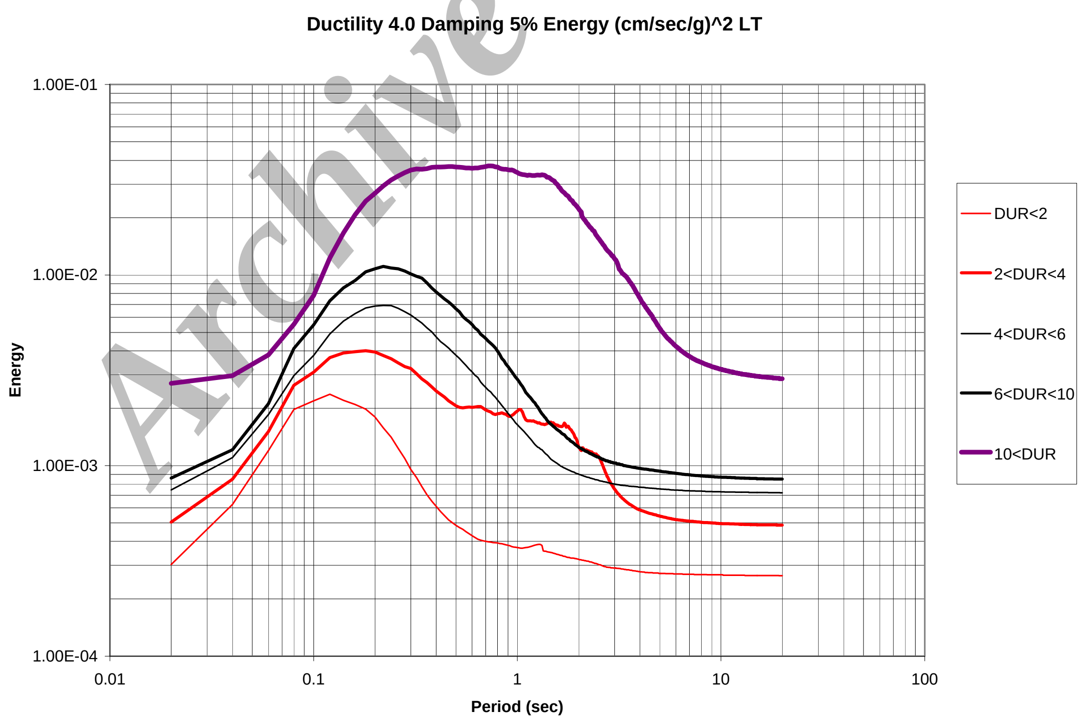

Figure 9. Average energy response spectra for different strong motion durations

1.5 Effect of Magnitude

It can be seen clearly from Figure 10 that larger magnitude results in greater pseudo-acceleration, except for periods shorter than 0.2 sec, where an increase in magnitude decreases the spectral value. Anyhow, this reduction in short periods is very small and the spectra are very close to each other. The spectrum of accelerographs with magnitudes more than six shows a significant change compared to other spectra. In other words, earthquakes having magnitudes more than six show a considerably larger acceleration magnification than those having fewer magnitudes.

The average nonlinear spectra for the classification based on magnitude are shown in Figure 11. As illustrated, the effect of magnitude on response spectra is very significant. Greater values of yield acceleration will be achieved with increase in magnitude of earthquake. In this figure again, the values of spectra are close in very short periods (less than 0.1 sec).

The magnitude of earthquake has an increasing effect on energy response spectra as shown in Figure 12. The magnitude of an earthquake is basically derived from the released energy at the time of the earthquake. Thus, its effect on energy spectra is important, and with higher magnitudes, the input energy increases, which mere effective in longer periods.

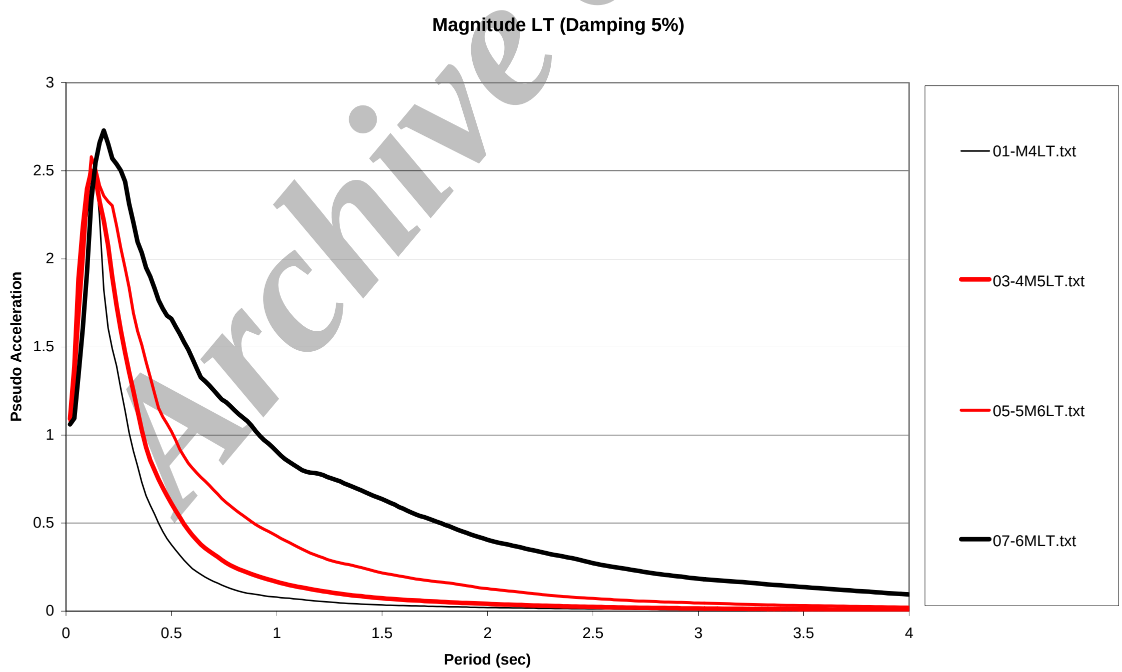

Figure 10. Average linear response spectra for different magnitudes

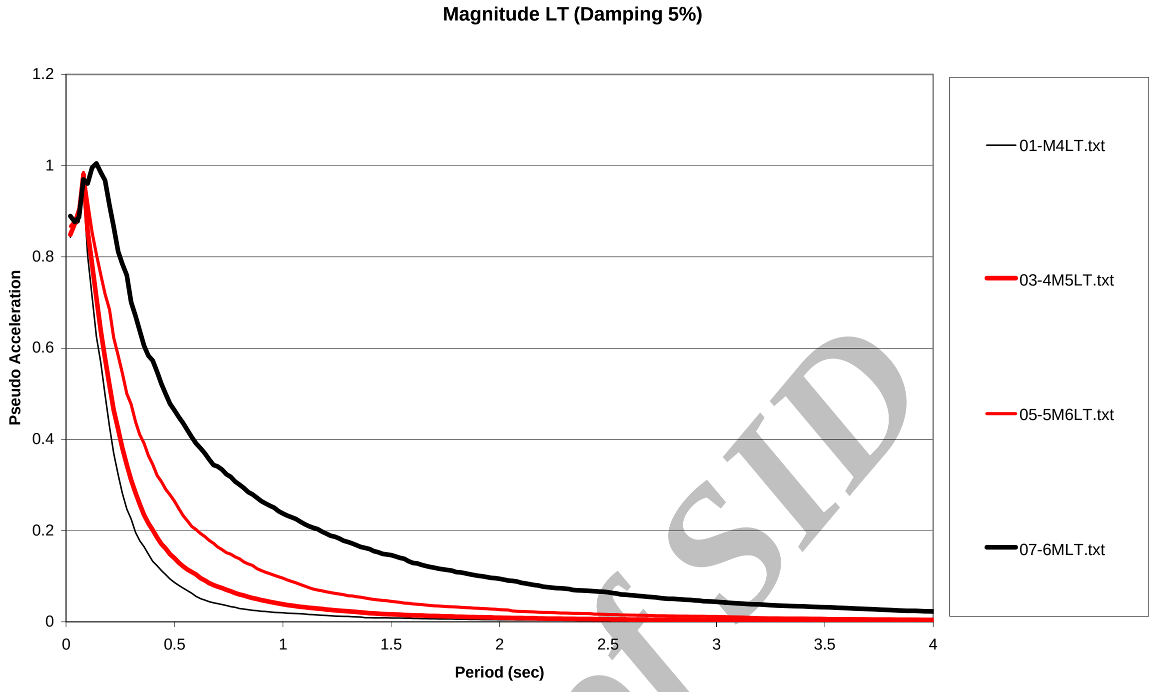

Figure 11. Average nonlinear response spectra for different magnitudes

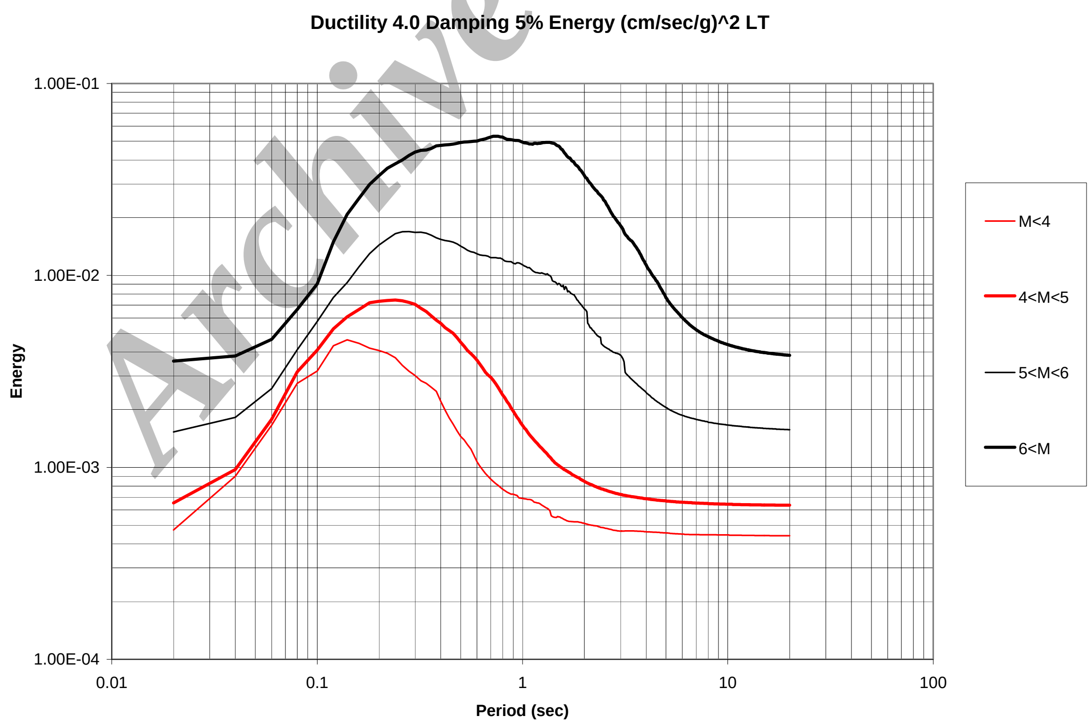

Figure 12. Average energy response spectra for different magnitudes

1.6 Effect of Epicentral Distance

The average linear response spectra for different epicentral distances are illustrated in Figure 13. It can be seen that an increase in epicentral distance results in larger amplification factors in long periods and smaller factors in short periods. This change occurs in a period between 0.2 and 0.3 sec. In some period ranges the response spectrum of epicentral distances less than 10km shows larger values than that of 10 to 20km in periods longer that 0.5 sec.

Considering a specific soil type separately (e.g. soil type III, which is shown in Figure 14), it is observed that the relatively near-field response spectra are close to each other. On the other hand, the response spectra of epicentral distances more than 50km, yield very different values which are smaller in short periods (shorter than 0.2 sec) and larger in long periods. As an exception, in a wide range of long periods, the response spectra of the records within 20km of epicenter, show larger spectral values than that of 20 to 50km epicentral distance.

It can be seen that the nonlinear response has a similar behavior with change in epicentral distance, as shown in Figure 15. The spectra are close for periods less than 0.1 sec. Furthermore, the average response spectrum of accelerographs having an epicentral distance less than 10km is very close to that of epicentral distance between 10 and 20km in all periods.

Figure 16 shows the energy response spectra of the accelerographs classified based on epicentral distance. It is observed that the spectra of the accelerographs recorded within 50km of the epicenter, are close to each other especially in very short and very long periods, but with the increase of the epicentral distance beyond 50km, there is a significant increase in the energy response spectrum.

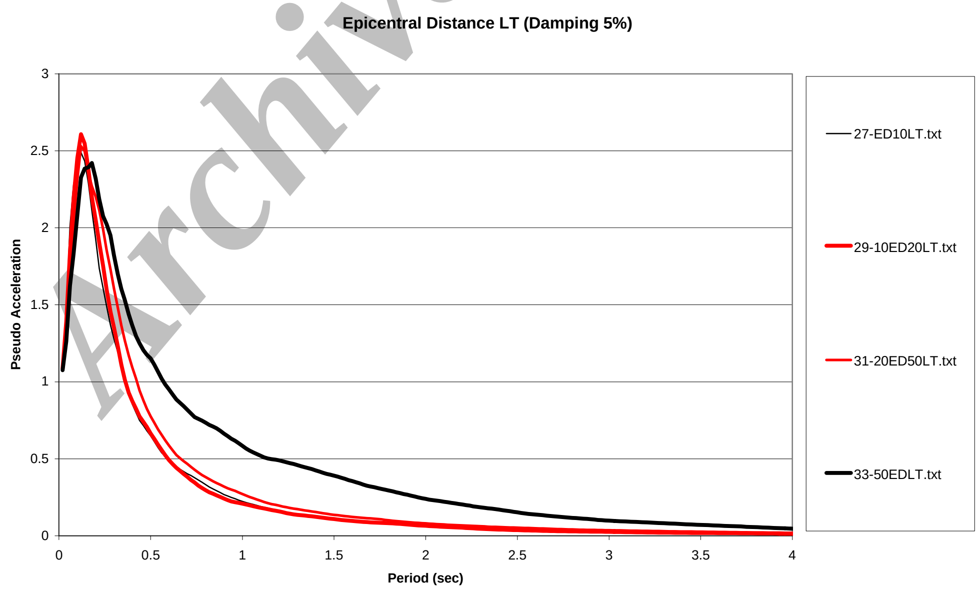

Figure 13. Average linear response spectra for different epicentral distances

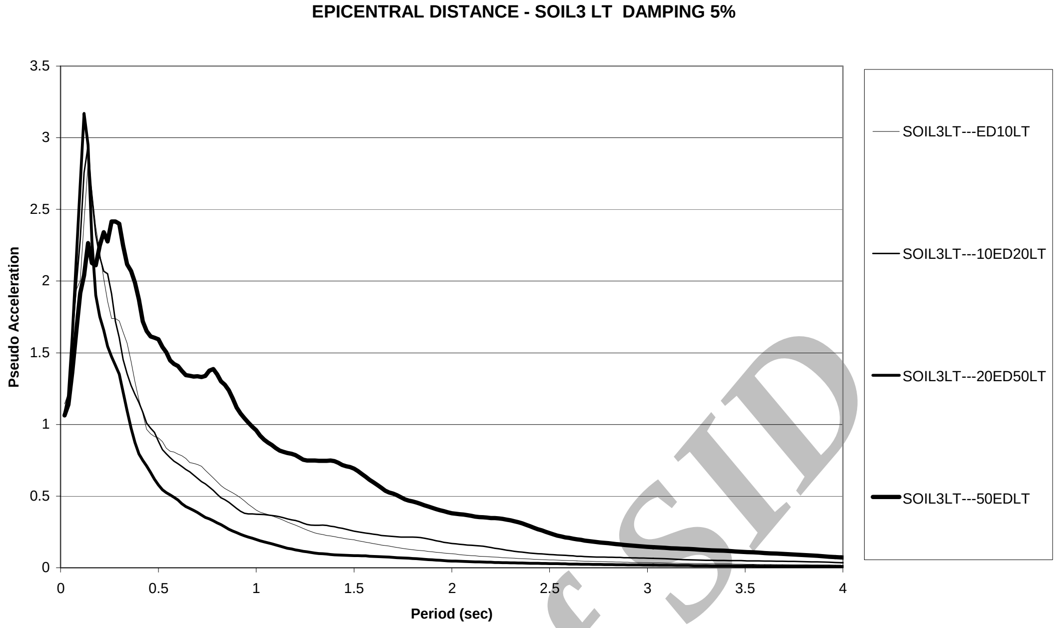

Figure 14. Average linear response spectra for different epicentral distances (soil type III)

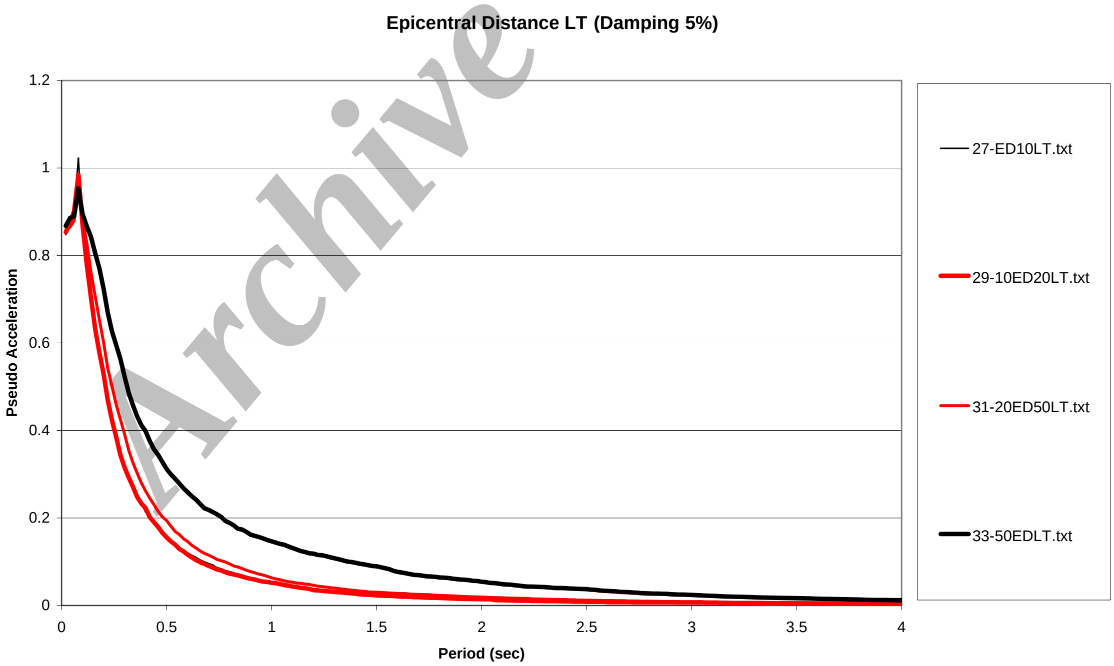

Figure 15. Average nonlinear response spectra for different epicentral distances

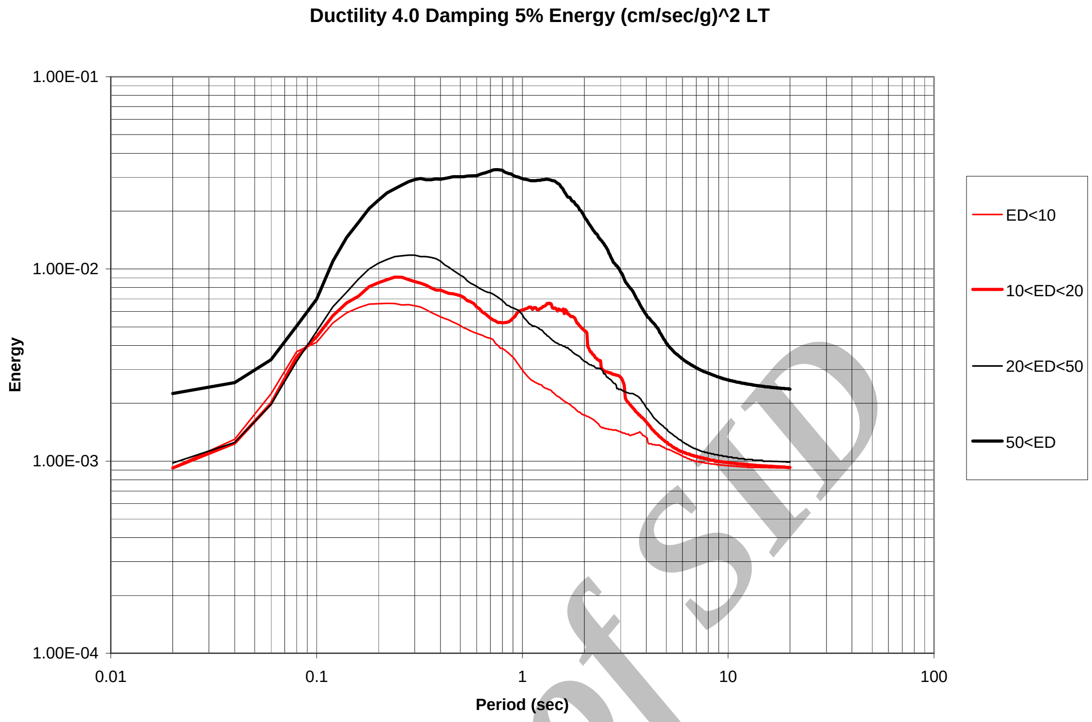

Figure 16. Average energy response spectra for different epicentral distances

1.7 Effect of Damping

An example of damping effect on the linear response spectra of soil type II is shown in Figure 17. The proposed design spectra are calculated using average linear response spectra for each soil type with 5% damping. The ratios of average response spectra for other damping ratios (2, 10 and 20%) to that of 5% damping are calculated and their average plus standard deviation are proposed as the correction factor for damping. These factors can be seen in Table 3, where it can be seen that this coefficient has minor variations (with the exception of 2% damping) with changes in soil type.

Table 3. Damping correction coefficients

Damping ratio	**Soil I**		**Soil II**		**Soil III**		**Soil IV**	
	H	**V**	**H**	**V**	**H**	**V**	**H**	**V**
2%	1.23	1.28	1.25	1.29	1.27	1.32	1.38	1.40
10%	0.89	0.86	0.89	0.87	0.89	0.88	0.86	0.85
20%	0.77	0.72	0.77	0.73	0.77	0.74	0.72	0.69

The effect of damping on energy response spectra is studied in Figures 18 through 20. The relative, absolute and maximum response spectra of the input energy for soil type 2 are shown in these figures respectively.

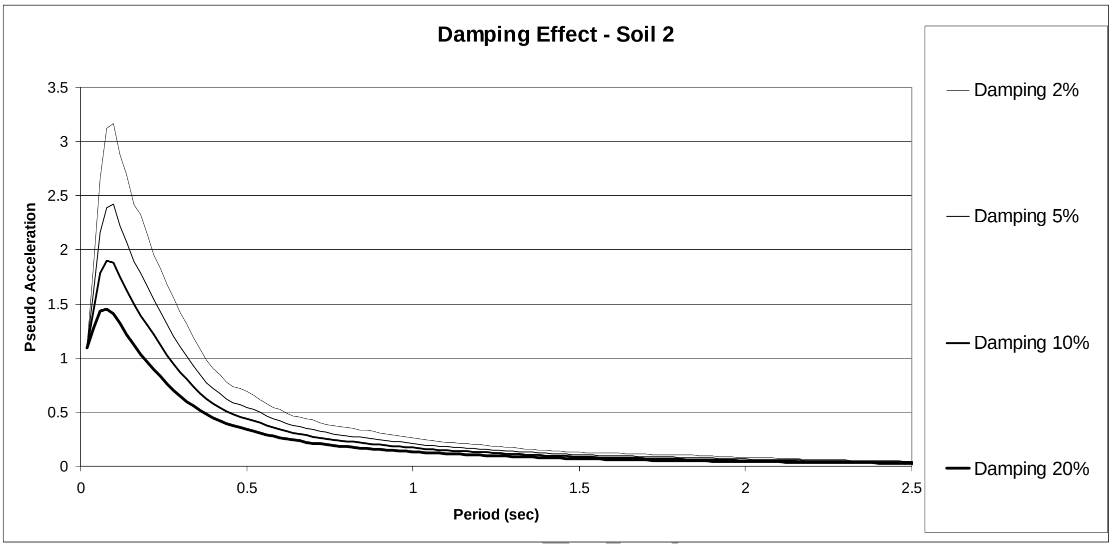

Figure 17. Average linear response spectra for different soil types

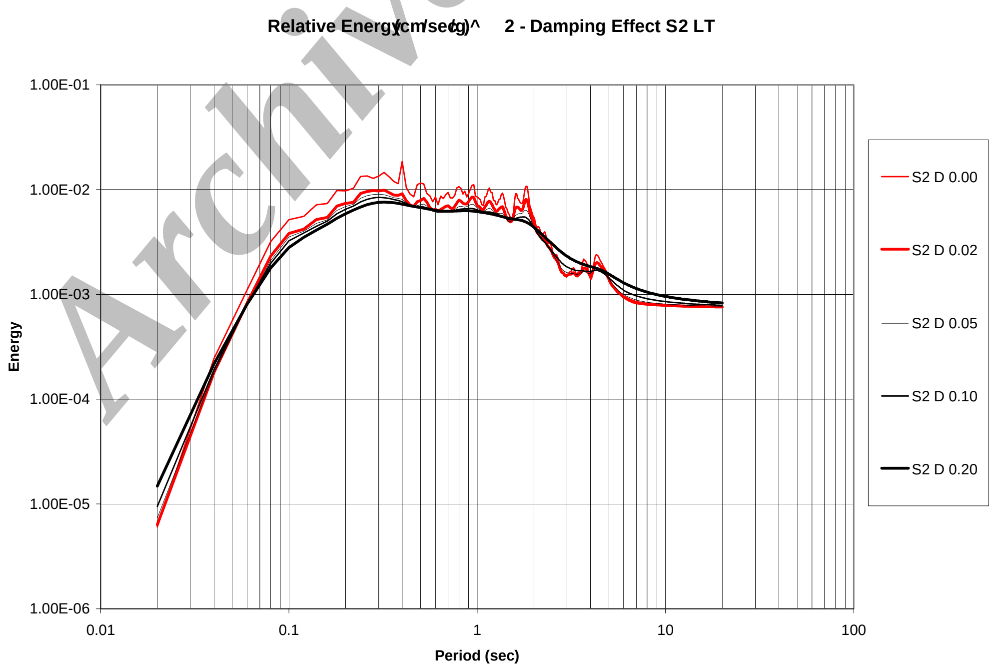

Figure 18. Average relative energy response spectra for different damping ratios

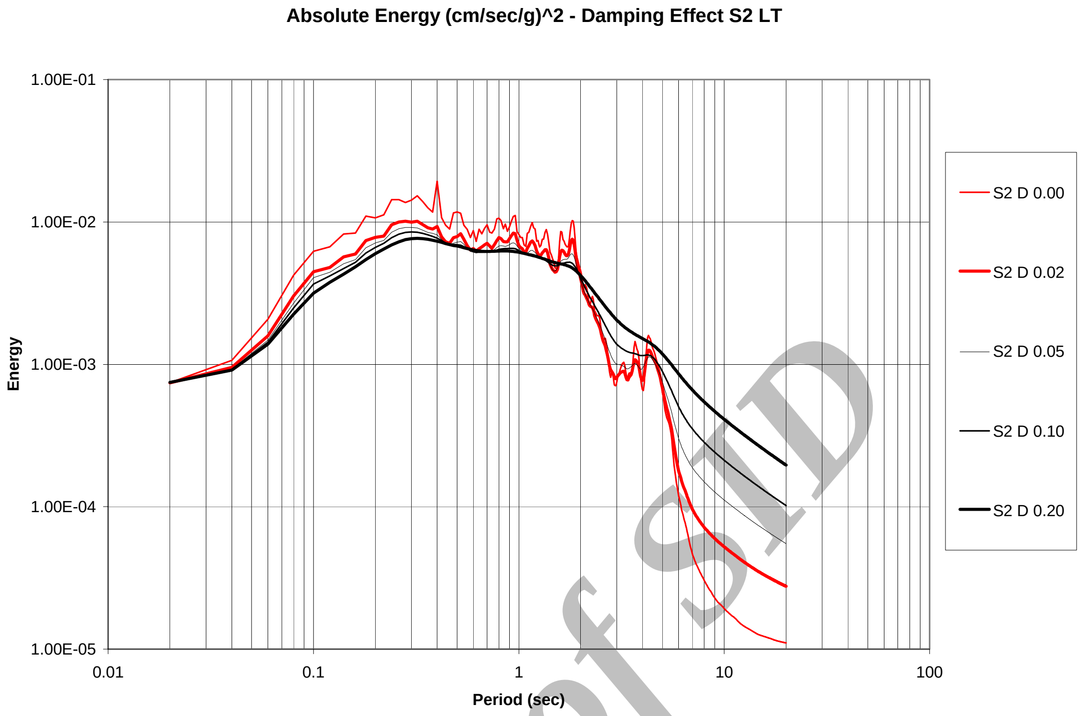

Figure 19. Average absolute energy response spectra for different damping ratios

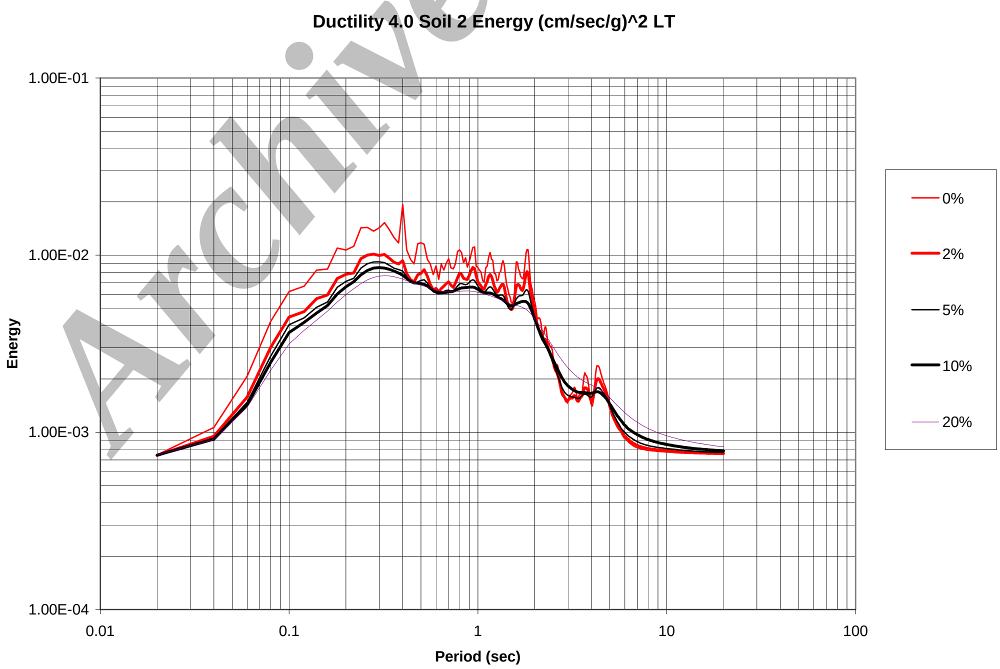

Figure 20. Average maximum energy response spectra for different damping ratios

Both relative and absolute energy response spectra show larger values with lower damping ratios in midrange periods. However, in long periods this manner changes and higher damping ratios result in higher input energy. In short periods, the spectral values are close to each other and relative input energy slightly increases for higher damping ratios.

The maximum energy response spectra, which can be used for the estimation of the input energy demand [4], are shown in Figure 20. In long periods, these spectra decrease with lower damping ratios. That is, if passive dampers are to be inserted in an existing long period structure, it should be noted that this act increases in the energy demand of the structure.

1.8 Effect of Ductility

As shown in Figure 21, increasing the ductility ratio, decreases the spectral acceleration, and consequently, decreases the design base shear of the structure. It is observed that the spectral values at very short periods decrease from 1.0 for ductility of 1.0 (linear state) to about 0.75 for ductility equal to 8.0.

The studies on the effect of ductility on energy response spectra are shown in Figures 22 through 24. In most periods, the maximum energy response spectra increase when the ductility increases. Some exceptions can be seen in the relative energy in short periods and the absolute energy in long periods. But since the maximum values are selected in Figure 24, these exceptions disappear and it can be concluded that the structures with lower ductility ratios should be designed for more input energy demand.

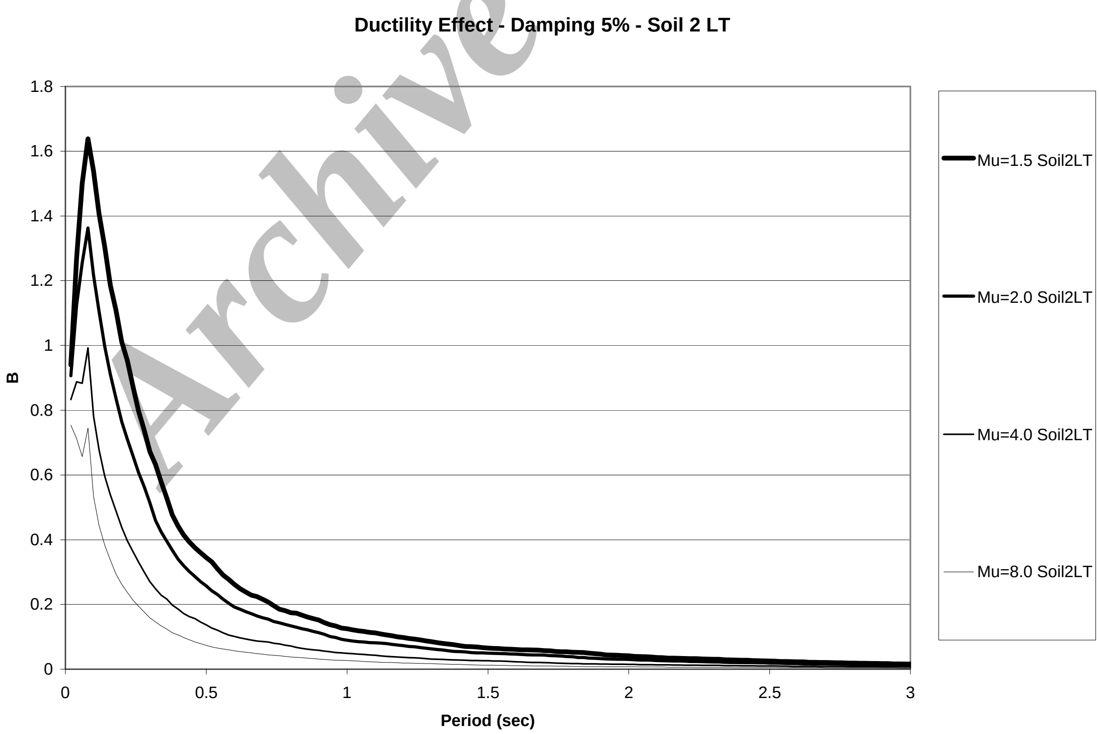

Figure 21. Ductility effect on soil type II spectra

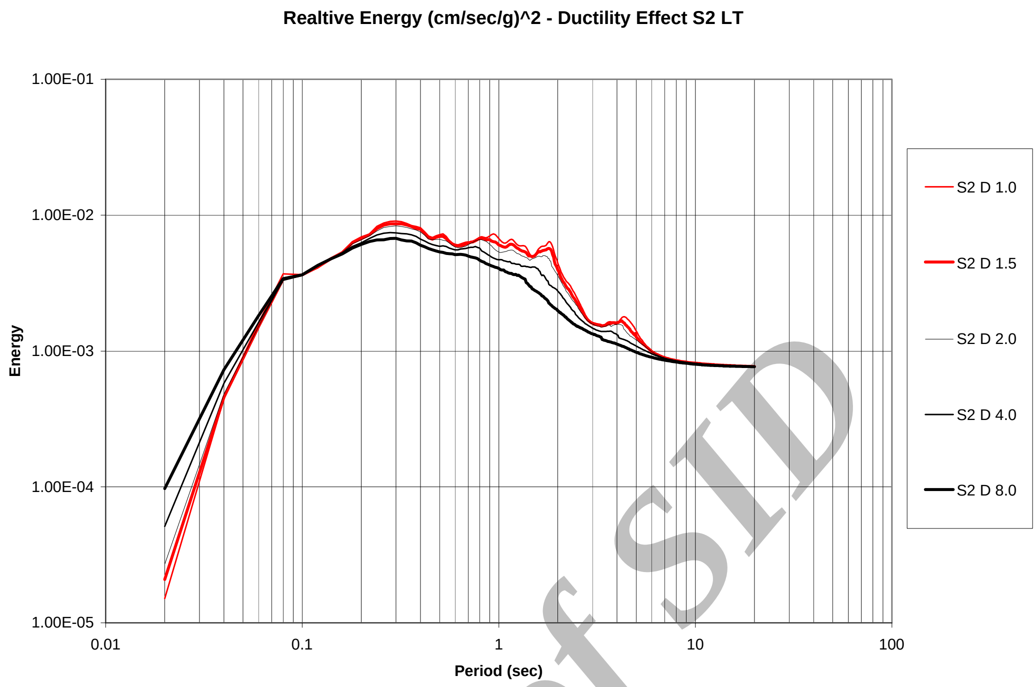

Figure 22. Average relative energy response spectra for different ductility ratios

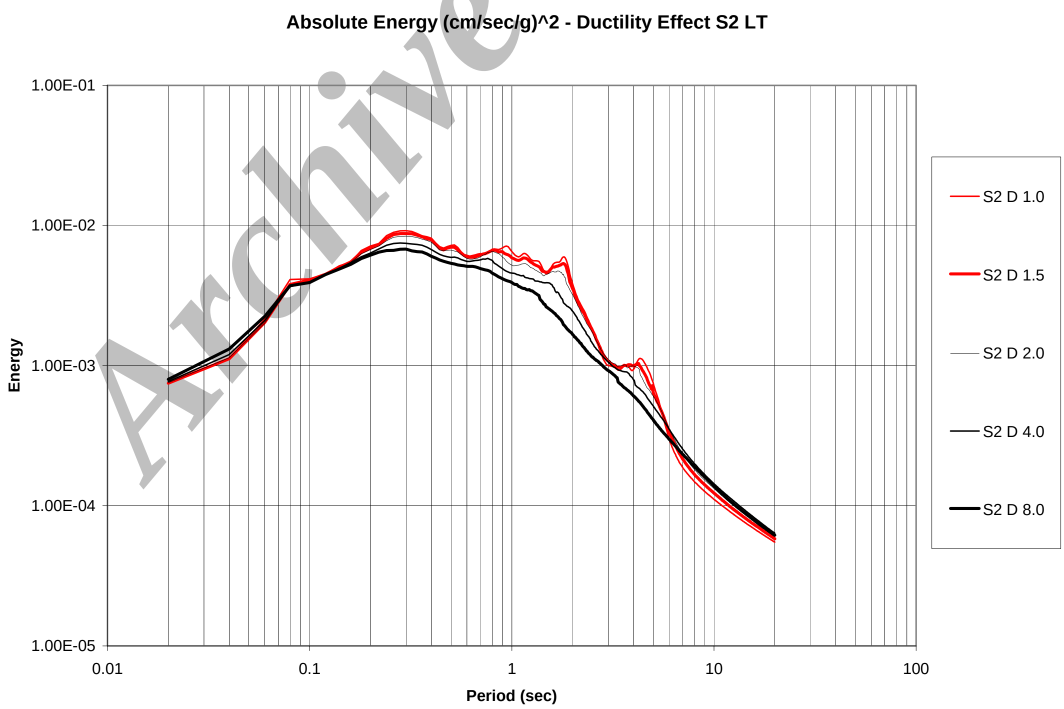

Figure 23. Average absolute energy response spectra for different ductility ratios

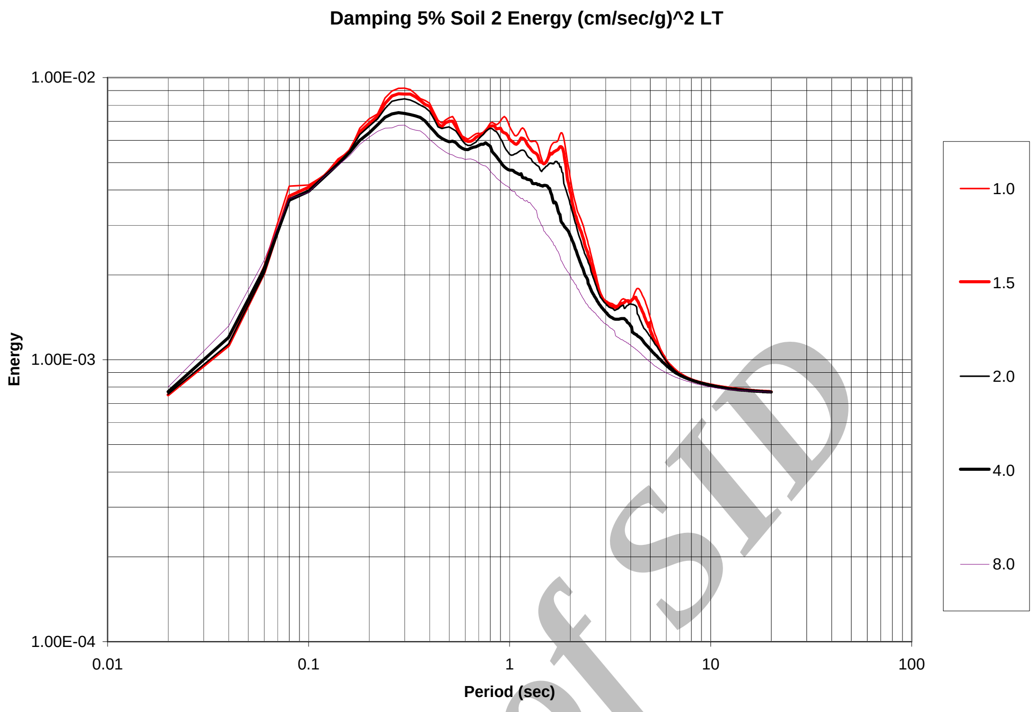

Figure 24. Average maximum energy response spectra for different ductility ratios

1.9 Proposed Spectra and Comparisons

In this section, the proposed linear design spectra for different soil types (damping 5%, horizontal, with 50% safety) will be compared to code design spectra, including UBC97, IBC2000, Eurocode 8 and Iran Standard no. 2800. It should be noted that the soil classifications are different for these codes, and the comparisons are made among spectra of the most similar soil classes.

Figure 25 shows these comparisons for soil type I. In this figure the design spectrum of sub soil class A of Eurocode 8 [6] and class B of UBC97 [7] and IBC2000 are included. As shown, the design spectra of UBC and IBC are the same in this soil class. It is seen that the peak values are the same in these spectra. Except for Iran2800 spectrum, which does not have the initial linearly increasing segment, other spectra are close to each other for very short periods too. On the other hand, the decreasing section of the proposed design spectra begins at period of 0.2 sec, while others begin at 0.4 sec.

Comparison of design spectra for soil type II is illustrated in Figure 26. As shown, the constant portion of proposed design spectra is extended up to the period of 0.25 sec, while others have a constant value beyond this limit up to about 0.5 sec. In most periods, the design spectrum of Iran2800 yields larger values than what others yield.

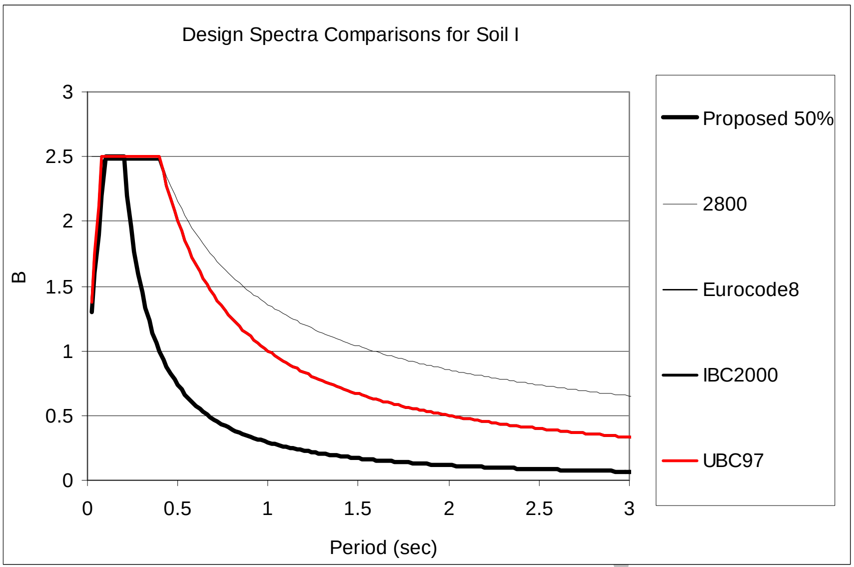

Figure 25. Comparison of proposed linear design spectra to code provisions for soil type I

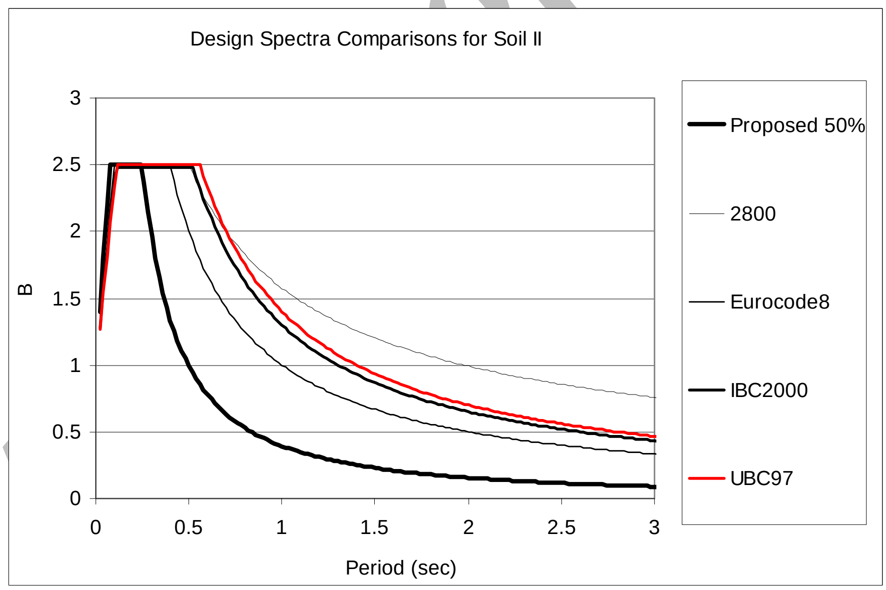

Figure 26. Comparison of proposed linear design spectra to code provisions for soil type II

2. CONCLUSIONS

The following conclusions can be derived from this study:

- The linear and nonlinear spectral accelerations for midrange and long periods are greater in soft soils, while in periods shorter than about 0.15 sec the values are slightly smaller for soft soils. The input energy demand is commonly higher in softer soils.

- An increase in strong motion duration causes the response spectrum to yield greater values for periods longer than 0.2 sec and smaller values for shorter periods. It is also concluded that structures with natural period about 0.2 sec are sensitive to short duration earthquakes. Strong motion duration has a considerable increasing effect on the maximum energy response spectra.
- An increase in magnitude increases the acceleration spectral value for periods longer than 0.2 sec and decreases it for shorter periods. The effect of magnitude on the energy response spectra is also important and records with larger magnitudes lead to higher input energy demands.
- The nonlinear response spectra for different classes become closer in periods shorter than 0.1 sec with increase in ductility ratio. That is, in short period structures the ductility demand increases significantly with minor changes in yield acceleration, making it necessary to design these structures for linear behavior.
- The response spectra of accelerographs, having epicentral distances less than 10km, do not follow the general behavior of other spectra. However, the spectral values of accelerographs are commonly greater in midrange and long periods for greater epicentral distances. Epicentral distance has also an increasing effect on the energy demand of structures, being more significant in midrange period ones.
- The conservative correction factors 1.4, 0.9, and 0.8 can be used to adjust the 5% damping response spectrum for other damping ratios of 2%, 10% and 20%, respectively.
- A comparison among the proposed linear design spectra and some current code provisions show that the proposed values are smaller in long periods (longer than dominant periods), and greater for shorter periods.

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