

## **DAMPING EFFECT ON ELASTIC INPUT ENERGY**

**Gholamreza GHODRATI AMIRI <sup>1</sup>, Gholamreza ABDOLLAHZADEH DARZI <sup>2</sup>**

### **ABSTRACT**

According to performance-based seismic design method by using energy concept, in this paper it was tried to investigate the structural damping effect on elastic input energy spectra due to strong ground motions. Using acceptable Iranian earthquake accelerograms recorded on the four types of soils, structures with different damping ratios were analyzed. For each earthquake record, equivalent velocity spectrum was computed by using its input energy spectrum. These spectra were normalized by their *PGA* and were drawn with different structural damping ratios. Then effect of structural damping was investigated on these spectra. Finally it was concluded that in different soil types, structural damping effect on input energy is not very considerable and among structures with different viscous damping ratios, input energy to structures with damping ratio about 5% has minimum value.

Keywords: *PGA*, structural damping ratio, input energy spectrum.

### **INTRODUCTION**

Design of structures based on performance-based seismic design, especially based on energy concepts, is one of methods that has been noticed by researchers in the recent years [Akbas et al., 2001; Benavent-Climent et al., 2002; Decanini and Mollaioli, 1998 and 2001; Leelataviwat et al., 1999; Manfredi, 2001; Ordaz et al., 2003; Trifunac et al., 2001]. Unlike the methods which are based on acceleration spectra and ignore duration and hysteretic behavior effects on structural design, design method based on energy concepts not only consider the effects of these parameters, but also it can describe treatment of structures during an earthquake, better than the acceleration-based methods. In energy based method, energy criterion expresses that when the energy capacity of structure is lower than its demand energy, the structure collapses. The input energy to the structure must be dissipated through inelastic deformations and structural dampers. But in a structure, if its capacity energy was larger than its imposed energy, all of energy that input to this structure during ground motion is dissipated through damping and hysteretic cyclic behavior of structure at the end of ground motion. Also, this inelastic cyclic behavior cause partial damages in structures which may collapse with accumulating these partial damages.

Researchers in this field considered that among various types of energy, the input energy,  $E_I$ , is very stable parameter in structural response, and is suitable for energy-based seismic design

---

<sup>1</sup> Associate Professor, Center of Excellence for Fundamental Studies in Structural Engineering, College of Civil Engineering, Iran University of Science & Technology, Iran, Email: [ghodrati@iust.ac.ir](mailto:ghodrati@iust.ac.ir)

<sup>2</sup> Ph.D. Candidate, College of Civil Engineering, Iran University of Science & Technology, Iran, Email: [abdollahzadeh@iust.ac.ir](mailto:abdollahzadeh@iust.ac.ir)

method. Input energy is a measure of energy that earthquake inputs to structures during ground motion.

Therefore input energy demand can be assumed as a reliable tool to predict the seismic hazard and seismic design. Thus evaluation of structural parameters, characteristics of earthquake records and soil conditions effects on input energy are important. In this paper effects of viscous damping of structure on input energy were studied, by use of 110 Iranian earthquake records.

## LITERATURE REVIEW

Previously many of researches investigated the damping of structure influences on input energy and obtained different conclusions. Zahrah and Hall [1984] computed the input energy for eight earthquake records and they considered that ductility, damping and past-to-pre yield stiffness ratios have small effects on the input and hysteretic energies for a structure with bilinear behavior. Based on many analyses, McKevitt et al. [1980], Akiyama [1985] and Nakashima et al. [1996] observed that damping does not have a significant influence on the earthquake input energy. Results of the study by Bruneau and Wang [1996] indicated that damping ratios smaller than 5% have a minor influence on input energy.

Khashaei et al. [2003] computed the relative input energy for structures with damping ratios 0, 2, 5, 10, 20 and 40% for three accelerations with short duration and three with long duration of strong ground motions. They observed that for damping ratios smaller than 5%, it has little influence on input energy, but for damping ratios greater than 5%, this effect will be a significant influence on input energy spectra. They concluded that for very long natural periods, when structural damping increases, input energy increases. In this paper effects of the viscous damping of structure on input energy were studied.

## THEORETICAL BACKGROUND

When a single mass oscillatory system, *SDOF*, make to vibrate subject to a unidirectional horizontal ground motion, its balance equation can be expressed as follows [Akiyama, 1985].

$$M\ddot{y} + C\dot{y} + F(y) = -M\ddot{y}_g \quad (1)$$

Where  $M$ ,  $C$ ,  $F(y)$  and  $y$  are mass, structural damping coefficient, restoring force and relative displacement, respectively.  $\dot{y}$  and  $\ddot{y}$  are the first and second derivation of  $y$ , with respect to time, respectively and  $\ddot{y}_g$  is ground acceleration. If both sides of last equation is multiplied by  $dy(= \dot{y}dt)$  and then is integrated over the entire duration of an earthquake,  $t_0$ , Equation (1) reduces to the following energy balance equation:

$$E_k + E_d + E_s = E_I \quad (2)$$

$$E_k = \frac{1}{2} M \dot{y}^2, \quad E_d = \int_0^{t_0} C \dot{y}^2 dt, \quad E_s = \int_0^{t_0} F(y) dy, \quad E_I = -M \int_0^{t_0} \ddot{y}_g y dt$$

Here  $E_k$ ,  $E_d$  and  $E_s$  are kinetic energy, the energy dissipated by structural damping mechanism and the energy absorbed by spring, respectively and  $E_I$  defined as the total amount of energy imposed by an earthquake to a structure (i.e. input energy). The strain energy deposited by spring system consists of cumulative plastic strain energy that dissipate in nonlinear hysteretic

cyclic behavior of spring, and recoverable elastic strain energy at the instant when earthquake motion vanishes.

Akiyama [1985] expressed  $E_I$  in terms of equivalent pseudo-velocity,  $V_E$ , which is defined as follows:

$$V_E = \sqrt{2E_I / M} \quad (3)$$

Also, for a given earthquake record, he defined a relationship between the input energy,  $E_I$ , expressed in terms of the equivalent pseudo-velocity  $V_E$  by equation (3), and the natural period of system,  $T$ , as input energy spectrum,  $V_E$  versus  $T$ .

In this research for obtaining input energy spectrum and for normalizing it, the following steps were performed:

1. For each ground motion acceleration record, the input energy is sum of the total input energy exerted by the north-south and east-west of equivalent pseudo-velocity for input energy components (i.e. two horizontal components of  $V_E$ ).
2. For each ground motion record, similar to the previous step, the total of peak ground accelerations ( $PGA$ ) exerted by two acceleration horizontal components of ground motion was computed.
3. Because of different records are collected from different earthquakes with various  $PGA$ , also in order that the earthquake  $PGA$  effects in response of each analyses are vanished, and further more these responses can be added together, for each record, the amount of  $V_E$  (computed in the first step) was divided by its  $PGA$  (computed in the second step) and consequently  $f = V_E / PGA$  for each record was computed and spectrum curve of  $f$  versus  $T$  was drawn.

## SELECTION OF EARTHQUAKE RECORDS

Similar to many other researches, in this research and in its first step, selection of suitable earthquake records was needed which these records were chosen in Iranian earthquake records. Iran is one of countries that is located over high seismicity region (Alpine-Himalaya seismic belt) and is very often subjected to relatively strong ground motions and have lost many human lives and a lot of money due to the occurrence of destructive earthquakes. This country had many destructive strong ground motions e.g. Naghan, Tabas, Manjil earthquakes and recently Bam earthquake that happened in December 26, 2003 and killed more than 40000 and injured more than 25000 people in Bam city [Ahmadizadeh et al., 2004].

Since the authors had a relatively complete knowledge of Iranian earthquake databases and the related necessary information (availability of data regarding the causative earthquakes, the possibility of proper correction of the records and geological information about the earthquake recording stations), 110 records were selected. After a comparative study of the different researches that have been performed in Iran in the past [Mahdavian, 2000; Mirzaei et al., 1999; Zare et al., 1999a; 1999b], the ground types on which recording machines were located on were classified according to the soil conditions defined by Iranian Earthquake Code of Practice, Standard No. 2800 [2005], which is based on the geological characteristics and the shear wave velocity [Ghodrati Amiri et al., 2003 and 2005]. In this code soils divided in 4

types, based on shear wave velocity,  $V_s$ . These groups are ground type 1 with  $V_s > 750$  m/s, ground type 2 with  $375 \text{ m/s} < V_s < 750 \text{ m/s}$ , ground type 3 with  $175 \text{ m/s} < V_s < 375 \text{ m/s}$  and ground type 4 with  $V_s < 175 \text{ m/s}$  that can be named bed rock, stiff soil, medium soil and soft soil, respectively. By these definition 110 records used in this research divided in 30, 27, 39 and 14 records for ground types 1, 2, 3 and 4, respectively. The minimum and maximum earthquake durations for these records are (1.25s, 34.76s), (0.35s, 20.48s), (0.77s, 38.66s) and (4.5s, 30.11s) in four ground types, respectively. All of these records have shallow focal depth and 82% of them have epicentral distances smaller than 60 km.

### INPUT ENERGY SPECTRA

For each ground motion record, the pseudo-velocity response spectrum,  $V_E$  versus  $T$ , corresponding to an elastic *SDOF* system was obtained by calculating pseudo-velocity components (i.e.  $V_{E,NS}$  and  $V_{E,EW}$ ) and then this was normalized by its *PGA*.

In the first step, based on the amount of earthquake durations, the ground type 3 records were divided in three groups and each of the other ground types records were divided in two groups. For each set, the normalized pseudo-velocity response spectra were calculated for elastic *SDOF* system with 10% damping ratio (Figures 1 to 4). Then for accessing structural damping ratios effects on input energy, these spectra were calculated and were drawn for elastic *SDOF* system with damping ratios  $x = 1, 3, 5, 7, 10, 15$  and 20% with different durations (Figure 5). Finally, for each ground types, the mean values of these spectral curves were calculated and were shown in Figures 6 and 7. It should be noted that in all following curves duration is based-intensity parameter that by definition is time between 5% and 95% of the total energy induced by result of two horizontal components of earthquake [Trifunac and Brady 1975].

### RESULTS AND DISCUSSIONS

Figure 5 shows structural damping effects on input energy. This figure indicates that in all ground types, damping effects on spectral normalized pseudo-velocity (or input energy) is small and with increasing in damping ratios almost  $f$  remains constant, in each natural period. Figure 6 that was drawn for mean  $f$  versus damping ratios for different natural periods, approves this result more obviously. But Figure 7 that was drawn by more noticeably and more exactly sense, shows damping ratios influence on input energy. This figure calculated for all natural periods, indicates that in all of ground types in small damping ratios ( $x < 5\%$ ) and in large damping ratios ( $x > 5\%$ ),  $f$  (or input energy) decreases and increases with increasing in damping ratios, respectively. In the other word, the amount of  $f$  in  $x = 5\%$  is minimum. However, in each two parts (small and large damping ratios) the variation of  $f$  is not fast. These results approve the results that were concluded by Bruneau and Wang [1996] and Khashaei et al. [2003].

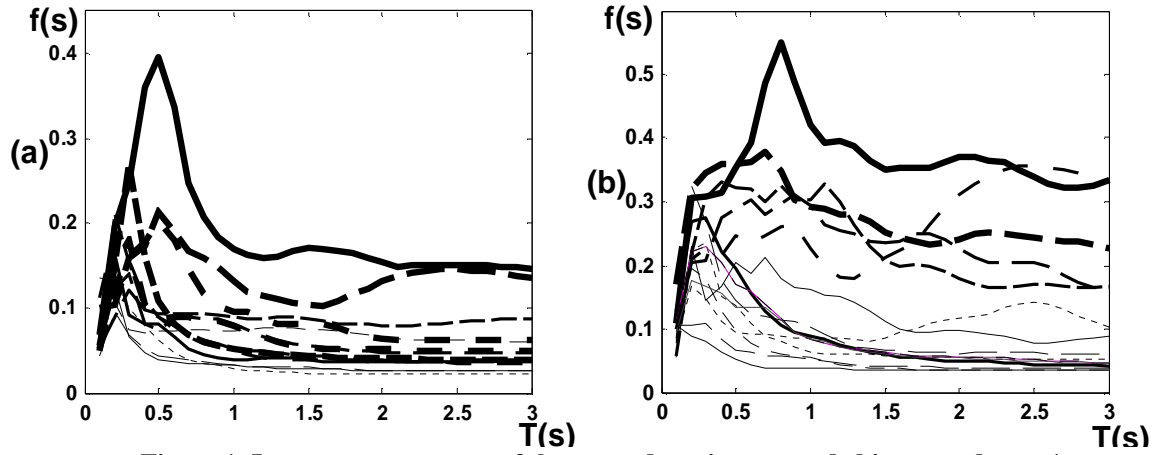


Figure 1. Input energy spectra of the ground motions recorded in ground type 1 for duration  $\leq 6$  sec (b) for duration  $> 6$  sec

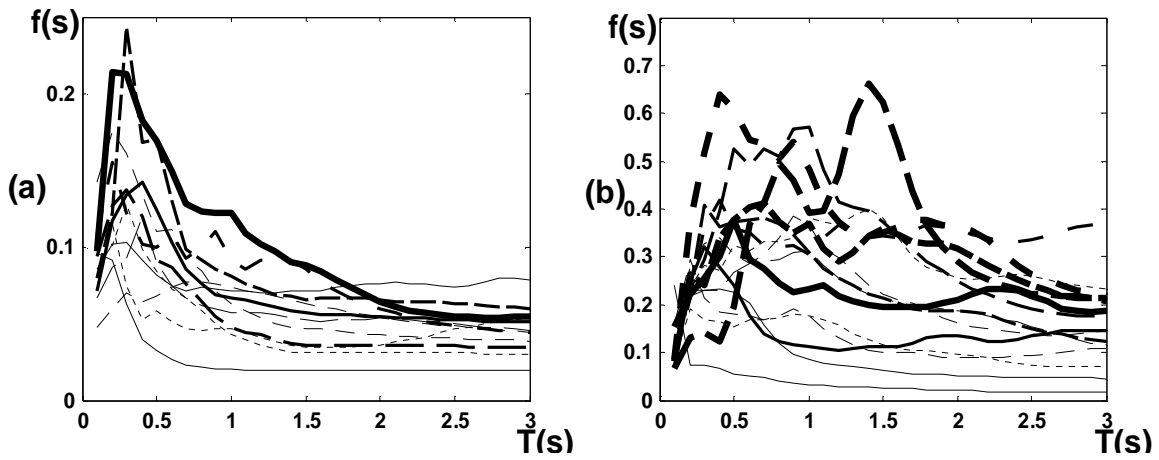


Figure 2. Input energy spectra of the ground motions recorded in ground type 2 for duration  $\leq 8$  sec (b) for duration  $> 8$  sec

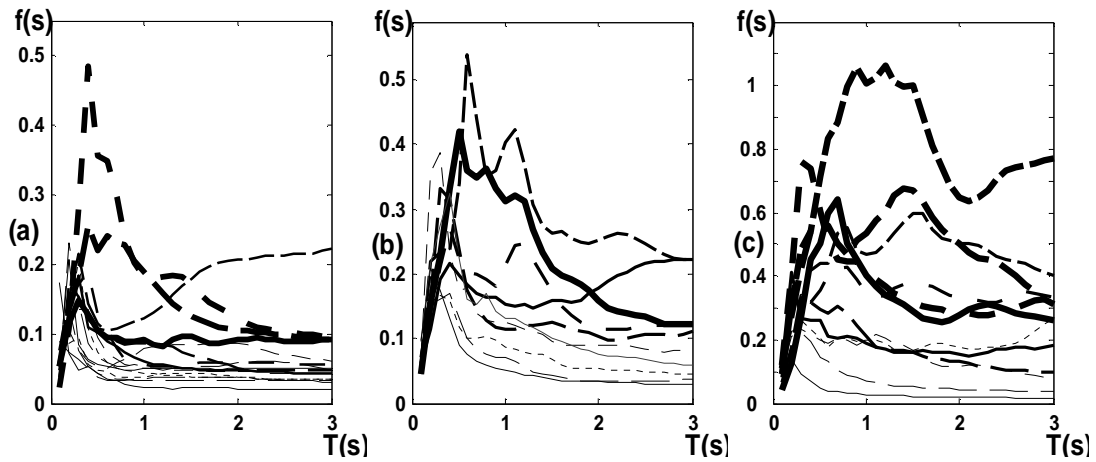


Figure 3. Input energy spectra of the ground motions recorded in ground type 3 (a) for duration  $\leq 7$  sec (b) for  $7 \text{ sec} < \text{duration} \leq 10 \text{ sec}$  (c) for duration  $> 10$  sec

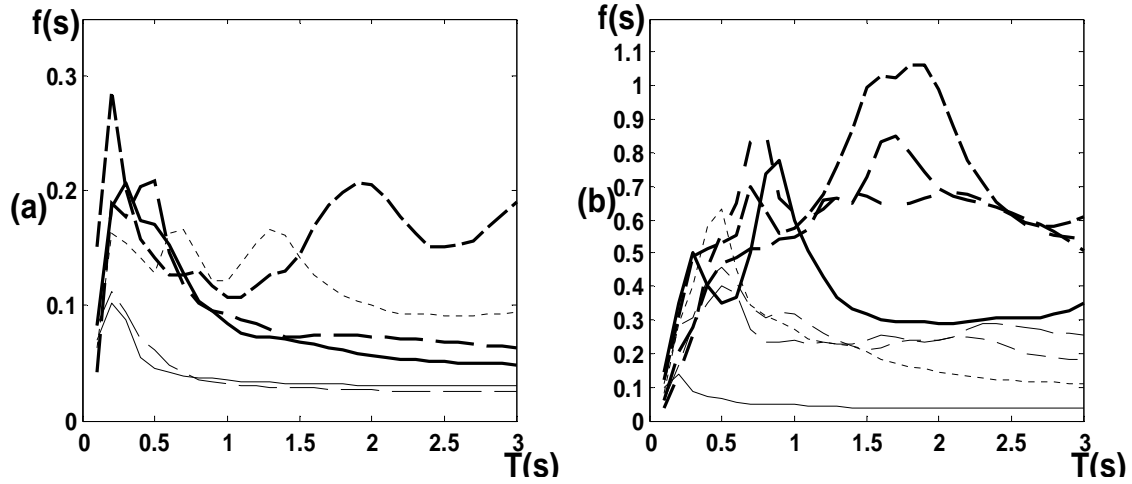


Figure 4. Input energy spectra of the ground motions recorded in ground type 4  
(a) for duration  $\leq 10$  sec (b) for duration  $> 10$  sec

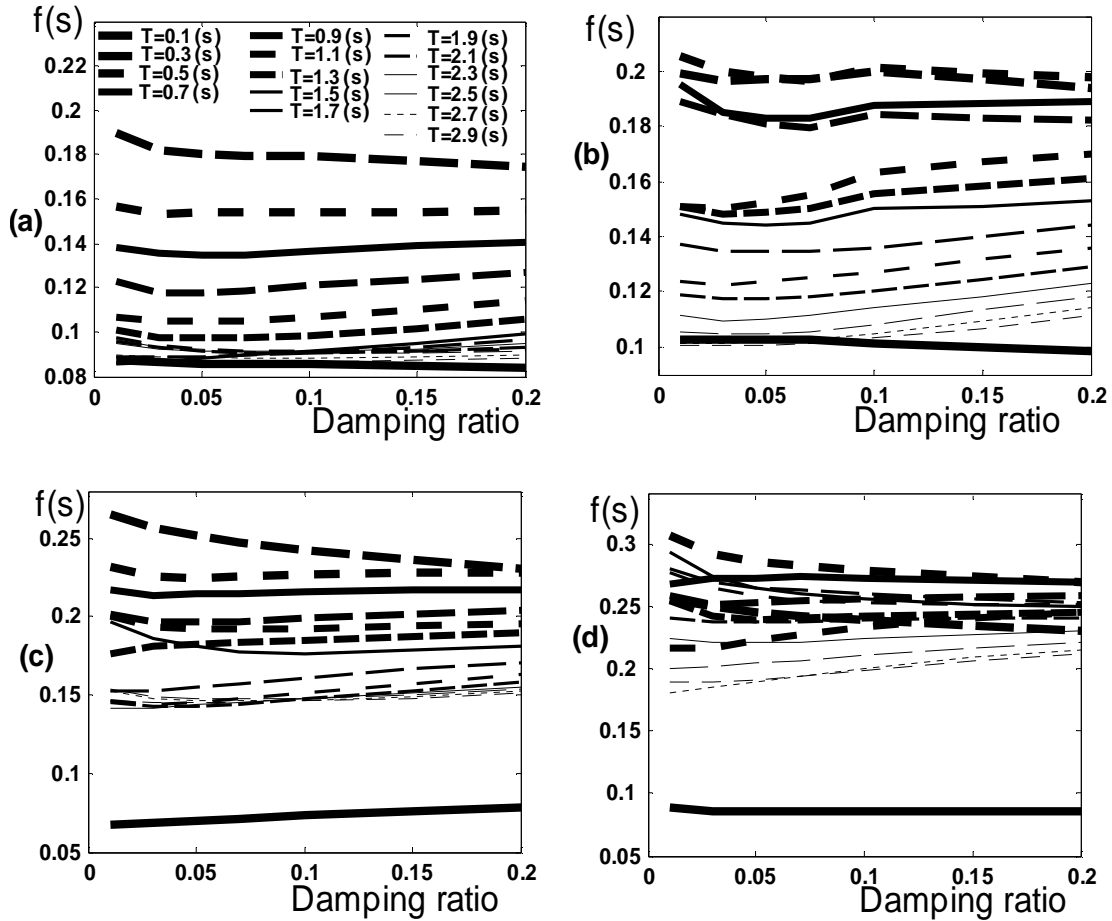


Figure 5. Spectral input energy versus damping ratio for structures with different natural periods of the ground motions recorded in ground (a) type 1 (b) type 2 (c) type 3 (d) type 4

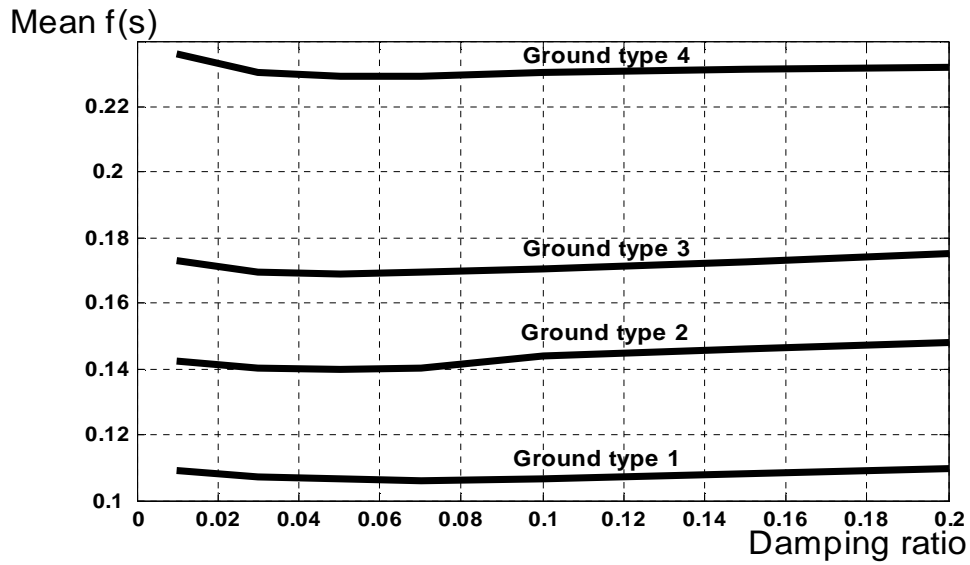


Figure 6. Mean spectral input energy versus damping ratio for structures with different natural periods of the ground motions recorded in four ground types

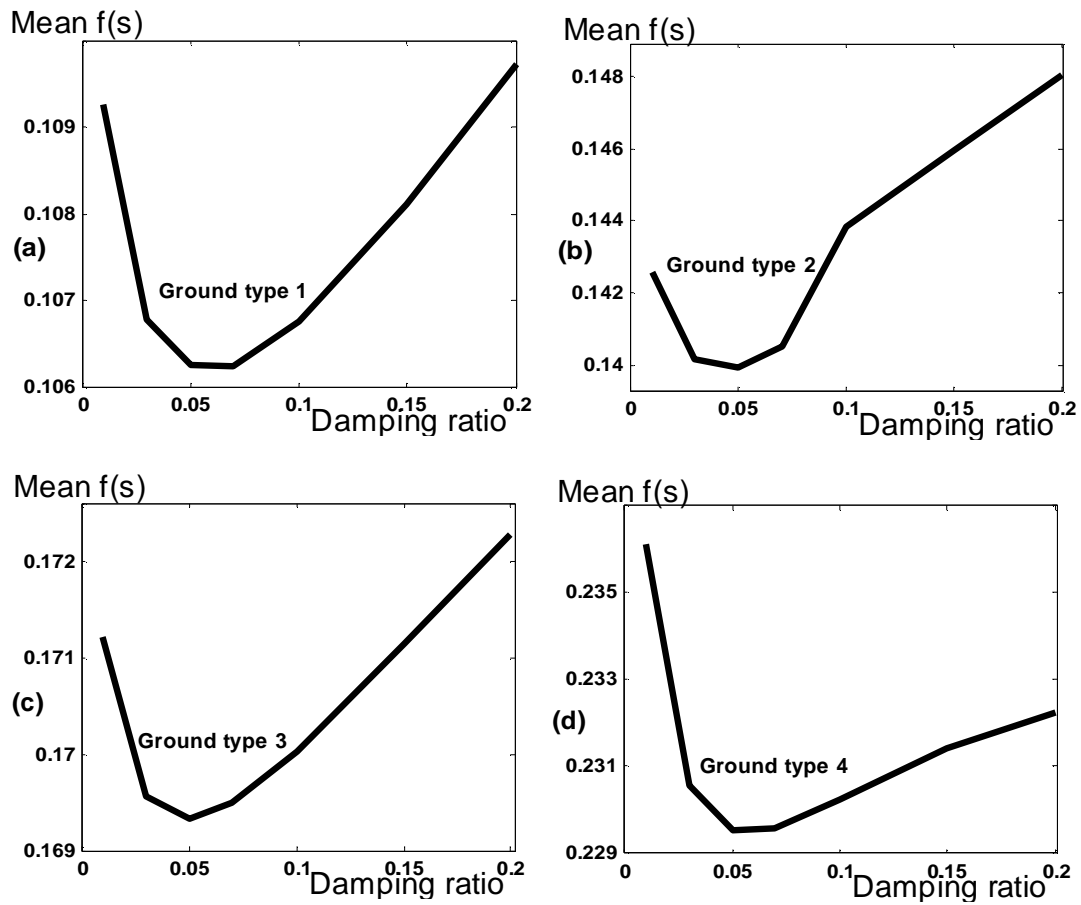


Figure 7. Mean spectral input energy versus damping ratio for structures with different natural periods of the ground motions recorded in ground (a) type 1 (b) type 2 (c) type 3 (d) type 4

## SUMMARY OF RESULTS

The main objective of this paper is to assess structural damping ratio effects on elastic input energy in *SDOF* systems. Using Iranian earthquake records, at first 110 earthquake records selected and divided in four ground types based on Iranian seismic code of practice [2005]. Then the elastic input energy spectra through dynamic response analyses were calculated with different damping ratios and expressed in terms of pseudo-velocity  $V_E$ . Next  $V_E$  was normalized with respect to the absolute peak ground acceleration of the results of two horizontal components ( $PGA$ ). Finally by investigating results, it was concluded that in all of ground types in damping ratios smaller and larger than 5% with increasing in the amount of damping, input energy decreases and increases, respectively. In the other words, the amount of input energy in damping ratio 5% is minimum. However, this variation is not very considerable.

## REFERENCES

- Ahmadizadeh, M. and Shakib, H. "On the December 26, 2003, southeastern Iran earthquake in Bam region", *Engineering Structures*, 26, 1055-1070, 2004.
- Akbas, B., Shen, J. and Hao, H. "Energy approach in performance-based seismic design of steel moment resisting frames for basic safety objective", *The Structural Design of Tall Buildings*, 10(3), 193-217, 2001.
- Akiyama, H. "Earthquake-resistant design method for buildings based on energy balance", *Gihodo Shuppan*, Tokyo, 25-26, 1999.
- Akiyama, H. "Earthquake-resistant limit-state design for buildings", University of Tokyo Press, Tokyo, 1985.
- Benavent-Climent, A., Pujades, L.G. and Lopez-Almansa, F. "Design energy input spectra for moderate-seismicity regions", *Earthquake Engineering and Structural Dynamics*, 31, 1151-1172, 2002.
- Bruneau, M. and Wang, N. "Normalized energy-based methods to predict the seismic ductile response of SDOF structures", *Engineering Structures*, 18, 13-28, 1996.
- Decanini, L.D. and Mollaioli, F. "An energy-based methodology for the assessment of seismic demand", *Earthquake Engineering and Structural Dynamics*, 21, 113-137, 2001.
- Decanini, L.D. and Mollaioli, F. "Elastic earthquake input energy spectra", *Earthquake Engineering and Structural Dynamics*, 27, 1503-1522, 1998.
- Ghodrati Amiri, G. and Manouchehri Dana, F.M. "Introduction of the most suitable parameter for selection of critical earthquake", *Computer and Structures*, 83, 613-626, 2005.
- Ghodrati Amiri, G., Motamed, R. and Rabet Es-Haghi, H. "Seismic hazard assessment of metropolitan Tehran, Iran", *Journal of Earthquake Engineering*; 7(3), 347-372, 2003.
- Iranian Code of Practice for Seismic Resistance Design of Buildings, Standard No.2800, 3rd Edition, Building and Housing Research Center, Tehran, Iran, 2005.
- Khashaee, P., Mohraz, B., Sadek, F., Lew, H.S. and Gross, J.L. "Distribution of earthquake input energy in structures", Report No. NISTIR 6903, Building and Fire Research Laboratory, National Institute of Standards and Technology, Gaithersburg, MD 20899, 2003.
- Leelataviwat, S., Goel, S. and Stojadinovic, B. "Toward performance-based seismic design of structures", *Earthquake Spectrum*, 15(3), 435-461, 1999.



- Mahdavian, A. "Design response spectra for large dams in Iran", China, International Commission of Large Dams (ICOLD), 2000.
- Manfredi, G. "Evaluation of seismic energy demand", *Earthquake Engineering and Structural Dynamics*, 30(4), 485-499, 2001.
- McKevitt, W. E., Anderson, D.L. and Cherry, S. "Hysteretic energy spectra in seismic design", *Proceedings of the 2<sup>nd</sup> World Conference on Earthquake Engineering*, 7, 487-494, 1980.
- Mirzaei, H. and Farzanegan, E. "Specifications of the Iranian accelerograph network stations", BHRC publication no. 266, Tehran, Iran, Building & Housing Research Center, 1999.
- Nakashima, M., Saburi, K. and Tsuji, B. "Energy input and dissipation behaviour of structures with hysteretic dampers", *Earthquake Engineering and Structural Dynamics*, 19(1), 77-90, 1996.
- Ordaz, M., Huerta, B. and Reinoso, E., "Exact computation of input energy spectra from Fourier amplitude spectra", *Earthquake Engineering and Structural Dynamics*, 32, 597-605, 2003.
- Trifunac, M.D. and Brady, A.G. "A study of the duration of strong earthquake ground motion", *Bulletin of the Seismological Society of America*, 65, 581-626, 1975.
- Trifunac, M.D., Hao, T.Y. and Todorovska, M.I. "Energy of earthquake response as a design tool", *Proceedings of the 13<sup>th</sup> Mexican Conference on Earthquake Engineering*, Guadalajara, Mexico, 2001.
- Zahrah, T.F. and Hall, W.J. [1984], "Earthquake energy absorption in SDOF structures", *Journal of Structural Engineering, ASCE*, 110(8), 1757-1772.
- Zare, M., Bard, P.Y. and Ghafory-Ashtiany, M. "The Iranian accelerometric data bank: a revision and data correction", *Journal of Seismology and Earthquake Engineering (Tehran, Iran)*, 1(1), 1-22, 1999a .
- Zare, M., Bard, P.Y. and Ghafory-Ashtiany, M. "Site characterization for the Iranian strong motion network", *Journal of Soil Dynamic and Earthquake Engineering*, 18(2), 101-23, 1999b.