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Energy-based response of simple structural systems by using simulated ground motions

Volkan Ozsarac [a], Shaghayegh Karimzadeh [b], Murat Altug Erberik [c,]*, Aysegul Askan [d]

[a] Graduate Student, Middle East Technical University, Ankara 06800, Turkey
[b] Post-Doctoral Researcher, Middle East Technical University, Ankara 06800, Turkey
[c] Professor, Middle East Technical University, Ankara 06800, Turkey
[d] Associate Professor, Middle East Technical University, Ankara 06800, Turkey

Abstract

For the last two decades, there has been a growing and remarkable attention on the energy-based design and assessment approaches for structural systems. These approaches have also been implemented to some of the national seismic design codes as alternative methods in addition to the traditional force-based design methodology. The underlying research has been often carried out by using actual ground motion records taken from many different earthquakes all over the world. However, such an attempt impairs the validity of the obtained results since it is generally not possible to construct a homogeneous ground motion record database with well-distributed source and ground motion parameters. In this study, in order to overcome the aforementioned disadvantage, a large set of simulated ground motion records are used in a parametric study to examine the influence of different intensity measures on the energy-based response of simple structural systems, i.e. single-degree-of-freedom (SDOF) systems. A set of ground motions is formed from simulation of potential events with a certain moment magnitude range, source-to-site distances and soil conditions. The simulations are performed on active faults around Erzincan city center located on the Eastern sections of North Anatolian Fault zone in Turkey. The output parameters are input energy, hysteretic energy and damping energy. The results show that the energy is a relatively stable parameter when compared to other response parameters. Hence energy seems to be a good candidate to be used in seismic design and assessment approaches.

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Keywords: Energy-based response; single-degree-of-freedom systems; time history analysis; simulated ground motions; stochastic finite-fault method

* Corresponding author. Tel.: +903122102443; fax: +903122105401
E-mail address: altug@metu.edu.tr

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1. Introduction

In earthquake engineering, energy-based analysis and design approaches have been studied since the pioneering work of Housner [1]. That study gave inspiration to many researchers, who made significant contributions to this research area [2-5] developed the fundamental framework of energy-based methodology, which was also implemented as an alternative method to the traditional force-based design approach in Japanese seismic code.

In the last two decades, many researchers studied the characteristics of energy related parameters in a detailed manner [6-11]. Their research was often carried out by using actual ground motion records taken from many different earthquakes all over the world. However, it is generally not possible to construct homogeneous ground motion databases with well-distributed ground motion parameters. In order to obtain energy response functions in the full range of seismic intensity parameters, an alternative approach is to employ simulated ground motion record sets.

In this study, the influence of different intensity measures on the energy-based response of single-degree-of-freedom (SDOF) systems is examined by using a large set of simulated ground motion records through a parametric study. The simulated ground motion records are obtained using the stochastic finite-fault methodology, which is efficient in simulating the frequencies of engineering interest [12]. A set of ground motions is formed from simulation of potential events within a selected moment magnitude range, different source-to-site distances and soil conditions. The simulations are performed on an active fault around Erzincan city center located on the Eastern sections of North Anatolian Fault zone in Turkey. Then, time history analyses on SDOF systems are conducted with simulated records to obtain the response statistics. The output parameters are input energy, hysteretic energy and damping energy.

2. Energy equation and the related parameters

Dynamic response of a SDOF system is represented by the equation of motion given in Eq.1:

$$m\ddot{u}(t) + c\dot{u}(t) + f_S(u) = -m\ddot{u}_g(t) \quad (1)$$

where $\ddot{u}$ and $\dot{u}$ are the acceleration and velocity terms, respectively; m and c are the mass and viscous damping terms of the SDOF system and $\ddot{u}_g$ stands for the input ground acceleration. The term $f_s(u)$ denotes the restoring force as a function of the system displacement u, which equals to $f_s=ku$ for linear elastic behavior. In the case of inelastic response, $f_s(u)$ is characterized by hysteretic relationships. Energy equilibrium equation is obtained by integrating both sides of Eq.1 with respect to u as:

$$\int_u m\ddot{u}\,du + \int_u c\dot{u}\,du + \int_u f_S(u)\,du = -\int_u m\ddot{u}_g(t)\,du \quad (2)$$

where the three terms on the left hand side of the formulation are kinetic energy (E_k), damping energy (E_ξ) and absorbed energy (E_a), respectively. Absorbed energy is composed of two parts; the recoverable elastic strain energy (E_s), and the irrecoverable hysteretic energy (E_h), where $E_s = f_s^2/2k$

Input energy (E_i) is on the right hand side of Eq.2. The integral shows that it is a function of both ground motion and system properties. Physically, E_i is the energy imparted to the structural system subjected to a ground motion record. During the dynamic response, E_i is temporarily converted into E_k and E_s, which vanish at the end of dynamic excitation. At this instant, all input energy should be dissipated by damping (through E_ξ) and inelastic action (through E_h). For elastic systems, the only way to dissipate energy is via damping.

As stated by Uang and Bertero [13], there are two different types of energy equations: absolute and relative. These two methods of energy formulation follow a similar procedure and yield the same response quantities like relative displacement. Absolute energy equation represents a moving base SDOF system whereas the relative energy equation represents an equivalent fixed-base SDOF system. In this study, absolute energy approach is employed.

3. Simulation of a regional ground motion set

The study area is Erzincan, a city located in the eastern segments of North Anatolian Fault zone with a relatively sparse ground motion network when compared to the western segments. In this study, in order to increase the variability in ground motions to be used in structural analyses while considering the regional seismic properties, a set of scenario events are simulated for different magnitude ranges (Mw=6.0, 6.5 and 7.0). In the simulations, local source, path and site conditions are taken into account. Simulations are performed at a total of 244 nodes inside of the Erzincan region bounded by 39°- 40° Eastern longitudes, 39°- 40° Northern latitudes with equal grid spacing. Stochastic finite fault method based on a dynamic corner frequency concept proposed by Motazedian and Atkinson [12] is used in simulations. The selected nodes are located on site classes C and D according to NEHRP site classification which are represented as S2 and S3, respectively in this study. Further details corresponding to ground motion simulations in the study area can be found in Askan et al. [14,15]. At each station, there is one random horizontal component simulated from stochastic finite fault technique. Therefore, the dataset for all scenarios at the selected 244 nodes consists of 732 records. For structural analyses, among the generated record set, a total of 240 records are selected. These records are categorized according to their soil class, source to site distances (Joyner and Boore distance: R_{JB}) and magnitude of the event as shown in Table 1. Variations of PGA and PGV with respect to R_{JB} for the selected ground motion records are shown in Fig. 1.

Table 1. Distribution of the records according to soil class, distance and magnitude

Distance (R_{JB})	Soil Type	S2 (Soft Rock)			S3(Stiff Soil)		
	Magnitude	Mw=6.0	Mw=6.5	Mw=7.0	Mw=6.0	Mw=6.5	Mw=7.0
0Km-5Km	Number of Records	10	10	10	10	10	10
5Km-10Km		10	10	10	10	10	10
10Km-20 Km		10	10	10	10	10	10
>20 Km		10	10	10	10	10	10

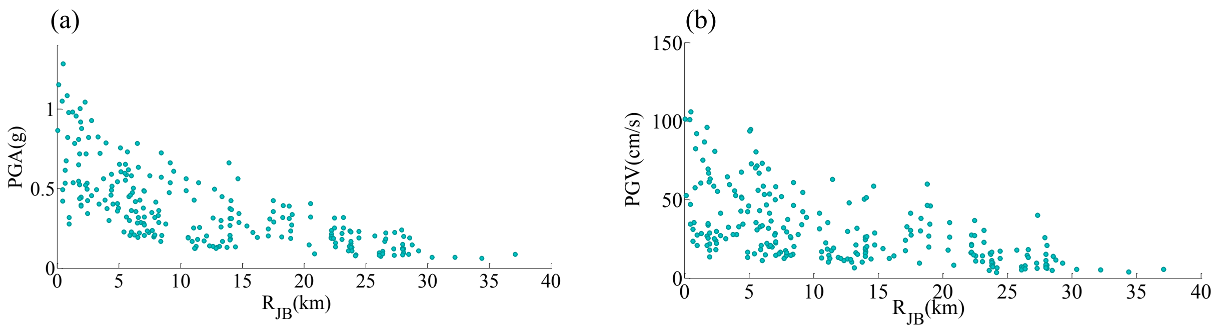

Fig. 1. Variation of (a) PGA and (b) PGV with respect to R_{JB} for the selected records

4. Dynamic Analyses of SDOF Systems

In this study, spectral variations of energy-based parameters are obtained for SDOF systems subjected to the simulated ground motion records shown in Table 1. In the first phase of analysis, linear elastic SDOF models are considered in order to examine the influence of aforementioned ground motion parameters on elastic input energy (E_I^e). In the second phase of analysis, inelastic SDOF models are considered in order to observe the relationship between elastic and inelastic input energies (E_I) and the ratio between hysteretic energy (E_H) and inelastic input energy (E_I). In order to achieve this task, elasto-plastic and stiffness degrading (i.e. Clough Johnston model) hysteresis models are used. The strength ratio (η), which is defined as the yield strength divided by the weight, is considered to take values of η=0.1, 0.2, 0.3 and 0.4. Damping ratio (ξ) is taken as ξ=2%, 5% and 8%.

5. Analysis Results

The investigated energy related parameters are elastic input energy, ratio of inelastic to elastic input energy and ratio of hysteretic energy to inelastic input energy. The latter two are defined as follows:

$$R_{IE} = E_I / E_I^e \tag{3}$$

$$R_{HI} = E_H / E_I \tag{4}$$

Fig.2.a shows elastic input energy spectra for records of event with M=7 recorded at $0<R_{JB}<5$ km. Investigated parameters are site class (S2 and S3) and damping ratio (ξ=2, 5 and 8%). It is observed that after T=0.3 seconds, input energy for S3 class becomes larger than input energy for S2 class. This shows that after a certain period, as site conditions get softer (or weaker), input energy increases. This observation is consistent with similar analyses which employs real ground motion records. The spectral shape of elastic input energy is also in agreement with previous studies [5,7,9,11]. For design purposes, these researchers recommended either a bilinear or a trilinear shape to represent elastic input energy spectra. The trend in this study seems to be much closer to a trilinear shape with an initial ascending region, a constant-valued plateau and a descending region. Damping does not seem to have a pronounced effect on E_I^e. It only reduces vibrational response at periods with extreme values up to a difference of 30%. Fig.2.b presents elastic input energy amplification by considering the ratio of E_I^e for softer site class (i.e. S3) to E_I^e for harder site class (i.e. S2). As observed from the figure, energy amplification takes values around 3 for T>0.75 seconds.

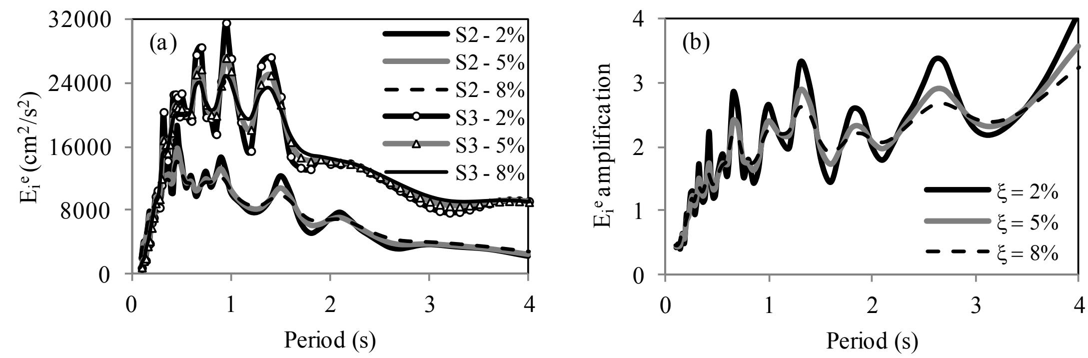

Fig.2. (a) Elastic input energy spectra for different site classes and damping ratios; (b) input energy amplification due to different site conditions

Fig.3.a shows elastic input energy spectra for records with $0<R_{JB}<5$ km and ξ=5%. Investigated parameters are site class (S2 and S3) and magnitude (M=6, 6.5 and 7). It is observed that magnitude affects E_I^e significantly. For M=7, energy imparted to structure becomes very large when compared to input energy for both M=6 and 6.5. Fig.3.b. yields E_I^e amplification due to magnitude by comparing the energy values for M=7 with values for M=6 and 6.5. For S2 class, energy imparted when M=7 is on the average ten folds than the energy imparted when M=6. For S3 class, the same trend holds up to T=2 seconds and after that increase in energy becomes more pronounced with 15 folds at T=3 seconds and nearly 30 folds at T=4 seconds. This reveals that for flexible structures like tall buildings, large magnitude earthquakes are very critical with regards to energy imparted to the structure.

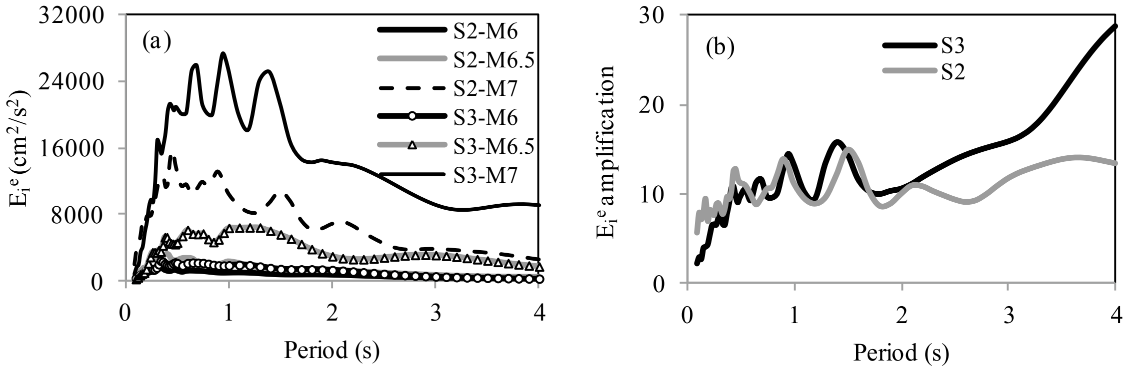

Fig.3. (a) Elastic input energy spectra for different site classes and magnitudes; (b) input energy amplification due to different magnitudes

Fig.4 present elastic input energy spectra for records with M=7 and ξ=5%. Investigated parameters are site class (S2 and S3) and distance (0< R_{JB}<5, 5< R_{JB}<10, 10< R_{JB}<20, R_{JB}>20). It is observed that input energies for the first two distance intervals (i.e. 0< R_{JB}<5 and 5< R_{JB}<10) can be distinguished clearly from input energies for the other two distance intervals (i.e. 10< R_{JB}<20 and R_{JB}>20). Hence elastic input energy becomes critical when R_{JB} <10 km. The decrease in input energy as distance increases seems to be very drastic for all periods in both classes (i.e. S2 and S3) even though this observation is more predominant for S3.

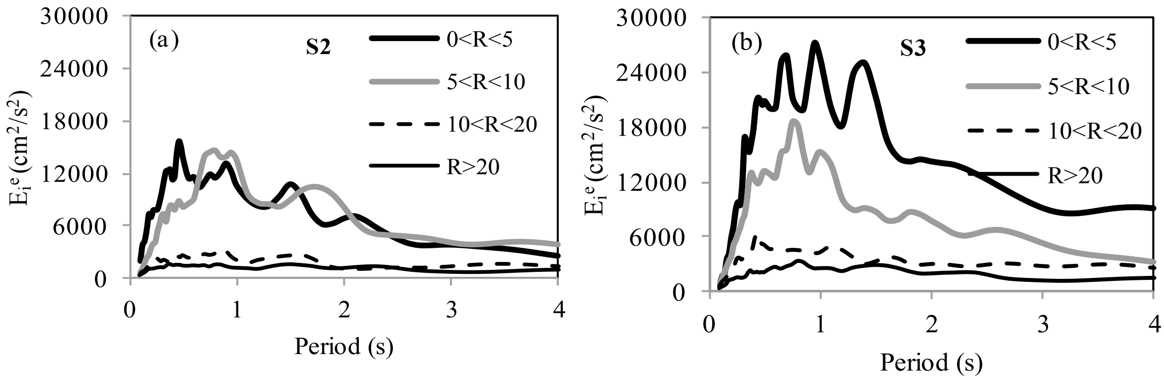

Fig. 4. Elastic input energy spectra for (a) different site classes and (b) distance intervals

Fig.5.a illustrates the variation of R_{IE} (defined in Eq.3) for S2 and S3 classes by using two different hysteresis models (i.e. elasto-plastic and Clough Johnston models). For SDOF systems, it is assumed that η=0.1 and ξ=5%. In Fig.5, the ratio takes high values in the short period range with a sharp descending trend. At T=0.3 seconds, the curves begin to stabilize around the values of 0.6-0.7 with a slight increase at longer periods converging to the value of 1.0. There seems to be no effect of either site class or hysteresis model on the spectral variation of R_{IE}. Hence it can be stated that except the short period region, the parameter R_{IE} is very stable. For design purposes, this ratio can be assumed to be equal to 1.0 for moderate and long period ranges, which in turn means elastic and inelastic input energies are equal to each other. In the short period range, or in other words for very rigid structures, inelastic energy demand seems to be very high. That is why generally force-based design strategy, which ensures elastic behaviour, is used for these structures.

Fig 5.b shows the variation of R_{HI} (defined in Eq.4) again for S2 and S3 classes and two considered hysteresis models (η=0.1, ξ=5%). The ratio seems to be rather stable with values around 0.5-0.7 in the moderate period range. This means that in the period range for which most of the building structures reside, 50%-70% of input energy should be spent through inelastic action. The effect of site conditions is slightly present in the short and long period ranges. Similar to the previous parameter, the effect of hysteresis model is not observed for the whole period range.

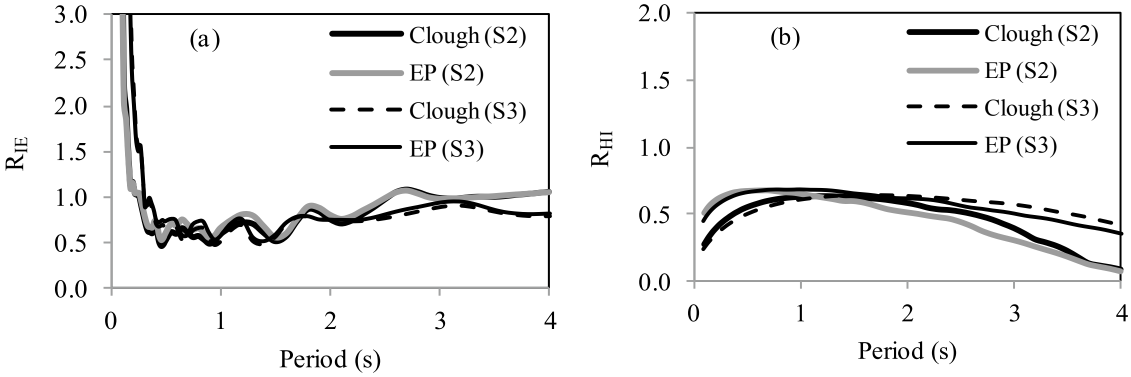

Fig.5. Spectral variation of (a) R_{IE}; (b) R_{HI} for different site classes and hysteresis models

6. Conclusions

This study focuses on the evaluation of energy-related parameters, especially input energy, by considering the dynamic analysis results of elastic and inelastic SDOF systems subjected to a simulated ground motion set. Similar studies were conducted before by using actual records. However, the results were not very reliable either due to scarcity of data (especially for large magnitude and short distances) or the large scatter due to selection of records from totally different earthquakes. This study tries to overcome these issues by simulating ground motion records that cover the whole possible range of regional values for major seismological parameters like magnitude, site class and distance. A parametric study is conducted to observe the characteristics of elastic and inelastic input energies and the percentage of hysteretic energy that should be dissipated through inelastic action. The obtained results seem to be consistent with those of previous studies and encourage the use of simulated ground motions to develop simple and practical energy-based design and evaluation procedures for structural systems.

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