AN ENERGY-BASED SEISMIC RESPONSE EVALUATION OF SIMPLE STRUCTURAL SYSTEMS WITH SIMULATED GROUND MOTIONS

S. Karimzadeh¹, V. Ozsarac², A. Askan³ and M.A. Erberik³

ABSTRACT

In recent years, there has been a strong interest on energy-based design and assessment methods for structural systems. The underlying research has been mostly performed using real ground motion records taken from existing earthquakes worldwide. Results may involve bias due to lack of homogeneity of the available ground motion dataset in terms of magnitudes, source to site distances or soil conditions. In this study a large set of ground motion records is simulated within a parametric exercise to investigate the effect of different intensity measures on the energy-based response of simple SDOF structures. To generate simulated records, the stochastic finite-fault methodology which is effective in simulating a wide range of frequencies including those that influence the built environment is used. The simulations are performed on active faults around Duzce city center located on the western segments of North Anatolian Fault zone in Turkey. The simulated records cover a wide range of moment magnitude, source-to-site distances and soil conditions. To assess the response statistics on SDOF models, time history analyses with simulated records are performed. Input energy, damping energy and hysteretic energy are considered as the main output parameters. The results of this study reveal that energy is a more stable parameter than the other response parameters such as displacement and force. However, it is important to dissipate the estimated input energy through damping and inelastic action. Finally, it is believed that conducting parametric seismic analysis based on simulated records yield realistic results since these records provide variability in seismic demand.

¹Post-Doctoral Researcher, Dept. of Civil Engineering, Middle East Technical University, Turkey, Ankara (email: shaghkn@gmail.com)
²Graduate Student, Dept. of Civil Engineering, Middle East Technical University, Turkey, Ankara, 06800
³Professor, Dept. of Civil Engineering, Middle East Technical University, Turkey, Ankara, 06800

An Energy-Based Seismic Response Evaluation of Simple Structural Systems with Simulated Ground Motions

S. Karimzadeh¹, V. Ozsarac², A. Askan³ and M.A. Erberik³

ABSTRACT

In recent years, there has been a strong interest on energy-based design and assessment methods for structural systems. The underlying research has been mostly performed using real ground motion records taken from existing earthquakes worldwide. Results may involve bias due to lack of homogeneity of the available ground motion dataset in terms of magnitudes, source to site distances or soil conditions. In this study a large set of ground motion records is simulated within a parametric exercise to investigate the effect of different intensity measures on the energy-based response of simple SDOF structures. To generate simulated records, the stochastic finite-fault methodology which is effective in simulating a wide range of frequencies including those that influence the built environment is used. The simulations are performed on active faults around Duzce city center located on the western segments of North Anatolian Fault zone in Turkey. The simulated records cover a wide range of moment magnitude, source-to-site distances and soil conditions. To assess the response statistics on SDOF models, time history analyses with simulated records are performed. Input energy, damping energy and hysteretic energy are considered as the main output parameters. The results of this study reveal that energy is a more stable parameter than the other response parameters such as displacement and force. However, it is important to dissipate the estimated input energy through damping and inelastic action. Finally, it is believed that conducting parametric seismic analysis based on simulated records yield realistic results since these records provide variability in seismic demand.

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] and developed the fundamental framework of energy-based methodology. The main principle of energy-based design is that the input energy transmitted by the design earthquake to the structure should be at least equal or less

¹Post-Doctoral Researcher, Dept. of Civil Engineering, Middle East Technical University, Turkey, Ankara (email: shaghkn@gmail.com)
²Graduate Student, Dept. of Civil Engineering, Middle East Technical University, Turkey, Ankara, 06800
³Professor, Dept. of Civil Engineering, Middle East Technical University, Turkey, Ankara, 06800

than the sum of the absorbed and dissipated energy capacities of the structural system. A challenging task in such an approach is the reliable prediction of seismic input energy from a suitable ground motion record. In the last two decades, many researchers studied the characteristics of energy related parameters in a detailed manner (e.g.: [6-11]). The related research was often carried out by using actual ground motion records taken from many different earthquakes all over the world. However, due to inherent scarcity of the earthquake process; it is very difficult to construct homogeneous ground motion databases with well-distributed ground motion parameters. In addition, previous studies revealed that using earthquakes even with the same inelastic response spectra resulted in different seismic input energies transmitted to the structures [6]. To overcome this issue, an alternative approach is the use of regionally simulated ground motion record sets for obtaining energy response functions within the full range of seismic intensity parameters for a specific region. Among different methods of ground motion simulation, stochastic method is mostly practical and thus preferred to simulate the ground motion amplitudes corresponding to the engineering frequency range of interest in regions where there is lack of well-defined regional source and velocity models (e.g.: [12-19]).

Until now, majority of the past studies have investigated the efficiency of simulated motions from alternative techniques in prediction of dynamic structural responses such as story displacements and drift ratios to be used in performance-based seismic design approaches (e.g.: [18-22]). A topic that remains to be studied is the investigation of the suitability of simulated motions for estimation of structural responses (such as input energy, hysteretic energy and etc.) to be used in energy-based seismic design approaches. The objective of this study is to investigate the influence of different intensity measures on the energy-based response of single-degree-of-freedom (SDOF) systems. For this purpose, a large set of simulated ground motion records are employed 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 [13]. A set of ground motions is constructed through the simulations 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 Duzce city center located on the Western 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.

**Energy Equation and the Related Parameters**

There are two alternative forms of energy equations according to Uang and Bertero [5]: Absolute and relative. The difference in between the methods depends on whether Eq. 1 or 2 is integrated to derive the energy equation. Two alternative forms of equation of motion for a damped SDOF system are as follows:

\[ m\ddot{u}_t(t) + c\dot{u}(t) + f_s(u) = 0 \]  
(1)

\[ m\ddot{u}(t) + c\dot{u}(t) + f_s(u) = -m\ddot{u}_g(t) \]  
(2)

where \( m \) and \( c \) stand for the mass and viscous damping of the SDOF system. \( \ddot{u}_t \) is the absolute (or total acceleration of the mass (\( \ddot{u}_t = \ddot{u} + \ddot{u}_g \)). The term \( \ddot{u}_g \) corresponds to the input ground
acceleration. \( \ddot{u} \) and \( \dot{u} \) are the relative acceleration and velocity terms, respectively. \( f_s(u) \) 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, hysteretic relationships determine the \( f_s(u) \).

Absolute energy equation corresponds to the work done by the total base shear at the foundation of the moving base SDOF system while the relative energy equation represents the work done by the static equivalent relative force \((-mu_g)\) on the equivalent fixed-base SDOF system. The two alternative methods result in different input and kinetic energy terms for very short and very long periods. Still, both approaches result in the same responses such as the hysteretic energy, damping energy, elastic strain energy and relative displacement. In this study, for all response analyses the relative energy approach is utilized.

Integrating both sides of Eq.1 with respect to \( u \) leads to the relative energy equilibrium equation as follows:

\[
\int m\ddot{u}(t) \, du + \int c\dot{u}(t) \, du + \int f_s(u) \, du = -\int m\ddot{u}_g(t) \, du
\]  

(3)

where the three terms on the left-hand side of the formulation are kinetic energy \( (E_k) \), damping energy \( (E_\xi) \) and absorbed energy \( (E_a) \), respectively. Absorbed energy is composed of two parts; the irrecoverable hysteretic energy \( (E_h) \) and the recoverable elastic strain energy \( (E_s) \), where \( E_s = f_s^2/[2k] \). The right-hand side of Eq.3 is input energy \( (E_i) \) which 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 \( E_\xi \)) and inelastic action (through \( E_h \)). For elastic systems, damping is the only way of dissipating energy.

**Simulation of a Regional Ground Motion Dataset**

The western segments of the North Anatolian Fault zone (NAFZ) are considered critical due to the existence of most densely-populated areas of Turkey surrounded by major industrial facilities. Duzce (Turkey), located on an alluvial pull-apart basin in the western part of NAFZ, is selected as the study area. Duzce earthquake (Mw=7.1), which occurred on 12 November 1999 in Turkey, led to large ground motion amplitudes and significant damage within the city causing almost 900 mortalities and 3000 injuries [23]. Despite the seismic hazard of the study area, the regional records from earthquakes with different magnitudes are limited in number. Therefore, to increase the variability in seismic demand for dynamic response analyses, in this study a set of scenario events compatible with regional seismicity are simulated. For ground motion simulations the stochastic finite fault methodology based on a dynamic corner frequency approach proposed by Motazedian and Atkinson [13] is used. In stochastic finite-fault methodology, the rectangular fault plane is divided into subfaults with specified width and length sizes to consider the effects of finite dimension of fault plane. The contributions of all these subfaults are summed in time domain by considering each subfault as a single point source with an \( w^2 \) spectrum. It is assumed that the hypocenter is located at the center of one of subfaults and the rupture initiates propagating radially from the hypocenter by a constant rupture velocity. Each subfault is triggered when the rupture reaches the center of that subfault. Finally, to calculate the final ground motion from the entire
fault at the receiver, contributions of all subfaults are summed in time domain by taking into account the corresponding time delay of each subfault. In the dynamic corner frequency concept, the total energy radiated from the fault is conserved regardless of the selected subfault size. In this study, the dynamic corner frequency approach as implemented in the computer program EXSIM [13] is used.

The acceleration spectrum $A_{ij}(f)$ of the $ij^{th}$ subfault is defined in terms of source, path and site effects as follows:

$$A_{ij}(f) = CM_{0ij}H_{ij} \left[ (2\pi f)^2/[1 + (f/f_{cij})^2] \right] e^{-\pi f R_{ij}} G(R_{ij}) A(f) e^{-\pi k f}$$

where $C = \frac{\rho \theta \phi \sqrt{\pi}}{4\pi \rho \beta}$ is a scaling factor, $\Re\phi$ is the radiation pattern, $\rho$ is the density, $\beta$ is the shearwave velocity, $M_{0ij} = \frac{M_{0}S_{ij}}{\sum_{k=1}^{n} \sum_{l=1}^{m} S_{kl}}$ is the seismic moment, $S_{ij}$ is the relative slip weight and $f_{cij}(t)$ is the dynamic corner frequency of the $ij^{th}$ subfault where $f_{cij}(t) = N_R(t)^{-1/3} 4.9 \times 10^6 \beta \left( \frac{\Delta \sigma}{M_{0ave}} \right)^{1/3}$. Here $\Delta \sigma$ is the stress drop, $N_R(t)$ is the cumulative number of ruptured subfaults at time $t$, and $M_{0ave} = M_0/N$ is the average seismic moment of subfaults where is $N$ the total number of subfaults. $R_{ij}$ is the distance from the observation point, $Q(f)$ is the quality factor, $G(R_{ij})$ is the geometric spreading factor, $A(f)$ is the site amplification term, and $e^{-\pi k f}$ is a high-cut filter included to provide the spectral decay at high frequencies described with the kappa factor of soils. $H_{ij} = (N \ast (\Sigma(f^2/(1 + (f/f_0)^2))/\Sigma(f^2/(1 + (f/f_0)^2))))^{1/2}$ is a scaling factor introduced to conserve the high-frequency spectral level of the subfaults.

The time series are simulated for different magnitude ranges (Mw=5.0, 5.5, 6.0, 6.5, 7.0, 7.1, and 7.5) considering the local source, path and site conditions. Ground motions are simulated at a total of 370 nodes inside of the Duzce region bounded by 30°- 32° Eastern longitudes and 40°- 41° Northern latitudes. The selected nodes are located on soils with site classes C and D according to site classifications of National Earthquake Hazards Reduction Program [24] site classification which are represented as S2 and S3, respectively in this study [25]. For ground motion simulations of all scenarios at the selected nodes, the source, path and site parameters verified by Ugurhan and Askan [15] for the 1999 Duzce earthquake (Mw=7.1) are used. Further details corresponding to ground motion simulations in the study area can be found in Ugurhan and Askan [15] and Karimzadeh et al. [19].

The stochastic finite fault simulation method provides only one random horizontal component at each station per scenario. Therefore, the total number of the simulated time histories at the selected 370 nodes is 2590. To perform structural analyses, among the generated time series, a database of 560 records is selected. In the selection process, these records are categorized into 56 bins where inside of each bin a total of 10 records are selected. These bins are classified with respect to their source-to-site distances (Joyner and Boore distance: 0<=RJB<5, 5<=RJB<10, 10<=RJB<20, and RJB>=20), soil class (S2: Soft Rock and S3: Stiff Soil) and moment magnitude of the event (Mw=5.0, 5.5, 6.0, 6.5, 7.0, 7.1, and 7.5). Figure 1 illustrates the variations of PGA.
Results of Dynamic Analyses of SDOF Systems

The aim of this study is to obtain spectral variations of energy-based parameters for SDOF systems with varying periods subjected to the selected set of simulated ground motions. To examine the influence of ground motion parameters including magnitude, source-to-site distance and soil class on elastic input energy ($E_I^e$), first linear elastic SDOF models are employed. Then, inelastic SDOF models are utilized to investigate the relationship between elastic ($E_I^e$) and inelastic input energies ($E_I$) as well as the ratio between hysteretic energy ($E_H$) and inelastic input energy ($E_I$). In the inelastic analyses, elasto-plastic and stiffness degrading (i.e. Clough Johnston model) hysteresis models are employed. All analyses are performed with three different damping levels of $\xi=2\%$, 5\% and 8\% where $\xi$ is the damping ratio. The strength ratio ($\eta$), which is determined as the yield strength divided by the weight, is assumed to take values of $\eta=0.1, 0.2, 0.3$ and 0.4.

In this study, the relationships between different energy response parameters and the abovementioned ground motion parameters are investigated. The energy parameters considered herein are the elastic input energy, ratio of inelastic to elastic input energy and ratio of hysteretic energy to inelastic input energy. The ratio of inelastic to elastic input energy ($R_{IE}$) and ratio of hysteretic energy to inelastic input energy ($R_{HI}$) are determined, respectively as follows:

$$R_{IE} = E_I/E_I^e$$ (5)

$$R_{HI} = E_H/E_I$$ (6)

Fig. 2a shows elastic input energy spectra for records of a sample scenario event with Mw=7.1 (the 1999 Duzce, Turkey event) recorded at 0<RJB<5 km. Investigated parameters are site class (S2 and S3) and damping ratio ($\xi=2\%, 5\% \text{ and } 8\%$). It is observed that input energy for S3 (softer soil) is slightly higher than input energy for S2 (stiffer soil) for periods less than approximately 0.25 seconds. After T=0.25 seconds, input energy for S3 class generally becomes significantly larger than input energy for S2 class up to the period of 4.0 seconds. Both this observation and the spectral shape of elastic input energy are consistent with similar analyses in previous studies which employs real ground motion records (e.g.: [3, 6, 8, and 9]). For design purposes, previous studies 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. Fig. 2a also shows that damping does not seem to have a noticeable effect on \( E_I^e \) except at peak responses. The maximum difference in \( E_I^e \) caused by damping is around 32\% at \( T=0.28s \) for scenario event of \( M_w=6.5 \) and soil class \( S_2 \). Fig. 2b presents elastic input energy amplification which is the ratio of \( E_I^e \) for softer site class (i.e. \( S_3 \)) to \( E_I^e \) for stiffer site class (i.e. \( S_2 \)). For this scenario event it is observed that the energy amplification reaches to the maximum value of 5 at period of 0.8 seconds, then gradually decreases for periods larger than a 0.8 seconds and oscillates around the value of 2.0.

![Simulation of the 1999 Duzce (Mw=7.1) Earthquake](image1)

Figure 2. (a) Elastic input energy spectra with respect to different site classes and damping ratios; (b) Input energy amplification (\( S_3/S_2 \)) spectra with respect to different damping ratios. (\( M_w=7.1 \) and \( 0=\lt R_{JB} \lt 5 \) km)

Fig. 3 shows elastic input energy spectra for records of \( \xi=5\% \) at \( 0=\lt R_{JB} \lt 5 \) km. Investigated parameters are site class (\( S_2 \) and \( S_3 \)) and magnitude (\( M_w=5.0, 5.5, 6.0, 6.5, 7.0, 7.1, \) and \( 7.5 \)). It is observed that regardless of the soil class, magnitude has a significant effect on \( E_I^e \) where the energy imparted to structure for \( M_w=7.5 \) becomes very large compared to input energy for smaller magnitudes. This observation is consistent with the energy response analysis using the real records (e.g. [6]). Finally, when the results for two alternative soil classes are compared, it is seen that for softer soils (\( S_3 \)) the values of elastic input energy are almost two times of those corresponding to harder soils (\( S_2 \)).

![Simulation of the 1999 Duzce (Mw=7.1) Earthquake](image2)

Figure 3. Elastic input energy spectra with respect to different magnitudes for site class (a) \( S_2 \) and (b) \( S_3 \). (\( 0=\lt R_{JB} \lt 5 \) km and \( \xi=5\% \))

Fig. 4 presents elastic input energy spectra for scenario event of \( M_w=7.1 \) using \( \xi=5\% \). Investigated parameters are site class (\( S_2 \) and \( S_3 \)) and distance (\( 0< R_{JB} \lt 5, 5< R_{JB} \lt 10, 10< R_{JB} \lt 20, R_{JB} \gt 20 \)).
For both soil classes, the increment in the source-to-site distance (R_{JB}) results in the reduction of energy imparted to the structure for all period ranges. Therefore, elastic input energy becomes critical for closer distances especially less than 10 km due to the anticipated near-field effects. Comparison of Fig. 4a and Fig. 4b reveals that as soil condition becomes softer the value of elastic input energy increases for all period ranges. This observation is also in agreement with the analysis results of Decanini and Mollaioli [6] which are obtained based on limited number of real ground motion records.

![Figure 4](image)

Figure 4. Elastic input energy spectra with respect to different source-to-site distance intervals for site class (a) S2 and (b) S3. (\(\xi=5\%\))

Fig. 5a illustrates the variation of R_{IE} (defined in Eq.5) for S2 and S3 classes and scenario event of Mw=7.1 (0=<R_{JB}<5 km) by using two different hysteresis models (i.e. elasto-plastic and Clough Johnston models). For SDOF systems, it is assumed that \(\eta=0.1\) and \(\xi=5\%\). The results show that R_{IE} takes large values in the very short period range (less than approximately 0.3 seconds) followed by a sharp descending trend. For this scenario event, regardless of the hysteresis model and soil class the curves begin to merge around T=0.3 seconds to approach R_{IE}=1. This indicates that within the short period range, or for very rigid structures, inelastic energy demand seems to be very high. That is why generally force-based design strategy, which ensures elastic behavior, is used for these structures. There also seems to be no significant effect of either site class or hysteresis model on the spectral variation of R_{IE}. Hence, it can be stated that except in the short period region, the parameter R_{IE} is mostly stable. This observation is consistent with the recommendations of FEMA 440 [26]. For design purposes, this ratio can be assumed to be 1.0 for moderate and long period ranges, which in turn means elastic and inelastic input energies are practically equal to each other. Fig. 5b shows the variation of R_{HI} (defined in Eq.6) for scenario event with Mw=7.1 (0=<R_{JB}<5 km), alternative soil classes and two hysteresis models considered (with \(\eta=0.1, \xi=5\%\)). It is observed that as the period of structure increases, R_{HI} firstly increases with a sharp slope up to a transient corner period (0.35 for S2 and 0.65 for S3) and then decreases with an approximately constant slope for each soil type. This is consistent with the fact that larger events create enhanced longer period response. The effect of site conditions is also present in all period ranges. It is also observed that the values of R_{HI} from S3 soil class are larger than those corresponding to S2 soil class for most period ranges with some exceptions in the short period range for both hysteresis models. The effect of hysteresis model is observed for the whole period ranges while Clough model provides larger hysteresis to input energy ratio at periods larger than the transient corner period corresponding to each soil type. For periods less than the transient corner period elasto-plastic model provides larger R_{HI} values.
Fig. 6 presents the variation of inelastic input energy for scenario event of Mw=7.1, elasto-plastic model and two alternative soil classes using different strength factors. For periods less than almost 0.25 seconds, as the strength factor increases, inelastic energy slightly decreases while the opposite is valid for larger periods. For site class S2, the effect of strength factor is significant within a relatively short period band (1-1.6 seconds). For site class S3, it is seen that the effect of strength factor is generally more significant and effective for a wider period band (0.3 to 2.1 seconds) when compared to S2. Overall, the results for different soil classes demonstrate that softer soil conditions (S3) provide larger inelastic energy compared to stiffer soil conditions (S2).

![Figure 5.](image5.png)  
**Figure 5.** Spectral variation of (a) $R_{IE}$ (b) $R_{HI}$ with respect to different site classes and hysteresis models for scenario event with Mw=7.1, (0=<RJB<5 km) ($\eta=0.1$, $\zeta=5\%$)

![Figure 6.](image6.png)  
**Figure 6.** Inelastic input energy spectra for soil class (a) S2 and (b) S3 using an elasto-plastic model and different strength factors for scenario event of Mw=7.1 (0=<RJB<5 km and $\zeta=5\%$)

**Conclusions**

This study focuses on the evaluation of energy-related parameters, particularly input energy, by considering the dynamic analysis of elastic and inelastic SDOF systems subjected to a simulated ground motion dataset. Similar previous studies were performed using real ground motion records. However, the conclusions of those studies were not fully generalized either due to scarcity of data (especially for large magnitude and short distances) or the large scatter due to selection of records from 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 such as 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 results of this study seem to augment the results
of previous studies while they are consistent with the physical conclusions. The numerical observations herein encourage the use of simulated ground motions to develop simple and practical energy-based design and evaluation procedures for structural systems.

Acknowledgments

This study is partially funded by JICA-SATREPS through the MarDiM project entitled “Earthquake and Tsunami Disaster Mitigation in the Marmara Region and Disaster Education in Turkey”.

References


