An evolutionary-based approach to synthesize earthquakes using de-noised small earthquakes - simulating the 2003 Bam earthquake (Iran)

Yasser ESLAMIAN[1)*)], Mohammad Reza ADLPARVAR[2)], Mohsen BOZORGNASAB[3)] &
Mohammad Ali SADREDINI MEHRJARDI[4)]

[1)] Civil Engineering Department, Iran University of Science and Technology, Tehran, Iran;

[2)] Technical & Engineering Faculty of Qom University, Qom, Iran;

[3)] University of Mazandaran, Mazandaran, Iran;

[4)] Islamic Azad University of Abarkooh, Abarkooh, Yazd, Iran;

[*)] Corresponding author, y_eslamian@iust.ac.ir

KEYWORDS

Empirical Green's function method
Elastic response spectra
Genetic algorithm
Bam earthquake

Abstract

The main objectives of this article are to develop a technique to find source models that allow one to replicate observed strong ground motion records. The empirical Green's function is used for synthesizing process. A genetic algorithm is applied to reduce the differences between synthesized and recorded data in the form of elastic response spectra and consequently to obtain appropriate seismological parameters for simulation procedure. Also, some other parameters like the peak ground acceleration, peak ground velocity, Arias intensity, and strong motion duration are validation of the results. The small earthquakes used in the empirical Green's function method are de-noised to improve the efficiency of the method. Relative good match of the simulated and recorded data confirms the ability of proposed technique to generate suitable synthetic seismograms. As a case study, proposed technique is applied to synthesize the 2003 Bam earthquake at two stations, Mohammad-Abad and Abaragh stations. This method can be used in performance evaluation of existing and/or new important structures at sites around the causative fault on the basis of the requirements prescribed in the standard codes of practice such as FEMA274, FEMA356 and ASCE7-2005.

Das vorrangige Ziel dieser Arbeit ist es, eine Methode zur Auffindung von Herdmodellen zu entwickeln, die es erlauben, Aufzeichnungen von starken Bodenbewegungen zu replizieren. Für diesen Modellierungsprozess wird die empirische Green'sche Funktion verwendet. Ein genetischer Algorithmus wird angewandt, um die Abweichungen zwischen den modellierten und den aufgezeichneten Daten innerhalb des elastischen Frequenzspektrums zu minimieren und somit entsprechende seismologische Parameter für den Simulationsprozess zu erhalten. Ebenso werden andere Parameter wie die Spitzenwerte für die Bodenbeschleunigung und die Geschwindigkeit, die Intensität nach Arias und die Bewegungsdauer zur Validierung der Ergebnisse herangezogen. Die schwachen Erdbeben, welche in der empirischen Green'schen Funktion verwendet werden, sind rauschfrei, um die Effizienz der Methode zu steigern. Eine relativ gute Übereinstimmung zwischen den modellierten und den aufgezeichneten Daten bestätigt das Potential der vorgeschlagenen Methode zur Erzeugung passender Modellseismogramme. Als Fallstudie wird die vorgeschlagene Methode zur Modellierung des Erdbebens in Bam im Jahr 2003 an zwei Stationen, Mohammad-Abad und Abaragh, angewandt. Diese Technik kann verwendet werden, um das Verhalten von bereits existierenden und/oder neuen wichtigen Strukturen in Gebieten um die Störungszone basierend auf den Anforderungen von standardisierten Verfahrensregeln wie etwa FEMA274, FEMA356 und ASCE7-2005 zu bewerten.

1. Introduction

Various methods for estimating ground shaking have been suggested in the literature over the last decade. Theoretically, the first calculation of strong motion was made by Aki (1968) and Haskell (1969). They used a kinematic source model for propagating dislocation over a fault plane in an infinite homogeneous medium with five parameters, the fault length and width, rupture velocity, final offset of dislocation and rise time which were included in the their model (e.g. Irikura, 1983).

The point source method introduced by Brune (1970) and extended by Boore (1983) is widely used in ground motion modeling for engineering purpose. Despite the popularity of this approach, the point source approximation is unable to characterize key features of large earthquakes such as their long duration (Beresnev and Atkinson, 2002). Meanwhile, the finite fault method that is developed by Irikura (1983) and Beresnev and Atkinson (1997) can solve some of the problems of the point source model.

It is possible to generate synthetic ground motion assuming an appropriate scaling of the time histories and adding them by proper delays for representing propagation of fault rupture (Anderson, 2001). The use of recording of small events for studying large earthquakes was introduced by Hartzell (1978) as empirical Green's function (EGF).

The EGF approach can be applied both in direct and inverse problems. In direct problems, this technique is widely used in strong motion simulation of expected future events. Some seismologists like Irikura (1983), Joyner and Boore (1986); Boatwright (1988); Kanamori et al. (1993); Tumarkin et al. (1994); Valle'e (2004); Hutchings et al. (2007) and Nicknam et al. (2009) have utilized this approach to synthesize strong motions. In the inverse problems, adopted in this study, EGF helps to estimate source information such as slip distribution on a fault (Plicka, 2003). Some investigators such as Mueller, (1985), Frankel et al., (1986), Mori and Frankel (1990), Velasco et al. (1994), Courboulex et al. (1997) , Plika and Zahradnik (2002) and Nicknam et al. (2009) have used an EGF model by which only limited numbers of small earthquake are required.

One of the main merits of EGF approach is that, the effect of surface soil overlying bedrock on earthquake ground motions, particularly in the high frequency range, is directly taken into account (Lam et al., 2000). Hutchings (1991) used empirical Green's functions to constrain propagation path and site response information and proposed a range of simple kinematic rupture models to describe the source in predicting strong ground motion for the full time history. This simple earthquake model was tested by Jarpe and Kasameyer (1996) for the 1989 Loma Prieta earthquake with source parameters determined from different studies of the earthquake. Wu (1978) and Hutchings and Wu (1990) examined the theoretical relation between rupture parameters and synthesized seismograms using an exact solution to the representation relation, in the frequency and time domain that uses empirical Green's functions. It is noticeable that, empirical Green's functions from all locations along a fault of interest are not practically possible. Also, EGFs may originate from sources with a focal mechanism different from the desired mechanism, while Hutchings and Wu (1990) found that the variability in ground motion due to differences in source location and/or focal mechanism solutions are much less than that due to the site response. Hutchings (1991, 1994) and Jarpe and Kasameyer (1994) interpolated the source locations of empirical Green's functions to fill in the fault. They pointed out that this interpolation works quite well.

It should be pointed out that the EGF approach is chosen here to synthesize earthquakes at two sites, Mohammad-Abad and Abaragh stations, far away from the causative source. Because of at region under study many seismological source parameters and path effects were unclear, it is beneficial to use the EGF method instead of using the more advanced and more appropriate full-wavefield methods. Empirical Green's functions include the actual effects of velocity structure, attenuation, and geometrical spreading (Hutchings et al., 1997). Moreover, at two selected stations there were sufficient recorded after-shocks to use EGF method for synthesizing earthquakes.

The first part of our paper introduces the considered case study, in the Bam region. Thereafter, the objectives and scopes of the paper are stated. Then the paper flowed by discussion on the GA and small earthquakes denoising procedures. Finally, the results are discussed and some comparisons and sensibility analysis are made.

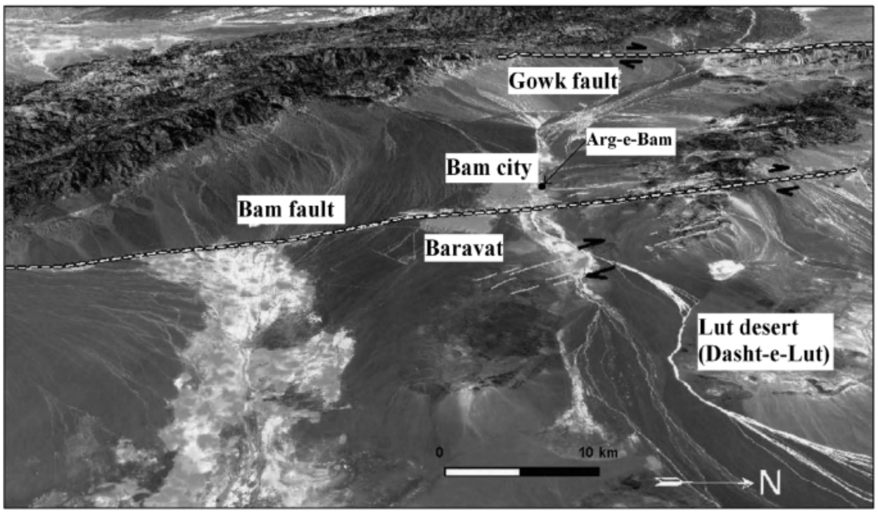

Figure 1: Shaded relief map of the Bam region and location of the Arg-e-Bam, a historical adobe building, and Gowk and Bam faults within the Lut desert.

2. A case study- the 2003 Bam earthquake at far source site

On December 26, 2003, an earthquake Mw 6.5 struck Bam city, one of the historical towns in Iran, causing large structural damage and loss of human life. It was reported by the U.N. Office for the Coordination of Humanitarian Affairs (OCHA) that the earthquake caused approximately 43,200 fatalities and approximately 20,000 injuries. About 75,600 people (14,730 house-holds) were displaced (EERI Special Earth-quake Report, 2004).

The city of Bam is located on the eastern side of the Gowk fault and to the west of the strike slip fault systems bordering the Lut desert, which lies in the south-eastern part of Iran. On both eastern and western sides of the Lut desert (Dasht-e-Lut), there are systems of N–S right-lateral strike-slip faults that accommodate ~13–16 mm/yr of N–S right-lateral shear on a part of rigid Eurasia, between central Iran and western Afghanistan (Jackson et al., 2006) (Fig. 1). On the Gowk fault zone,

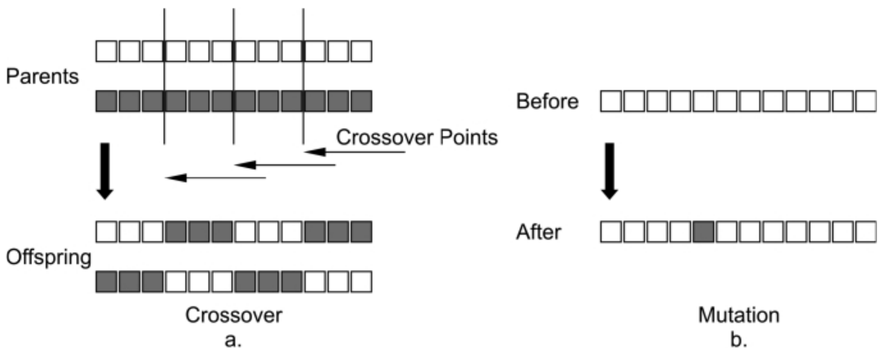

Figure 2: Genetic operators, crossover (a.) and mutation (b.).

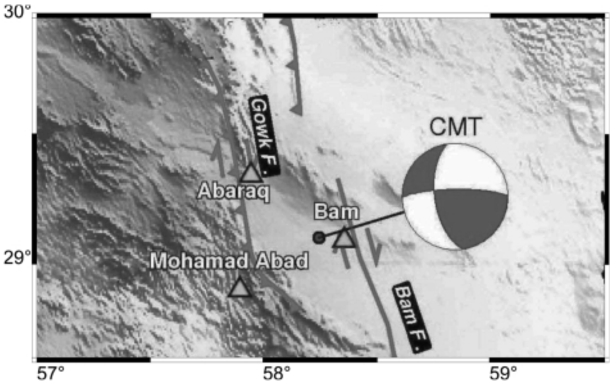

Figure 3: Location of the stations used in this study: Mohammad-Abad and Abaragh stations, and proposed Harvard CMT epicenter location and fault mechanism for the 2003 Bam earthquake.

several earthquakes have occurred during the last two decades; in 1981 (Mw 6.6 and 7.0), 1989 (Mw 5.8) and 1998 (Mw 6.6). The coseismic surface ruptures and focal mechanisms of these earthquakes, together with their associated geomorphology, document the current activity in this zone (Jackson et al., 2006); however, historically, there are no recorded earthquakes at Bam. The notable point is that Arg-e Bam, a historical adobe building, which was destroyed in the Bam earthquake, stood unharmed for more than ten centuries (Talebian et al., 2004).

Field surveys carried out by Talebian et al. (2004) in the week after the earthquake found no major surface rupture but showed small-scale fissuring along the fault trace south of the Posht-rud river, and along a 5 km lineament north of the river. These observations suggested that the rupture had occurred at on a buried fault associated with the surface traces (Talebian et al., 2004). Surprisingly, the more detailed studies by Talebian et al. (2004) showed that the main rupture in the earthquake did not occur on a fault relating to the obvious surface traces, but on a geologic structure further west, in a region with complete absence of surface features. This fault lies immediately south of the Bam and extends directly beneath the city at its northern end (Talebian et al., 2004).

3. Objectives and scopes

The currently used methods for determining ground motions are mostly based on the traditional probabilistic seismic hazard analysis (PSHA) approaches by which an attenuation relationship is used for estimating the probabilistic-based sitespecific spectral response acceleration (Sadigh et al. 1993; Fukushima et al. 1990; Abrahamson et al. 1997). The credibility of these approaches depends upon the validity of attenuation law used.

The main objectives of this study are to propose a technique for simulating strong motions at far field site aimed at generating strong motions more consistent with the source-path and site conditions. Synthesized data applying the EGF method is used to compensate for the lack of actually recorded data in the region under study.

4. Proposed genetic algorithm-based technique

One method to obtain a solution in non-linear inversion problems and a lot of imprecise variables is known to be genetic algorithm (GA). A generic algorithm is a computer simulation of natural evolutionary processes to solve search and optimization problems.

Jimenez et al. (2005) applied the GA method in an inversion method to find earthquake source parameters and attenuation factors. Wu et al. (2008) used the GA approach to find focal mechanism in Taiwan. Nicknam et al. (2009) applied the GA approach to find appropriate source models to the synthesize 2006 Silakhor earthquake. In this study, a genetic algorithm is developed as an optimization tool through which the seismological source parameters are estimated. A GA technique is developed to fit the elastic response spectra of three components of synthesized and observed ground motions in the frequency band between 0.2-25 Hz. The differences between simulations and observations are gradually reduced through the process of comparing the corresponding acceleration response spectra (5% damping ratio) at each period.

The GA works with the binary encodings, chromosomes, and it starts with a group of chromosomes known as the population. Each chromosome consists of several bit string parameters incorporated into the GA procedure. In this study the binary strings are converted to real numbers using (1).

$$Z = \min_Z + \frac{\max_Z - \min_Z}{2^{n_j} - 1} \times d, \quad (1)$$

Z : Phenotype of bit string
$\max_z$: Maximum value of the parameter
$\min_z$: Minimum value of the parameter
d : Decimal value of bit string
nj : Length of bit string

Station	Longitude (°E)	Latitude (°N)	Orient. L,T-90 (in °)[2]	No of EGFs recorded	Geological Classification	
					Standard NO. 2800[1]	NEHRP CODE
Mohammad-Abad	57.888	28.908	N 350 E	3	II	C
Abaragh	57.94	29.34	72	4	N.R.	N.R.

1. Iranian Code of Practice for Seismic Resistant Design of Buil dings (Standard No. 2800)
2. Recorded horizontal components angle from north (T Component angle = L Component angle + 90 °)
N.R.: Means not reported.

Table 1: Station names, locations and number of EGFs recorded at stations in 2003 the Bam earthquake used in this study.

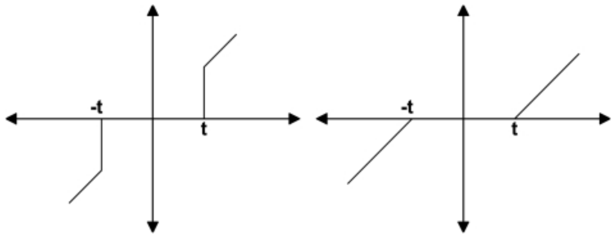

Figure 4: Definition of TH for hard-thresholding (left) and TS for soft-thresholding (right).

The simplest form of genetic algorithm involves three types of operators: selection, crossover (single point), and mutation.

Selection operator selects chromosomes in the population for reproduction. The fitter the chromosome, the more times it is likely to be selected to reproduce.

Crossover operator randomly chooses a locus and exchanges the subsequences before and after that locus between two chromosomes to create two offspring. The three-point crossover is used as the crossover operator. After the two parent chromosomes are selected, three random numbers, less than or equal to chromosome length, are generated and the bits associated with these numbers are used as the boundaries for dividing chromosomes into four sections. Thereafter, the second and forth sections of the two selected chromosomes are exchanged (Fig. 2a).

Mutation operator randomly flips some of the bits in a chromosome. In this study a simple mutation operator is used, in which a random number less than or equal to the chromosome length is generated and the value of the associated bit is flipped (Fig. 2b).

The main steps of the proposed GA-based algorithm are described here. The initial population for first generation is generated randomly. Starting with this population the main GA loop is initiated. Each chromosome in the population contains the seismological parameters. These parameters are the objectives for the GA to optimize. The parameters are entered into the synthesizing program, EMPSYN, which operates based on the EGF approach. The outputs of this stage are the acceleration time histories (Two horizontal components and a vertical component). The time histories are analyzed in order to generate the elastic response spectra (5% damping ratio). The fitness value will be relative inversely to the error between the spectra of the synthesized and recorded acceleration time histories. The mathematical forms for evaluating errors and fitness functions, corresponding to each series of model parameters in each generation, using the two horizontal compo-

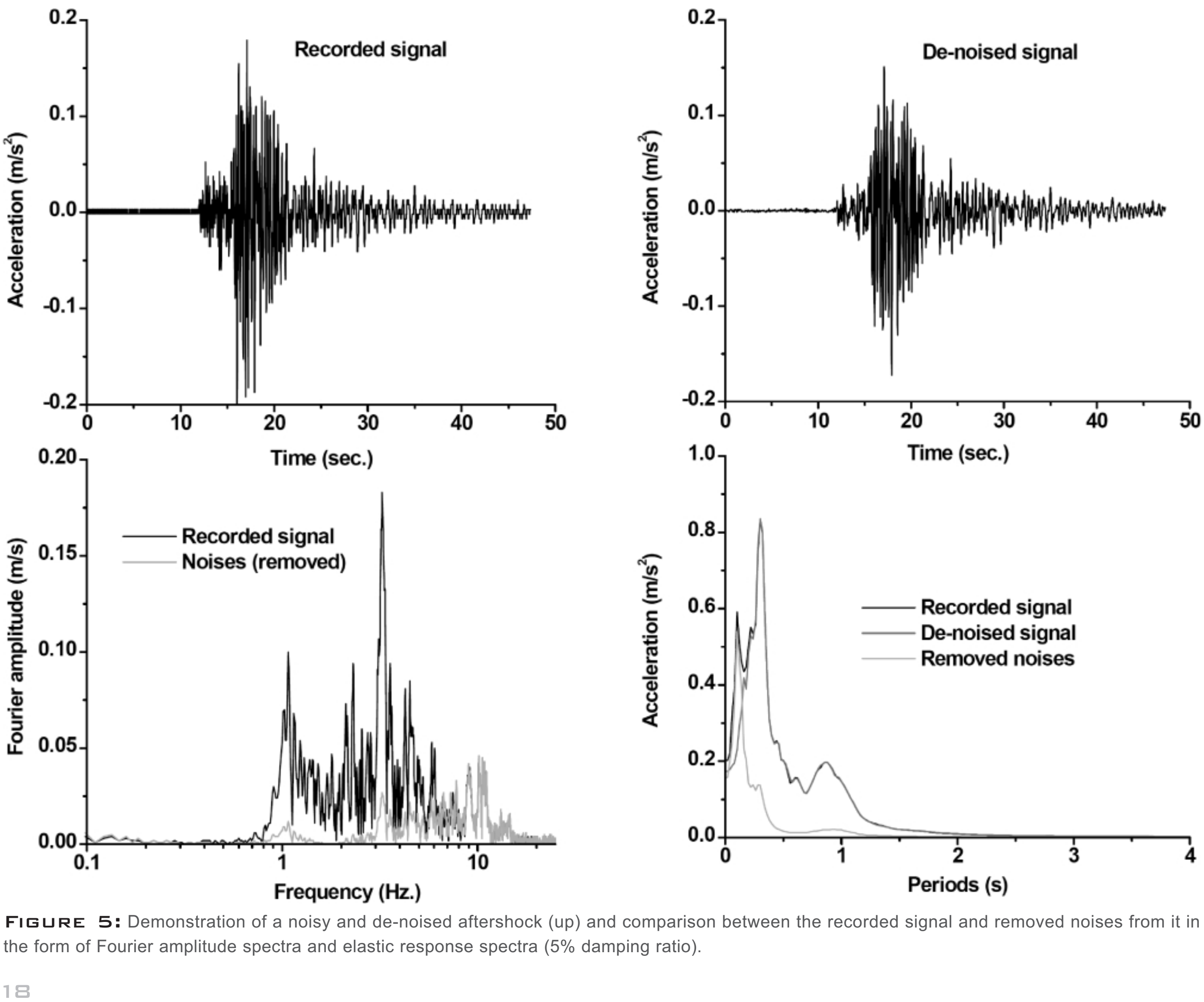

Figure 5: Demonstration of a noisy and de-noised aftershock (up) and comparison between the recorded signal and removed noises from it in the form of Fourier amplitude spectra and elastic response spectra (5% damping ratio).

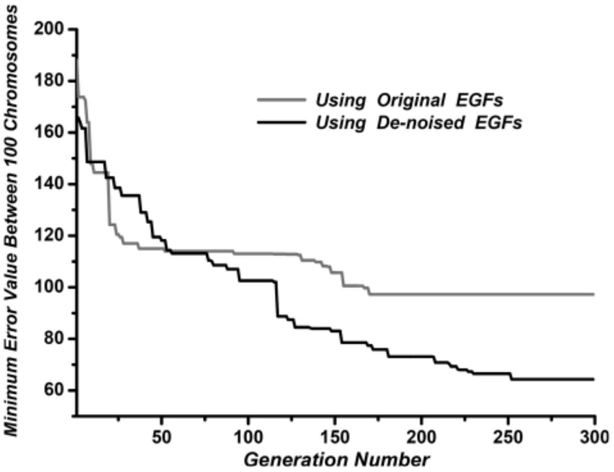

Figure 6: Minimum Error value in each generation.

nents (L, T) and a vertical component (V), are:

$$Error\_Func.=[Err\_Lcomp.+Err\_Tcomp.+Err\_Vcomp.] \quad (2)$$

$$Fitness\_Func.=\frac{1}{Error\_Func.} \quad (3)$$

Where, each of the *Err_Lcomp.*, and *Err_Tcomp.* are calculated using sum of the absolute differences between synthesized and recorded elastic response spectra at each period. *Fitness_Func.* is fitness function defined for GA.

These calculated fitness functions for each population have a major role to selection of best chromosomes and create the next generation (The larger the fitness value of the chromosome, the more chance it has to be selected). The GA will be terminated if the number of generations when the population is no longer improved meets a specific number (n_g).

In general, 12 parameters of the earthquake are optimized in this process. These are listed as follows: 3 parameters for hypocenter location, 4 parameters for distances of edges of the fault from hypocenter, 1 parameter for the sub-fault dimension, 1 parameter for the magnitude of the earthquake and 3 parameters for the focal mechanism (strike, dip and rake angels) of the ground motion. For all these parameters upper and lower bounds are assumed. The bounds for values of the parameters are determined according to those of other references.

5. Source of data

A number of aftershocks have been recorded at some stations surrounding the Bam earthquake epicenter of December 2003 (Building and Housing Research Center in Iran, BHRC). The selected stations, Mohammad-Abad and Abaragh, including sufficient recorded aftershocks are sufficiently far away from the causative fault, so their recorded time histories were

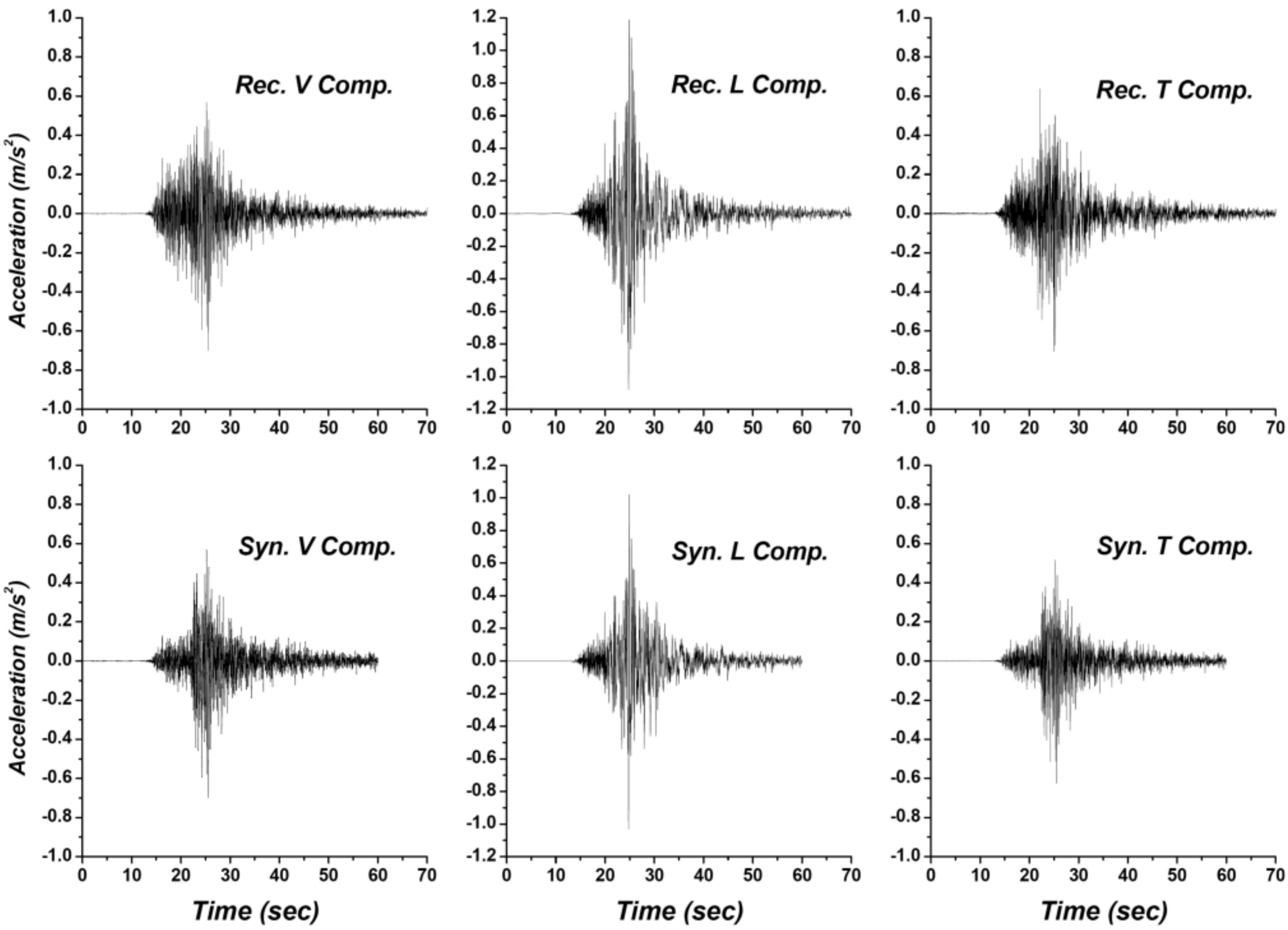

Figure 7: Synthesized and recorded strong motions at Mohammad-Abad station.

less influenced by near field problems. Figure 3 shows the location of stations used in this study for simulating earthquake using EGF method.

Table 1 shows the selected stations along with their locations, the number of aftershocks recorded at each station and the site soil conditions which are classified according to the Iranian standard No. 2800 which is compatible with the NEHRP Code (2001). The geology beneath the site is assumed to respond linearly, therefore, soil nonlinearity is not taken into account in this study. This is the same assumption made by Hutchings et al. (1997).

The reason for selecting these two stations is that there exist enough usable EGFs recorded in these to stations; meanwhile the other stations recorded only the main shock during the 2003 Bam earthquake.

	Recorded			Synthesized		
	V Comp.	L Comp.	T Comp.	V Comp.	L Comp.	T Comp.
Peak Ground Acceleration (m/sec^2)	0.68	1.24	0.67	0.69	1.03	0.61
Peak Ground Velocity (cm/sec)	2.70	11.94	3.70	2.65	9.62	2.86
Peak Ground Displacement (cm)	0.70	2.51	0.96	0.71	1.96	0.61
Arias Intensity (m/sec)	0.066	0.171	0.065	0.052	0.212	0.051
Significant Duration (sec)	19.9	14.2	22.1	17.6	13.1	20.6

Table 2: Comparison of synthesized and recorded time histories parameters at Mohammad-Abad station.

6. Aftershocks de-noising process

In general, the measurements made in geophysical exploration are contaminated by unavoidable noises. A signal-to-noise ratio (SNR) is obtained by the ratio of the signal and noise spectra. Low signal to noise may become an inhibiting factor when trying to estimate ground motion and site response and its effects on large structures with natural frequencies below 0.5 Hz (Rodgers et al., 2006).

Donoho and Johnstone (1995) pioneered the work on filtering of additive Gaussian noise using wavelet thresholding. From their properties and behavior, wavelets play a major role in image compression and image de-noising. Wavelet coefficients calculated by a wavelet transform represent change in the time series at a particular resolution. The term wavelet thresholding is explained as decomposition of the data into wavelet coefficients, comparing the detail coefficients with a given threshold value, and shrinking these coefficients close to zero to take away the effect of noise in the data. The time history is reconstructed from the modified coefficients. This process is also known as the inverse discrete wavelet transform. During thresholding, a wavelet coefficient is compared with a given threshold and is set to zero if its magnitude is less than the threshold; otherwise, it is retained or modifieddepending on the threshold rule. Thresholding distinguishes between the coefficients due to noise and the ones consisting of important signal information.

The choice of a threshold is an important point of interest. It plays a major role in the removal of noise. There exist various methods for wavelet thresholding, which rely on the choice of a threshold value. It is necessary to know about the two general categories of thresholding. They are hard-thresholding and soft-thresholding types. In the hard-thresholding TH can be defined as (Donoho, 1995):

$$T_H = \begin{cases} = x & if \quad |x| < t \\ = 0 & otherwise \end{cases} \tag{4}$$

Here t is the threshold value. Thus, all coefficients whose magnitude is greater than the selected threshold value *t*, remain as they are and the others with magnitudes smaller than t are set to zero. It creates a region around zero where the coefficients are considered negligible. Soft-thresholding is where the coefficients with greater than the threshold are shrunk towards zero after comparing them to a threshold value. It is defined as follows (Donoho, 1995):

$$T_S = \begin{cases} = sign(x)(|x| - t) & if \quad |x| < t \\ = 0 & otherwise \end{cases} \tag{5}$$

Here *t* is the threshold value. A plot of T_H (left) and T_S (right) are shown in Figure 4.

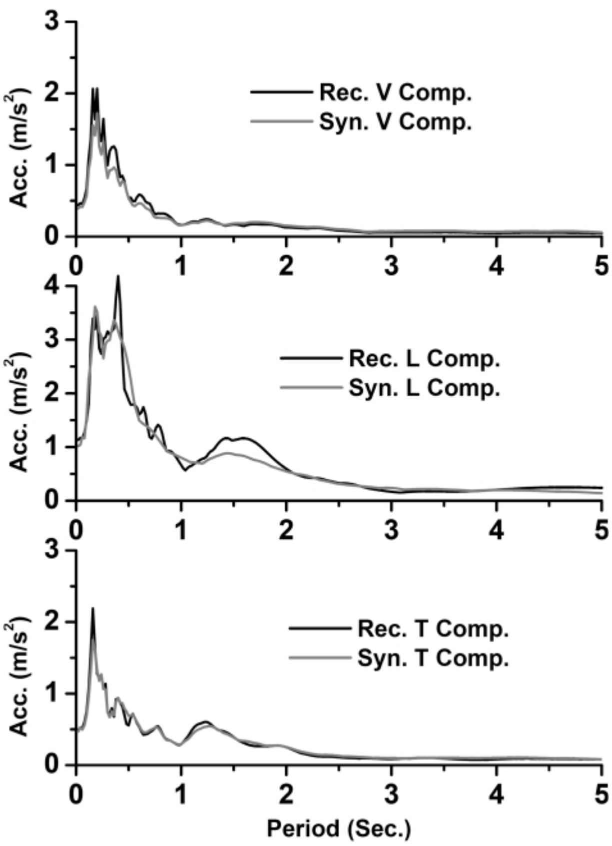

Figure 8: Comparison illustration of the synthesized time series and recorded data in terms of elastic response spectra (5% damping ratio) at Mohammad-Abad station.

The soft method is much better and yields a smaller minimum mean squared error compared to the hard form of thresholding (Donoho, 1995). Therefore, in this article the Soft-thresholding method is employed for aftershock de-noising process. All of calculations are done using MATLAB software. Figure 5 shows a typical noisy and de-noised aftershock used in the simulation process, EGF method, in this study. As shown in the figure (down) high frequencies noises removed from recorded signal. Also, as shown in the figure (below - right) removing theses noises haven't any significant effect on the elastic response spectra of recorded and de-noised signals.

7. Simulating the 2003 Bam earthquake at far source sites

The computer code EMPSYN (Hutchings, 1988), was used for simulating far field sites in this study. It calculates synthetic seismograms by numerically computing the discrete representation relation with empirical Green's functions (EGF). The formula used has the following form (Hutchings et al., 2007):

$$U(X,t)=\sum_{i=1}^{N}\frac{\mu_i A_i S(t')_i}{M_{0i}^{e}}*e_n(X,t'-t_r)_i \qquad (6)$$

where X and t are position and time in space relative to the hypocenter and the origin time of the synthesized earthquake. N is the number of sub faults and i denotes the values at an element. A_i is the area of an element of the fault such that sum of all Ais equals the total rupture area. μ_i is the rigidity at an element. $S(t')_i$ is the desired slip function, i.e. Kostrov slip function with variable rise time and constant stress drop (Hutchings et al., 2007), at an element analytically deconvolved with the step function. $e_n(X, t')_i$ is the recording of a small earthquake with effectively a step source time function, and interpolated to have a source and origin time at the location of the i_{th} element. t' is relative to the origin time of the synthesized earthquake. t_r is the time that rupture reaches from the hypocenter to the element. It is the radial distance from the hypocenter of the synthesized earthquake divided by the rupture velocity, which can be a function of position on the fault. M^e_{0i} is the scalar seismic moment of the source event, and * stands for the convolution operator. U has the same units as e_n (Hutchings et al., 2007).

Since the simulated seismograms are supposed to be used in response analysis of existing structures at the site of interest, the response spectrum of each simulated component is compared with corresponding recorded data. This approach has been used by many investigators as a validation procedure (e.g., Lam et al. 2000, Somerville et al. 2000, Motazedian et al. 2006, Hutchings et al., 2007).

The three components of strong motion, L, T and V, recorded at Mohammad-Abad station located at about 47 km from

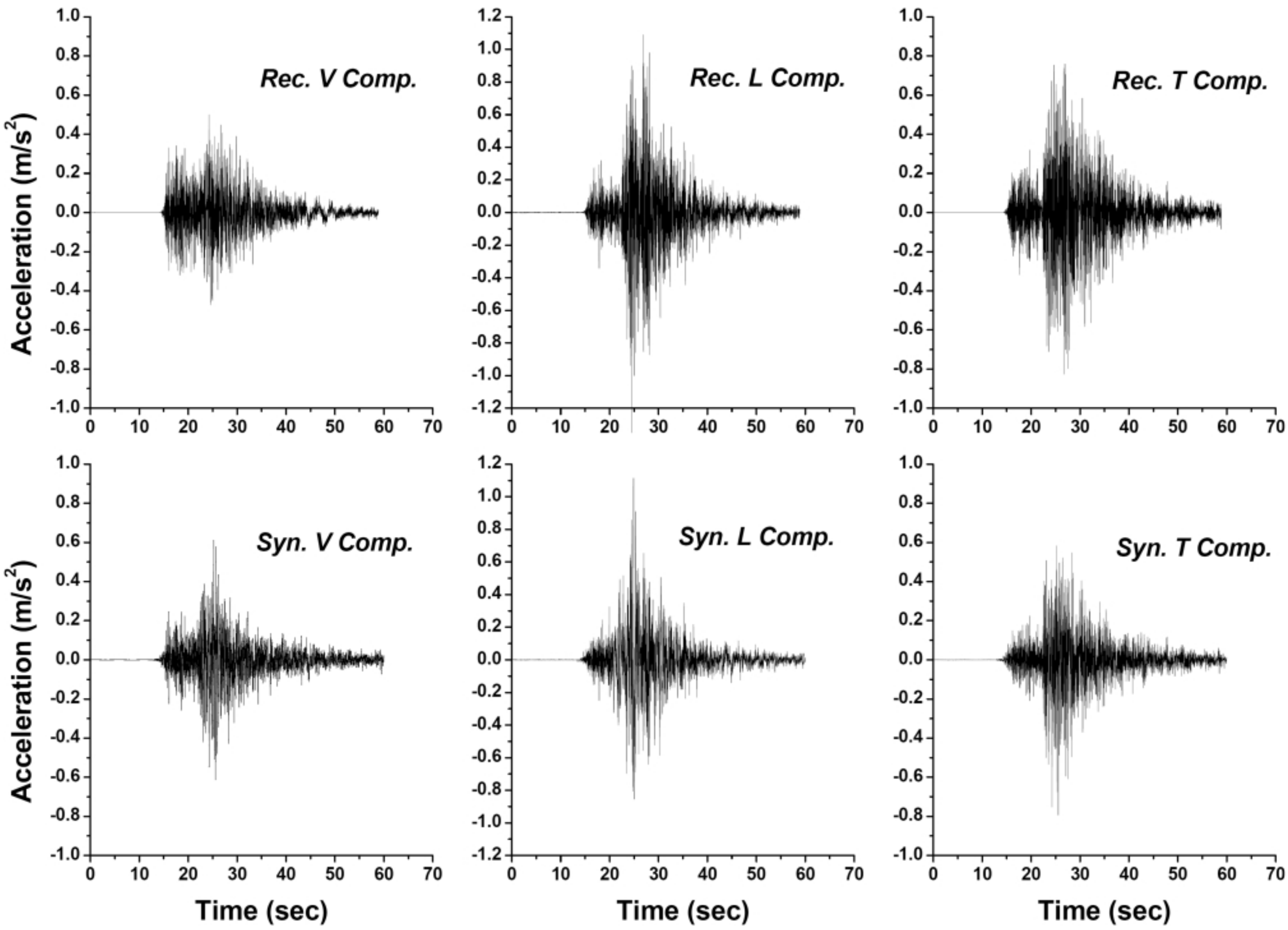

Figure 9: Synthesized and recorded strong motions at Abaragh station.

the causative fault was chosen for simulating and fitting purposes. The upper and lower bounds of parameters used for the simulation process are chosen consistent with those of other investigators previously estimated for the Bam earthquake (Jackson et al., 2006, Talebian et al., 2004 and Funning et al., 2005).

The process of generating time series and comparing with those of the recorded data were continued until the residuals, the differences between elastic response spectra of synthesized and recorded data, Equation 2, are minimized. The utilized GA information is summarized below.

Population size in the GA optimization was set to 100, crossover rate to 0.8 and mutation rate to 0.08 by experience. Three-point crossover, as mentioned above, together with a roulette wheel selection was used. The number of bits for each chromosome was set to nj =8. The maximum number of generations used as the termination criterion was n_g=50.

Figure 6 shows the minimum error value, in each generation which contains 100 chromosomes.

As it can be seen, the differences between the estimated and observed data are reduced as the generation number increases, confirming the applicability and effectiveness of the technique used in estimating the seismological parameters such as fault dimensions, hypocenter location and rupture parameters. As shown in Figure 6, the curve becomes asymptotic to a horizontal line expressing the adequacy of modifying process. This figure shows that using de-noised EGFs in empirical Green function method can reduce residuals (Equation 2) which ends with better response spectral fits. It is worth mentioning that, since the noisy aftershock contains high frequencies, then calculated results, seismograms, have high frequency noises. This issue causes the GA process to ends with higher error residuals thus less agreement between synthesized and recorded data over the whole response spectrum.

8. Validation of the results, results and discussion

Traditionally, seismic provisions in building codes such as FEMA274 (Chapter 2.6) and ASCE 7-2005 (chapter 21, page 206) and FEMA 356 (chapter 1.6), state that, the performance evaluation of existing and/or new structures is permitted to be used by design response spectra and in particular cases the specific site response spectrum. For this reason and since the results of this study are supposed to be used in performance evaluation of important structures in the region under study, the validation process has been done by comparing the response spectra corresponding to the synthesized three components time histories at selected stations for validation purposes.

We simulated three components of recorded ground shakings at one station and predicted those at other stations for validation purpose. The source parameters acquired from GA analysis at Mohammad-Abad station were used to synthesize the strong ground motion at Abaragh station. The inverse problem was not solved at this station and a forward simulation was made incorporating the estimated source parameters and

Longitude	Latitude	Depth	Moment	Focal mechanism	Reference
(deg.)	(deg.)	(km)	Mw	Strike, Dip and Rake (in °)	
58.365	29.050	N.R.	6.5	N.R.	BHRC[1]
58.240	29.100	15	6.6	172 , 59 , 167	Harvard CMT[2]
58.266	29.010	14	6.5	174 , 88 , 178	NEIC[3]
58.353 58.357 58.356	29.037 29.038 29.040	5.2 5.5 6.4	6.5 6.6 6.6	354 , 84 , -178 355 , 86 , -178 355 , 86 , -178	Funning et al.
58.294 58.294	28.864 28.972	5 6	6.1 6.6	180 , 30 , 090 357 , 88 , -166	Talebian et al.
58.340	29.100	12	6.5	357 , 84 , -165	This study (GA)

N.R.: Not reported
1. Building and Housing Research Center, Iran (BHRC)
2. Harvard Centroid Moment Tensor (CMT)
3. National Earthquake Information Center (NEIC)

Table 3: The hypocenter and focal mechanism parameters of the main shock estimated by other references and those of this study.

	Funning et al. (2005) Uniform Slip	Funning et al. (2005) Variable Slip	Funning et al. (2005) Variable Slip and rake	This study (GA)
Rupture Length	12.0 km	12.0 km	20.0 km	18.0 km
Rupture Width	8.1 km	8.6 km	15.0 km	8.10 km
Rupture Area	97.2 km^2	103.2 km^2	300 km^2	146 km^2

Table 4: Fault dimensions purposed by other references and those of this study.

Fault edges from hypocenter (km)				Hypocenter location		
Up	Right	Down	Left	Longitude (°E)	Latitude (°N)	Depth (km)
2.4	12.0	5.72	6.0	58.34	29.10	12

Table 5: Extracted fault characteristics using GA method.

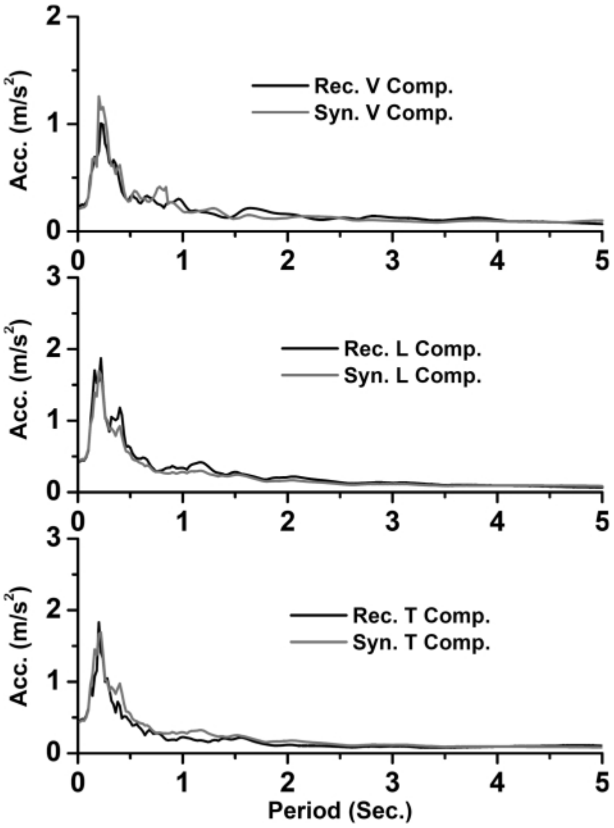

Figure 10: Comparing the predicted three components of strong motions with those of the recorded data at Abaragh Station in the form of elastic response spectra (5% damping ratio).

using the site specific EGFs. It is quite clear that, the more reliable results the more number of synthesized and recorded seismogram used in fitting process. It is notable that, only two far field stations with recorded aftershocks were available in the region under study, while the proposed technique ends with more reliable results in regions if more data were available (e.g. Nicknam et al., 2009).

Figure 7 shows the observed and simulated acceleration time histories at Mohammad-Abad station. The elastic response spectra (5% damping ratio) corresponding to the simulated three components of strong motion and those of the recorded data at this station are compared as demonstrated in Figure 8. Table 2 shows the comparison between three components (L, T and V) synthesized and recorded time histories parameters at Mohammad-Abad station. However, some of other comparison criteria such as PGA, PGV, Arias Intensity, and strong motion duration show some differences between synthesized and observed data.

To further validate the proposed approach and the adapted input seismological model parameters, the three components of strong motion recorded at Abaragh station, at about 52 km far away from the epicenter, were synthesized using the obtained model parameters from fitting the three elastic response spectra at Mohammad-Abad station. Figure 9 shows the observed and simulated acceleration time histories at Abaragh station. Finally, Figure 10 demonstrates the comparison of elastic response spectra (5% damping ratio) corresponding to simulated strong motions at Abaragh station with those of the recorded data.

The satisfactory agreement of simulated and observed time series in the form of elastic response spectra at Abaragh station confirms the validity of the technique to be used in simulating ground motions at far field in the region under study.

As already mentioned, the parameter values previously estimated by other studies (e.g. Talebian et al. 2004, Funning et al., 2005 and Jackson et al., 2006), were used as upper-lower bounds in GA procedure. The appropriate values of seismological parameters like fault dimensions, hypocenter location on fault plain, focal mechanisms (strike, dip and rake angle) and ratio of rupture velocity to shear wave velocity are evaluated through proposed GA technique for synthesizing method, Hutchings' model. Table 3 and 4 illustrate the comparison between adapted seismological model parameters and those of suggested by other investigators. Finally, Table 5 presents the hypocenter location and fault dimensions extracted from GA.

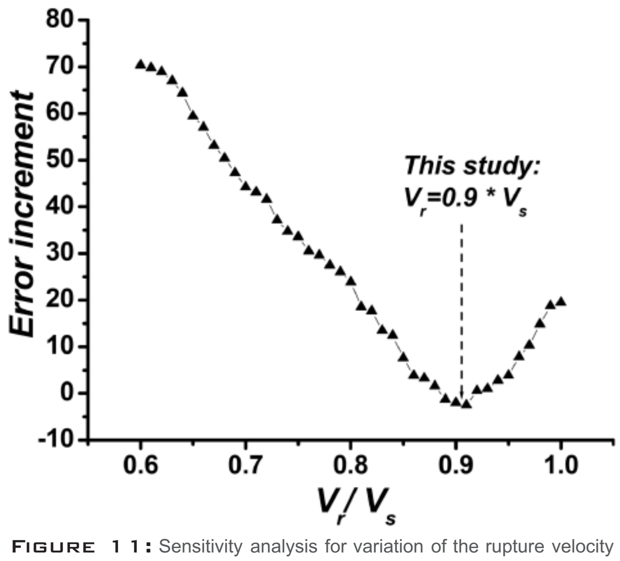

Figure 11: Sensitivity analysis for variation of the rupture velocity respect to the shear wave velocity.

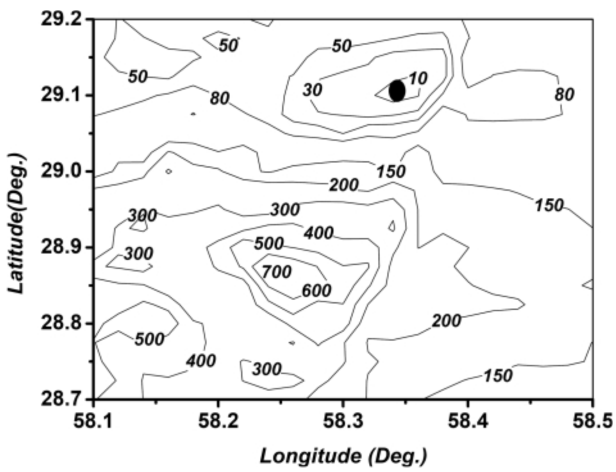

Figure 12: Sensitivity analysis for variation of epicenter location (contour lines show the increment of error values).

9. Sensitivity analysis of model parameters

A sensitivity analysis is performed for understanding the effect of model parameter changes on the residuals of fitting simulated and observed data (Equation 2). The aforementioned model parameters such as rupture velocities, epicenter location, focal mechanism (strike and dip), P-wave velocity in depth and fault dimensions are individually changed and their influences on the error values are calculated, while the remaining estimated parameters are kept constant. As already mentioned, the error value is defined as difference between the simulated data and those of recorded time series, in terms of elastic response spectra (Equation 2). The model parameters such as rupture velocities, epicenter location, focal mechanism (Strike and Dip) and fault dimensions are individually changed and their effects on the error values are calculated, while the remainder estimated parameters are kept constant. For this purpose and in order to graphically demonstrate the sensitivity of error residuals against the above mentioned model parameters, each parameter is individually changed within a predefined range obtained from previous studies and the error residuals are calculated. The results are shown in a manner that the differences between the optimized version (minimum error value) and those of other values are depicted in vertical axis or on counters. Figures 11, 12, 13, 14 and 15 demonstrate the effects of variation of rupture velocity, epicenter location, fault dimensions, P-wave velocity in depth and the variation of focal mechanism (Strike and Dip) on the error residuals increment (Equation 2) respectively. The circle on each figure reflects the situation corresponding to the values obtained from this study and the contours show the error residuals increment calculated using equation 2. As shown in the figures, incorporating other values for the above mentioned parameters give larger error residuals.

10. Conclusion

In this article, a technique is proposed which allows the simulation of the three strong motion components (L, T and V), recorded at a number of selected stations to be used in seismic evaluation of structures in the region under study. The EGF method is used to synthesize acceleration time histories at a station, Mohammad-Abad, and a GA approach is developed to minimize the residuals from fitting response spectra corresponding to the simulated and recorded data. A wavelet-based algorithm is used for de-noising aftershocks utilizing MATLAB software, which its effects on improving the simulation results are demonstrated. After final results of GA procedure, the results are validated by comparing some other parameters, PGA, PGV, Arias intensity and strong motion duration, of synthesized and recorded data. Also, the extracted parameters from GA process at Mohammad-Abad station is used to synthesize simulated three components of strong motion at another station, Abaragh. In addition, to overcome the effects of noises on the simulation process, the noises of small earthquakes are reduced and the results of this modification were shown on the evaluated error values.

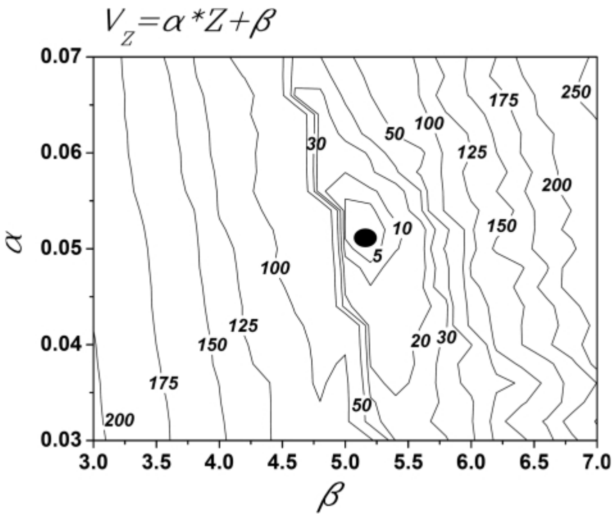

Figure 14: Sensitivity analysis for variation of P-wave velocity in depth, α and β in depth (contour lines show the increment of error values).

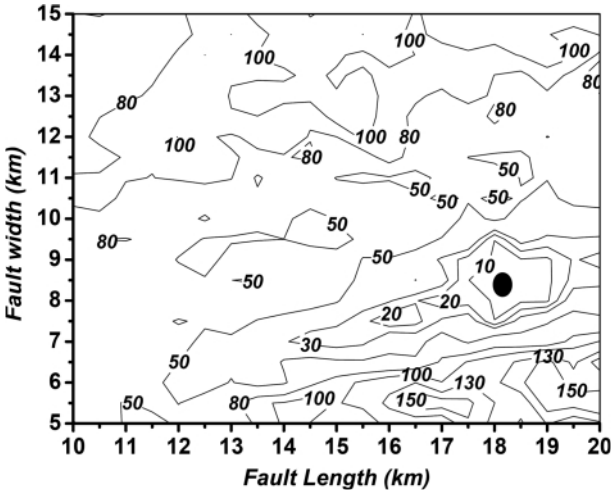

Figure 13: Sensitivity analysis for variation of fault dimensions (contour lines show the increment of error values).

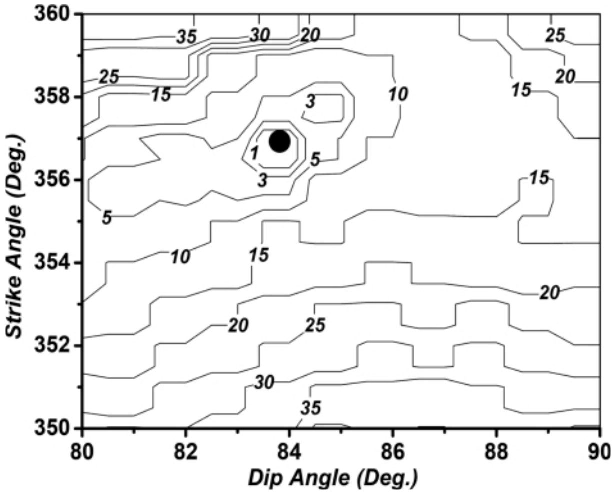

Figure 15: Sensitivity analysis for variation of fault strike and dip angles (contour lines show the increment of error values).

We do not claim that we have found the actual source parameters of the 2003 Bam earthquake and the synthesized seismograms are quite the same as those of recorded data; because the validation procedure is performed based on the elastic response spectra; however, we confirm that the evaluated parameters are suitable for the Hutchings' model to replicate the observed records in region under study; however, The match of elastic response spectra with those of the observed data at the two selected stations, demonstrates the suitability of the estimated seismological parameters and consequently the applicability of the method for regions with lack of reliable data.

The proposed technique can be applied in site-specific studies to be used in retrofitting process of the existing important buildings. It is notable that, the results of this study are not free from uncertainties due to many problems such as variation of source position/orientation, depth and dimensions. However, the method used in this study is regarded as superior to those of traditional approaches to evaluating elastic response spectra from attenuation laws at region under.

Acknowledgment

Our sincere thanks go to Profs. L.J. Hutchings for kindly offering the valuable simulation codes and Dr. Y. Fahjan for giving Windows EMPSYN FORTRAN codes and Dr. E. Adeli Mosabbeb for help us in the GA field. Finally, thank to BHRC for giving the valuable information of the 2003 Bam earthquake.

References

Abrahamson, N.A. and Silva W.J., 1997. Empirical response spectral attenuation relations for shallow crustal earthquakes. Seismic Research Letters, 68, 94-109.

Aki, K., 1968. Seismic displacements near a fault. Journal of Geophysical Research, 73, 5359-5376.

Anderson, J.G., 2001. Handbook of Earthquake and Engineering Seismology, Chapter 57. University of Nevada, Reno, NV, USA.

Arias, A., 1970. A measure of earthquake intensity, in Seismic Design for Nuclear Power Plants (ed. R.J. Hansen), MIT Press, Cambridge, Massachusetts, 438-483.

American Society of Civil Engineers (ASCE) 7-2005. Minimum Design Loads for Buildings and Other Structures, (ASCE 7-2005). (http://www.pubs.asce.org/).

Benjamin J.R., and et al., 1988. A criterion for determining exceedance of the Operating Basis Earthquake. EPRI Report NP-5930. Electric Power Research Institute, Palo Alto, California.

Beresnev, I.A., and Atkinson G.M., 1997. Modeling finite-fault radiation from the ω_n spectrum. Bulletin of the Seismological Society of America, 87, 67-84.

Beresnev, I.A. and Atkinson G.M., 2002. Source parameters of earthquakes in eastern and western North America based on finite-fault modeling, Bulletin of the Seismological Society of America, 92, 695-710.

Bommer, J.J. and Martínez-Pereira A., 1999. The effective duration of earthquake strong motion. Journal of Earthquake Engineering, 3(2), 127-172.

Bommer, J.J. and Martínez-Pereira A., 2000. Strong-motion parameters: definition, usefulness and predictability. Proceedings of the 12th World Conference on Earthquake Engineering, Auckland, Paper no. 206.

Bouchon, M., 1981. A simple method to calculate Green's functions for elastic layered media. Bulletin of the Seismological Society of America, 71, 959-971.

Building and Housing Research Center. Tehran, Iran (http://www.bhrc.ir).

Boore, D.M., 1983. Stochastic simulation of high-frequency ground motions based on seismological models of the radiated spectra. Bulletin of the Seismological Society of America, 73, 1865–1894.

Boore, D.M., 2003. Simulation of ground motion using the stochastic method. Pure and Applied Geophysics, 160, 635–676.

Boore, D.M. and Atkinson, G., 1987. Stochastic prediction of ground motion and spectral response parameters at hard-rock sites in eastern North America. Bulletin of the Seismological Society of America, 73, 1865-1894.

Brune, J.N., 1970. Tectonic stress and the spectra of seismic shear waves from earthquakes. Journal of Geophysical Research, 75, 4997-5010.

Camp, C., Pezeshk, S. and Cao G., 1998. Optimized Design of two-Dimensional Structure Using A Genetic Algorithm. Journal of Structural Engineering, 124, 551-559.

Courboulex, F., Singh, S.K., Pacheco, J.F. and Ammon, C.J., 1997. The 1995 Colima-Jalisco, Mexico, earthquake (Mw 8): a study of the rupture process. Geophysical Research Letters, 24, 1019-1022.

Donoho, D.L., 1995. De-noising by soft-thresholding. IEEE Transactions on Information Theory, 41, 613-627.

Donoho, D.L. and Johnstone, I.M., 1995. Adapting to unknown smoothness via wavelet shrinkage. Journal of American Statistical Association, 90(432),1200-1224.

Earthquake Engineering Research Institute (EERI), 2004. EERI Special Earthquake Report, 2004, Preliminary Observations on the Bam, Iran, Earthquake of December 26 2003.

Federal Emergency Management Agency, 1997. NEHRP commentary on the guidelines for the seismic rehabilitation of buildings (FEMA 274). Available from: http://www.fema.gov/plan/prevent/earthquake/professionals.shtm.

Federal Emergency Management Agency, 2000. Prestandard and commentary for the seismic rehabilitation of buildings (FEMA 356). Available from: http://www.fema.gov/plan/prevent/earthquake/professionals.shtm.

Frankel, A., Fletcher, J., Vernon, F., Haar, L., Berger, J., Hanks, T. and Brune, J., 1986. Rupture characteristic and tomographic source imaging of ML ~ 3 earthquakes near Anza, Southern California. Journal of Geophysical Research, 91, 12633-12650.

Fukushima, Y. and Tanaka, T., 1990. A new attenuation relation for peak horizontal acceleration of strong ground motion in Japan. Bulletin of the Seismological Society of America, 80, 757–783.

Funning, G.J., Parsons, B. and Wright, T.J., 2005. Surface displacements and source parameters of the 2003 Bam (Iran) earthquake from Envisat advanced synthetic aperture radar imagery. Geophysical Research, 110, B09406, doi:10.1029/2004JB003338.

Goldberg, D.E., 1989a. Genetic Algorithms in Search, Optimization, and Machine Learning. Reading, MA: Addison-Wesley.

Goldberg, D.E., 1989b. Sizing populations for serial and parallel genetic algorithms. In J. D. Schaffer (ed.), Proc. 3rd Int. Conf. on Genetic Algorithms. Los Altos, CA, Morgan Kaufmann, 70–9.

Hanks, T.C. and McGuire, R.K., 1981. The character of high frequency Strong ground motion. Bulletin of the Seismological Society of America, 71, 2071-2095.

Hartzell, S., 1978. Earthquake aftershocks as Green's functions. Geophysical Research Letters, 5, I-4.

Haskell, N.A., 1969. Elastic displacements in the near-field of a propagating fault. Bulletin of the Seismological Society of America, 59, 865-908.

Hutchings, L., 1988. Modeling strong earthquake ground motion within earthquake simulation program EMPSYN that utilizes empirical Green's functions, UCRL-ID-105890, Lawrence Livermore National Laboratory, Livermore, California, 122.

Hutchings, L., 1991. Prediction of strong ground motion for the 1989 Loma Prieta earthquake using empirical Green's functions. Bulletin of the Seismological Society of America, 81, 88-121.

Hutchings, L., 1994. Kinematic earthquake models and synthesized ground motion using empirical Green's functions. Bulletin of the Seismological Society of America, 84, 1028–1050.

Hutchings, L., Ioannidou, E., Foxall, W. and Voulgaris, N., 2007. A physically based strong ground-motion prediction methodology; application to PSHA and the 1999 Mw = 6.0 Athens earthquake. Geophysical Journal International, 168, 659–680.

Hutchings, L., Stavrakakis, G.N., Ioannidou, E., Wu, F.T., Jarpe, S. and Kasameyer, P., 1998. Strong Ground Motion Synthesis for an M=7.2 Earthquake in the Gulf of Corinth, Greece Using Empirical Green's Functions. Lawrence Livermore National Laboratory, Livermore, CA, UCRL-JC-129394.

Hutchings, L. and Wu, F.T., 1990. Empirical Green's functions from small earthquakes-A waveform study of locally recorded aftershocks of the San Fernando earthquake. Journal of Geophysical Research, 95, 1187-1214.

Hutchings, L., Wu, F.T., Rau, R.J., Jarpe, S., Kasameyer, P. and Foxall, W., 1997. Strong Ground Motion Synthesis along the Sanyi-Tungshih-Puli Seismic Zone using Empirical Green's Functions. Central Weather Bureau 100th Anniversary International Conference on Weather Analysis and Forecasting Taipei, Taiwan.

International Institute of Earthquake Engineering and Seismology (IIEES), 2004.

Institute of Geophysics, University of Tehran (IGTU), 2004. (http://geophysics.ut.ac.ir/En/).

Iranian Code of Practice for Seismic Resistant Design of Buildings (Standard No. 2800).

Irikura, K., 1983. Semi-empirical estimation of strong ground motions during large earthquakes. Bulletin of Disaster Research Institute, 33, 63-104.

Jackson, J., Bouchon, M., Fielding, E., Funning, G., Ghorashi, M., Hatzfeld, D. et al., 2006. Seismotectonic, rupture process, and earthquake-hazard aspects of the 2003 December 26 Bam, Iran, earthquake. Geophysical Journal International, 166, 1270–1292.

Jarpe, S.P. and Kasameyer, P.W., 1996. Validation of a procedure for calculation broadband strong motion time histories from Empirical Green's Functions. Bulletin of the Seismological Society of America, 86, 1116-1129.

Jimenez, A., Garcia, M.J. and Romacho, M.D., 2005. Simultaneous inversion of source parameters and attenuation factor using genetic algorithm. Bulletin of the Seismological Society of America, 95, 1401-1411.

Joyner, W.B. and Boore, D.M., 1986. On simulating large earthquakes by Green's-function addition of smaller earthquakes. Earthquake Source Mechanics, American Geophysical Monograph, 6, 269-274.

Konstantinides, K., Natarajan, B. and Yovanof, G.S., 1997. Noise estimation and filtering using block-based singular value decomposition. IEEE Transactions Image Processing, 6, 479-483.

Lam, N., Wilson, J., and Hutchinson, G., 2000. Generation of synthetic earthquake accelerograms using seismological modelling: A review. Journal of Earthquake Engineering 4(3), 321-354.

Mori, J. and Frankel, A., 1990. Source parameters for small events associated with the 1986 North Palm Springs, California, earthquake determined using empirical Green functions. Bulletin of the Seismological Society of America, 80, 278–295.

Motazedian, D. and Moinfar, A., 2006. Hybrid stochastic finite fault modeling of 2003, M6.5, Bam earthquake (Iran). Journal of Seismology, 10, 91–103.

Mueller, C.S., 1985. Source pulse enhancement by deconvolution of an empirical Green's function. Geophysical Research Letters, 12, 33-36.

Naeim, F., Alimoradi, A. and Pezeshk, S., 2004. Selection and scaling of ground motion time histories for structural design using genetic algorithms. Earthquake Spectra, 20, 413–426.

National Earthquake Information Center (NEIC), 2004.

NEHRP Recommended Provisions for Seismic Regulations for new Buildings and other Structures, 2000 Edition. Prepared by the Building Seismic Safety Council for the Federal Emergency Management Agency, Washington D.C., 2001.

Nicknam, A., Abbasnia, R., Eslamian, Y. and Bozorgnasab, M., 2009. Extrapolating strong ground motion of Silakhor earthquake (ML 6.1), Iran, using EGF approach based on Genetic algorithm. Canadian Journal of Earth Sciences, 46, 801–810. doi:10.1139/E09-052.

Plicka, V. and Zahradnik, J., 2002. The EGf method for dissimilar focal mechanisms: the Athens 1999 earthquake. Tectonophysics, 359, 81-95.

Rodgers, A., Tkalcik, H., McCallen, D., Larsen, S. and Snelson, C., 2006. Site response in Las Vegas Valley, Nevada from NTS explosions and earthquake data. Pure and Applied Geophysics, 163, 55–80. DOI 10.1007/s00024-005-0010-1.

Sadigh, K., Chang, C.Y., Abrahamson, N.A. and Power, M.S., 1993. Specification of long-period ground motions: updated attenuation relationships for rock site conditions and adjustment factors for near-fault effects. ATC 17-1.

Somerville, P.G., Graves, R.W. and Collins, N., 2000. Ground Motions for Site Response Estimates -1906 Earthquake. A report to the PEER program of applied earthquake engineering research on Lifeline systems. PEER utilities program report No. 2000/05.

Talebian, M., Fielding, E.J., Funning, G.J., Ghorashi, M., Jackson, J.A. and Nazari, H., 2004. The 2003 Bam (Iran) earthquake: Rupture of a blind strike-slip fault. Geophysical Research, 31, L11611, doi: 10.1029/2004GL020058.

Tatar, M., Hatzfeld, D., Moradi, A.S. and Paul, A., 2005. The 2003 December 26 Bam earthquake (Iran), Mw 6.6, aftershock sequence. Geophysical Journal International, 163, 90–105.

Valle´e, M., 2004. Stabilizing the Empirical Green Function Analysis: Development of the Projected Landweber Method. Bulletin of the Seismological Society of America, 94, 394–409.

Velasco, A.A., Ammon, C.J., and Lay, T., 1994. Empirical Green function deconvolution of broad-band surface waves: rupture directivity of the 1992 Landers, California (Mw = 7.3). Bulletin of the Seismological Society of America, 84, 735-750.

Wu, F.T., 1978. Prediction of strong ground motion using small earthquakes. 2nd International Microzonation Conference, San Francisco, 2, 701-704.

Wu, Y.M., Zhao, L., Chang, C.H. and Hsu, Y.J., 2008. Focal-mechanism determination in Taiwan by genetic algorithm. Bulletin of the Seismological Society of America, 98, 651 - 661.

Received: 5. November 2009
Accepted: 7. June 2010

Yasser ESLAMIAN[1)*)], Mohammad Reza ADLPARVAR[2)], Mohsen BOZORGNASAB[3)] & Mohammad Ali SADREDINI MEHRJARDI[4)]

[1)] Civil Engineering Department, Iran University of Science and Technology, Tehran, Iran;

[2)] Technical & Engineering Faculty of Qom University, Qom, Iran;

[3)] University of Mazandaran, Mazandaran, Iran;

[4)] Islamic Azad University of Abarkooh, Abarkooh, Yazd, Iran;

[*)] Corresponding author, y_eslamian@iust.ac.ir