ESTIMATING THE STRONG-MOTION OF THE DECEMBER 26, 2003 BAM (IRAN), EARTHQUAKE USING STOCHASTIC TECHNIQUES

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Abstract: *The main objective of this study is estimating the strong motion for the Bam region using the stochastically based seismological models. The two widely used synthetic techniques namely; point-source and finite-fault were utilized incorporating the source-path and site parameters into simple function. The decay factor kappa was estimated based on the data obtained from recorded strong motions to be used as an appropriate factor for the region. The results were validated against those of the recorded data during the destructive 26 December 2003 Bam earthquake in south east of Iran. The efficiency of these methods and estimating the appropriate regional model parameters are the main objectives of this study.*

The results of the synthesized ground motion, such as acceleration time history, PGA and elastic response spectra were compared /assessed with those of observed data. The Bias model (MB) is used to assess the validation of the simulated earthquakes against recorded horizontal acceleration time histories. The %90 confidence interval of the means averaged over the whole stations using t-student distribution was evaluated and it was shown to be in an acceptable range. The elastic response spectra of the simulated strong motion are showed to be in a good agreement between the recorded waveforms confirming the acceptability of the selected/evaluated source-path-site model parameters. The sensitivity of the simulated PGA and response spectra against kappa factor as well as the path-averaged frequency-dependent quality factor Q, is studied and discussed.

1. Introduction

Realistic time-histories acceleration should be used in structural analysis to reduce uncertainties in estimating the standard engineering parameters [1], particularly for non-linear seismic behaviour of structures [2]. So, designers need to know the dynamic characteristics of predicted ground motion consistent with source rupture for a particular site to be able to adequately design an earthquake-resistance structure.

Simulating ground motion as well as elastic response spectrum at specific sites of Bam region for

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given earthquake magnitude scale, focal depth, source physical properties such as source density, slip function, wave propagation from source-to-site and site effects, the assessment of regional model parameters particularly the proposed decay parameter kappa and finally the role of dividing the fault into sub-faults are the main objectives of this paper.

Ground motions are estimated by identifying the major regional faults and propagating seismic waves generated at these potential sources to the site of interest. While the gross path parameters, such as geometric spreading and inelastic attenuation, can be estimated quite well on average from either empirical or theoretical models, there is much debate as the nature of the seismic source radiation [3].

The two commonly used techniques, finite-fault and point source methods of Beresnev-Atkinson and Boore [4, 5, 6, and 7] are used for simulation of the destructive 26 December 2003 Bam main shock. In finite-fault technique the finite source is subdivided into a certain number of elements (subfaults). In the

former approach, each subfault is treated as a point source while the whole source acts as a point source in point-source technique. Both techniques are omega-square spectrum based.

2. The Earthquake Prone Area of Bam, Iran

Iran as one of the world's most earthquake-prone countries has been exposed to many destructive earthquakes in the past long years. The three regions of Zagros, Alborz, and Khorasan are exposed to high seismicity. The movement of African plate toward the Asian plate, pushing the Arabian plateau and southwest of Asian, leads to the creation of faults and rupture on the earth crust in the most parts of Iran. The Bam region in the south east part of Iran is located in an active seismic zone. There have also been other large earthquakes in the area in the last 40 years (Fig. 1), but the city of Bam has not been affected by such destructive earthquake for at least several hundred years.

A destructive earthquake struck the city of Bam in south east part of Iran at 5:26:52 AM (local time) on Friday, December 26, 2003. The U.N. Office for the Coordination of Humanitarian Affairs (OCHA) reported that the Bam earthquake caused the deaths of approximately 43,200 residents and injured approximately 20,000. Some 75,600 people (14,730 house-holds) were displaced, and 25,000 dwellings were razed [8].
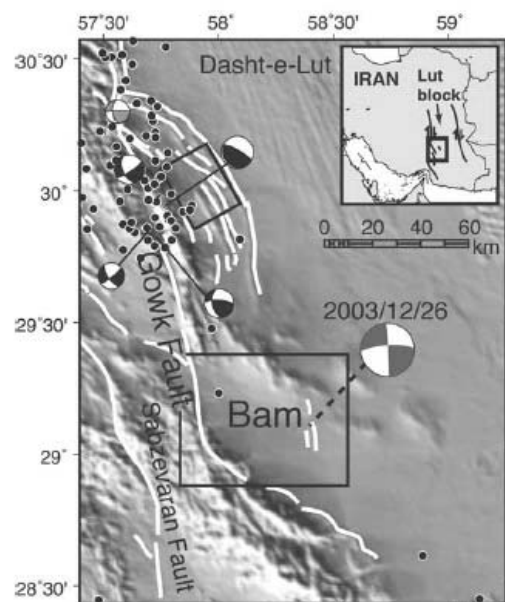

Fig 1. Region around bam with shaded relief (GTOPO30) with light from azimuth 225[12]

The location of the epicenter of this earthquake have been determined by IIEES [9] at 29.01N and 58.26E in 10km SW of Bam town that is close to the coordination mentioned by USGS (28.99N, 58.29 E [10]). The Moment Magnitude of 6.6 for this earthquake (Mw) have been measured based on the preliminary evaluations and the focal depth is

estimated to be 8km based on S-P evaluation on the records obtained from the main shock [11].

The 2003 Bam (Iran) earthquake is one of the first earthquakes for which Envisat advanced synthetic aperture radar (ASAR) data are available which show the complex faulting seen in the Bam earthquake has some similarities to patterns of faulting seen in other recent earthquakes, 14 March 1998 Mw6.6 Fandoqa earthquake and the 11 June 1981 Mw 6.6 Golbaf event in eastern Iran [12, 13]. Seismic body wave and preliminary Envisat radar interferometer analysis shows that the main moment release of the earthquake was right-lateral strike-slip motion on a nearly vertical fault oriented roughly north-south [12]. An N-S blind reverse fault believed to have been active during the late Quaternary, the Bam fault, passes some 4 km east of downtown of Bam city and just to the west Baravat city [14]. Jackson and his co-workers have tried to use the extraordinary wealth of diverse data from InSAR, seismology, geomorphology and surface observations to produce a coherent picture of the coseismic faulting in the 2003 Bam earthquake [15]. They concluded that more than 80 per cent of the moment release in the main shock occurred on a near-vertical right-lateral strike-slip fault extending from the city of Bam southwards for about 15 km. Surface ruptures and building damage of the 2003 Bam, Iran, earthquake mapped by satellite synthetic aperture radar interferometric correlation has been assesses by Fielding et al., 2005 (see more detail in reference [16]).

The site amplification characteristics of the 2003 Bam, Iran, earthquake were investigated based on geological studies as well as geophysical, microtremor and aftershock measurements conducted by IIEES in the study area[17].

3. Stochastic Simulation Techniques

During the past decades, much effort has been given in reliable simulation of strong ground motion that include theoretical or semi-empirical modeling of the parameters affecting the shape, the duration and the frequency content of strong motion records. These methods is based on the stochastic point source model, which stems out from the work of Hanks and McGuire [18] who indicated that the observed high frequency ground motion can be represented by windowed and filtered white noise, with the average spectral content determined by a simple description of the source. The stochastic ground-motion modeling technique, also known as the band limited white-noise method, was first described by Boore [19].Ever since; many researchers have applied the method to simulate ground motion from point sources [4, 20, and 21]. It is a simple tool that combines a good deal of empiricism with a little seismology and yet has been as successful as more sophisticated methods in predicting ground-motion amplitudes over a broad range of magnitudes, distances, frequencies, and tectonic environments. It has the considerable advantage of being simple and versatile and requiring little advance information on

the slip distribution or details of the Earth structure. For this reason, it is not only a good modeling tool for past earthquakes, but a valuable tool for predicting ground motion for future events with unknown slip distributions [22, 23, and 24]. Comparisons of stochastic-method predictions with empirically-determined ground motions indicates that the stochastic method is useful for simulating mean ground motions expected for a suite of earthquakes having a specified magnitude and fault–station distance[22].

Recently, Beresnev and Atkinson [5] have proposed a technique that overcomes the limitations posed by the hypothesis of the point source. Their technique is based on the original idea of Hartzell [18] to model large events by the summation of smaller ones. In Beresnev and Atkinson [5] technique, the high-frequency seismic field near the epicentre of a large earthquake is modelled by subdividing the fault plane into a certain number of sub-elements and summing their contributions, with appropriate time delays, at the observation point. Each element is treated as a point source with a theoretical ω^{-2} spectrum. A stochastic model is used to calculate the ground-motion contribution from each sub-element, while the propagation effects are empirically modelled.

3.1. Stochastic Point Source Model

The horizontal component of an acceleration amplitude spectrum $a(M, R, f)$, defined by a source and a propagation model, is a function of moment magnitude (M) and distance (R):

$$a(M,R,f) = \frac{\prec R_\phi \succ \times F \times V}{4\pi \times \rho \times \beta^3} \times S(M,f) \times D(R,f) \times P(f) \times A(f) \quad (1)$$

Where $\langle R_{\upsilon\varphi} \rangle$ is the radiation pattern averaged over an appropriate range of azimuth and take-off angle, F accounts for free surface effects, V represents the partition of a vector into horizontal components. ρ, β are the crustal density and shear wave velocity respectively. $S(M,f)$ is a source function, $D(R,f)$ is a seismic attenuation function filter, $P(f)$ is a high-frequency truncation filter and $A(f)$ is site amplification [21].

The wave transmission quality factor Q is defined as the following expression:

$$Q = Q_0 \left(\frac{f^n}{f_0} \right) \quad (2)$$

Where f_0 is the unity frequency (1 Hz), and Q_0 and n are the regional dependent factor and exponent respectively.

The $p(f)$ filter is the upper crust attenuation factor that is used to model the observation that an acceleration spectral density usually appears to fall off rapidly beyond a maximum frequency .We applied high frequency filter $p(f)$ in the following form [26]:

$$p(f) = \exp(-\pi \kappa f) \quad (3)$$

The decay parameter Kappa (κ), represents the effect of an intrinsic attenuation upon the wavefield as it propagates through below the site.

The simulation procedure is followed such that, the Fourier amplitude spectrum derived from the seismological model defines the frequency content of the earthquake ground motion. This frequency information can be combined with random phase angles in a stochastic process to generate synthetic accelelograms.

3.2. Stochastic Finite-Fault Simulation Method

Stochastic Finite-Fault Simulation Method is presented by Beresnev and Atkinson [5, 6, and 7]. The simulations are estimated using A FORTRAN program. In the adopted methodology, the fault plane is discretized into a finite number of elements (called subfaults), each of which is treated as a point source, and radiations from all subsources are appropriately lagged in time and summed at the observation site. Time histories from individual subsources are generated through the stochastic technique proposed by Boore [19], assuming that the Fourier amplitude spectrum of the seismic signal at the station is the product of the source spectrum and a number of filtering functions representing the effects of path attenuation and site response.

The corner frequency (f_0) and seismic moment (m_0) of the subfaults are derived in terms of subfault size (Δl):

$$f_0 = \frac{(^{yz}/_\pi)\beta}{\Delta l} \quad (4)$$

$$m_0 = \Delta\sigma\Delta l^3 \quad (5)$$

Where $\Delta\sigma$ is the Kanamori-Anderson [27] "stress parameter" (fixed at 50 bar), β is the shear wave velocity, y is the fraction of rupture-propagation velocity to β (assumed equal to 0.8 in the present study), and z is a parameter physically linked to the maximum rate of slip. The value of z depends on the definition of the rise time and for standard conventions z=1.68 [5, 6].

The first step is determining number of subfaults from:

$$N = \frac{M_0}{m_0} = \frac{M_0}{\Delta\sigma\Delta l^3} \quad (6)$$

Where M_0 is the seismic moment of main shock. The lower bound on Δl comes from the requirement that the corner frequency of subfaults lies between the frequency range of interest.

4. Model Parameter

During this earthquake, a regional network of 74 strong motion accelerograph stations of the Iranian Strong Motion Network (ISMN), maintained by the Building and Housing Research Center (BHRC) [28], was operating. The stations were equipped with SSA-2 instruments. Among these, 23 stations located within a 1–290 km range of the rupture registered the earthquake with peak acceleration of nearly 1.00 to 0.01 g.

The locations of accelerometers and accelerograph station data of the December 26 2003 Bam earthquake are shown in Fig.2. The strong motion recorded at Bam station shows the largest PGA of 0.78g and 0.62g for the east-west horizontal and north-south horizontal components, respectively, and 0.98g for the vertical component (all corrected values). The preliminary observation of damaged structures in the Bam city confirms the near field effects particularly the directivity effect.
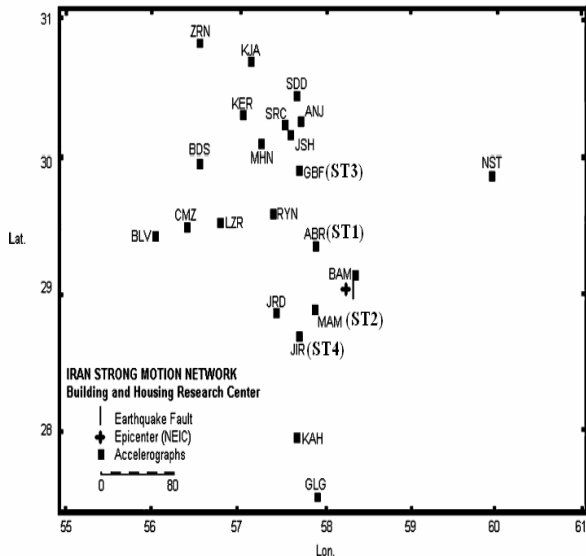

Fig 2. Location of accelerometers near Bam earthquake epicenter that recorded Bam earthquake (BHRC) [28]

Clearly, the Bam station records including the near source effects could not be taken into account for averaging with those of far station data.

However it is claimed that the finite- fault technique can be used for predicting the near source effects [25, 29, 30, 31, and 32]. Among the 23 recorded strong motions, the records of 4 stations were chosen so that they have not been affected by directivity effects. The four stations data used are, Mohammad Abad, Abaragh, Golbaft and Jiroft. The Iran standard soil types classified based on the average shear wave velocity of the upper 30 m of the site, are used as input data (Standard No:2800)[33]. The values of peak ground amplitudes (PGA) for selected stations and the corresponding soil types are shown in Table 1.

4.1. Estimation of Source-Path-Site Parameters

The soil types of Abaragh and Golbaft stations were estimated to be of types I and III respectively [28,

34]. Abaragh and Mohammad Abad Stations, located in the northern and southern parts of the event respectively, with about the same epicentral distances and similar site geology descriptions as reported by Mirzaei and Farzanegan [35].

Tab. 1. Soil type, corrected PGA and kappa parameter

NO	Station	Soil type	Corrected PGA(cm/sec^2)			Kapa (sec)
			L	V	T	
ST1	Abaragh	I	166.69	83.81	109.47	0.02
ST2	Mohammad-Abad	I	115.94	69.17	66.79	0.05
ST3	Golbaf	III	30.29	12.8	27.65	0.07
ST4	Jiroft	I	40.17	30.32	27.56	0.09

The site amplification factors employed in this paper are those of Boore and Joyner [36] for various sites which are characterized by the average shear-wave velocity over the upper 30m ($\bar{V}_{30}$). The average shear wave velocity of the stations and corresponding Iran standard soil types I and III to be used were considered equivalent to those of soil class B and D in NEHRP Code respectively.

The source material properties the density ρ, and shear wave velocity β, were estimated to be 2.8 gr/cm^3 and 3.5 km/sec, respectively. The geometric spreading operator $1/R$ for $R \le 70$ km, $1/R^0$ for $70 \prec R \le 130$ and $1/R^{0.5}$ for $R \succ 130 km$ was applied and the anelastic attenuation was represented by a mean frequency dependent quality factor $Q(f)$. The selected model factors used in this study are shown in Table 2.

Tab. 2. Parameters associated with the Q factor [42, 43]

No	Region	Q0	n
1	Quebec(CENA)	755	0.5
2	New Brunswick(CENA)	500	0.65
3	South eastern Canada(CENA)	680	0.36
4	California	204	0.56
5	Victoria, Australia	100	0.85
6	Bam region, Iran	350	1

Following Brune [37], the corner frequency is given by the following equation:

$$f_0 = 4.9 \times 10^6 \times \beta \times (\frac{\Delta\sigma}{M_0})^{\frac{1}{3}} \tag{7}$$

Where f_0 is in Hz, β (the shear-wave velocity in the vicinity of the source) in km/s, $\Delta\sigma$ in bars, and M_0 in dyne-cm. The stress drop $\Delta\sigma = 105 bar$ is computed from Eq. (8) with respect to the corner frequency $f_0 = 0.18$ Hz [38] and the moment magnitude $M_W = 6.6$ reported by USGS [10]. In the methodology of Beresnev and Atkinson [5,6], modeling of finite source requires information of the orientation and dimensions of fault plane, dimensions of subfaults and the location of hypocenter.

The trends of epicenteral and hypocenteral distribution are in accordance with the strike and dip

angle of the focal mechanism (strike, dip, slip) = (175, 85, 153) of the mainshock [39]. The source dimension is therefore roughly estimated to be 20 kmx16 km [39]. As shown in Fig 3, number of subfaults along strike and dip is 4 and 3 respectively. Rupture velocity has been assumed 0.8β in which β is crustal shear wave velocity correspond to 3.5 km/sec.

In general, the distribution of slip is not known for future events. This motivates us to follow the question: How well the ground motion could be synthesized if the slip distribution is not known? We applied a randomly drawn slip in our simulations for different stations.
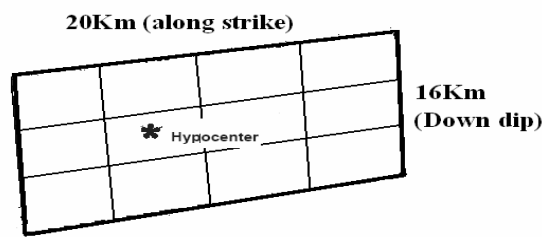
Fig 3. Effective area of bam mainshock rupture

4.2. Proposed Regional Attenuation Factor, Kappa

The frequency independent amplitude decay parameter kappa was estimated using the data of the recorded earthquakes and is explained here. High-frequency amplitudes are reduced through the kappa operator [26] by applying the factor $\exp(-\pi\times\kappa\times f)$. Kappa acts to rapidly diminish spectral amplitudes above some threshold frequency (Fig.4) and is believed to be primarily a site effect.

In this study, the kappa factor for each individual record is obtained from the slope of the smoothed log acceleration Fourier spectral amplitude at high frequencies, generally greater than 5 Hz, where frequency is in linear scale. A least-squares fit to the spectrum of each record is determined. The results of obtained average values kappa factor for L and T earthquake components are shown in Table 1. The obtained kappa at each station was incorporated in the model and the efficiency of the two methods was evaluated /assessed. The average value of kappa, 0.07 over 23 stations was incorporated in the two used stochastic models and the results in the form of model bias were compared with those of individual kappa value at each station. Fig. 13 presents this comparison.
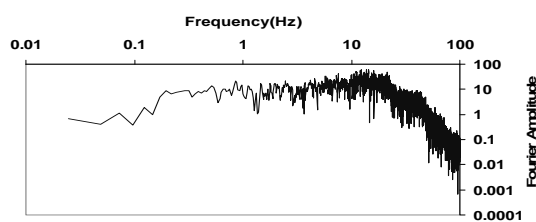

Fig 4. the Fourier amplitude spectrum used in seismological model

5. Results

We simulated strong ground motions from the mainshock of the 2003 Bam earthquake at 4 stations based on the two widely used synthetic techniques namely; point-source and finite-fault utilize incorporating the source-path and site parameters into estimation as a simple function. Figures 5-12 show the comparison of simulated and observed accelerograms as well as elastic response spectra of time-series regarding the individual decay parameter kappa, at each station.

It is worth mentioning that, records of two horizontal components are obtained from orthogonally oriented components, consequently two records were available at each station. Comparison of the simulated with each of which and/or combination of the two components seems to be questionable. In this paper, the two records are combined into a single measure using the geometric mean of elastic response spectrum [40]. The geometric mean of the spectral elastic responses of the x and y components for the selected period T_i is defined as:

$$S_{a_{GMXY}}(T_i) = \sqrt{S_{a_x}(T_i) \times S_{a_y}(T_i)} \qquad (8)$$

Where, $S_{a_x}(T_i)$ and $S_{a_y}(T_i)$ are the elastic spectral responses of each component [41].

The path-averaged frequency-dependent shear wave crustal quality factor Q, which is a regional parameter has been estimated by many researchers [42, 43]. Six forms of this factor Q1, Q2, Q3 Q4, Q5 and Q6 shown in Table 2 were used in this study and the corresponding simulated response spectrum are presented in Figs 5, 7, 9, 11. As it can be seen, the results of Q1, Q2, Q3 and Q6 are approximately close to each other and to the observed (with quite close to Q1, Q2 and Q6), while those of Q4 and Q5 are away from the first those.

The Bias model (MB) is used to assess the validation of the simulated earthquakes against recorded horizontal acceleration time histories. MB is defined as the ratio of observed to simulated spectrum at each individual station, averaged over all stations [3, 44, and 45]. In this study, the elastic acceleration response spectra of simulated and observed acceleration time histories of Bam earthquake on selected stations are compared and the MB of the results (elastic response spectra) are estimated at each individual frequency. The frequency range of this study is from 0.2 Hz to 10 Hz. .The t-student distribution with three degree of freedom (df=3) is used for estimating %90 confidence interval of the mean value (the df is equal to the sample size minus 1). Fig 13 shows the results of such estimation with dashed lines. The obtained results are quite comparable with those of Beresnev et al [6, 7] confirming that the finite-fault radiation technique has the potentiality of providing accurate prediction of the mean spectral content of earthquake acceleration time histories. As it can be seen from Figs 13, the mean spectral content of

amplitude ratios (i.e. the ratios of observed to simulated spectral amplitudes) are not significantly far from unity at the 90% confidence interval and agreement between the predicted and observed data confirms the validation of selected/evaluated regional parameters.

The recorded data at 23 stations have been used for estimating an appropriate regional decay parameter kappa factor which yielded to 0.07. Fig 14 shows the comparison of using the averaged value of kappa factor with case that we have used individual kappa for each station in our simulation. As can be seen, the model bias and response spectra estimated from the averaged kappa value are comparable with those of individuals. In the other words, the effect of applying of average value for kappa factor in simulation results has been assessed. It is be noted that, the kappa factor controls the peak ground acceleration as well as response spectrum values at high frequencies (i.e., f>10 Hz) [46].

6. Conclusions

The recorded destructive 26 December 2003 Bam earthquake was estimated two widely utilized stochastic point/finite source techniques. The data from sufficiently far stations were chosen so that the directivity effects could not affect the results. The elastic acceleration response spectra and peak ground acceleration (PGA), at four free-field (strong motion) stations located at 49, 52, 74 and 114 kilometers away from epicenter were predicted. The accuracy of each method and the reliability of source-site selected/evaluated parameters for the Bam region were discussed and assessed by comparing the estimated strong motion data with those of the observed data. It is shown that the synthetic time-series were relatively comparable with those of the recorded data within 90% confidence level for means averaged over the four stations.

It should be mention that, the results of this study are reliable in the frequency ranges between 0.2 and 10 Hz, which are practically used in engineering structures. The following results could be concluded from the (limited available) data used in this study.

• The stochastic finite-fault model, which treats earthquakes as a summation of Brune point sources, distributed over a finite fault plane, provides accurate ground-motion estimates for Bam earthquakes M 6.6, over the frequency range from 0.2 to 10 Hz. The key assumption in the finite-fault simulations that leads to the improved agreement between simulated and observed spectra (relative to the Brune point source) is the representation of fault radiation as a sum of contributions from smaller subfaults (each of which has an ω^2 point-source spectrum).

• The results of this study confirm that, the hypothesis made in the simulation process such as constant stress drop, density parameter (ρ), shear

wave velocity (β) and site effect parameters, would end with successful and adequately accurate results.

• It was shown that, the results of simulation are not highly sensitive against the path-averaged frequency-dependent quality factors. However, the results incorporating the quality factors Q1, Q2, Q3 and Q6 were more accurate and close to the observed data and could be used reliably for bam region.

• The proposed averaged spectral decay factor kappa= 0.07 which is estimated based on the available data, could be used for the decay factor in the Bam region.

• The use of a randomly drawn slip model does not lead to any appreciable increase in simulation uncertainty, on average. This suggests that knowledge of the slip distribution is not required for the accurate average prediction of acceleration spectra from large events.

• The source – path – site model parameters selected/evaluated in this study can be used for estimating the strong motion time-histories of the region to be used in hazard analysis of specific sites for different structural performance levels, such as life-safely range.
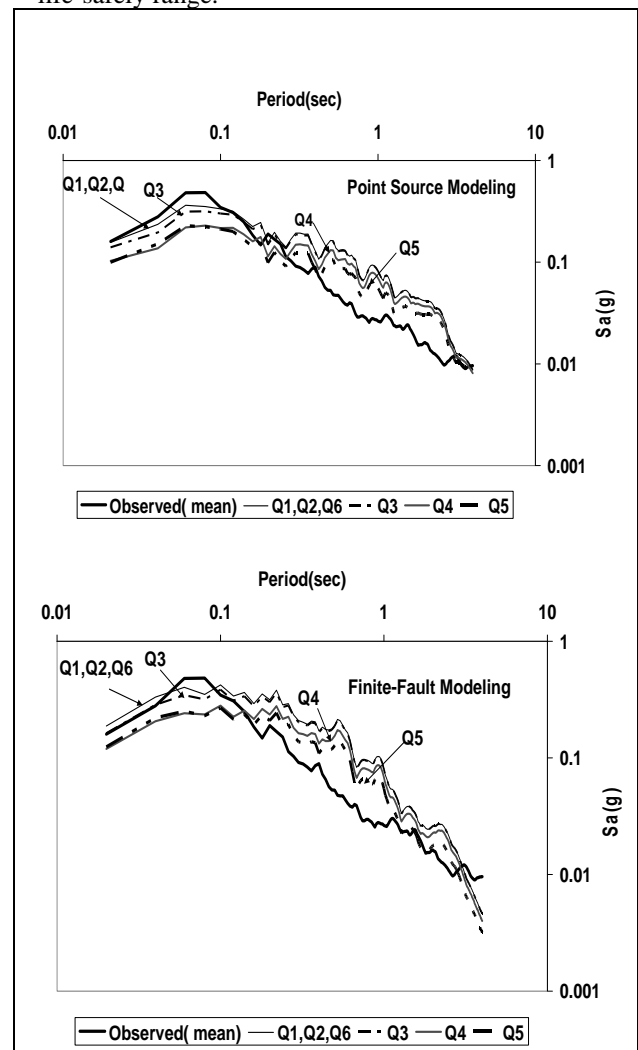

Fig 5. Simulated and observed 5%-damped pseudo-acceleration response spectra for St1
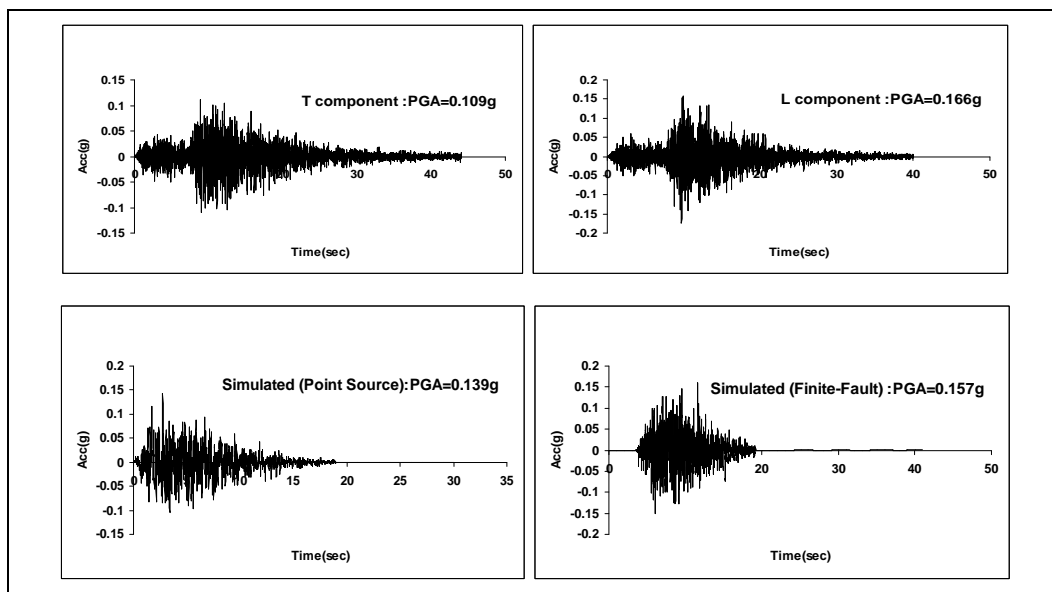
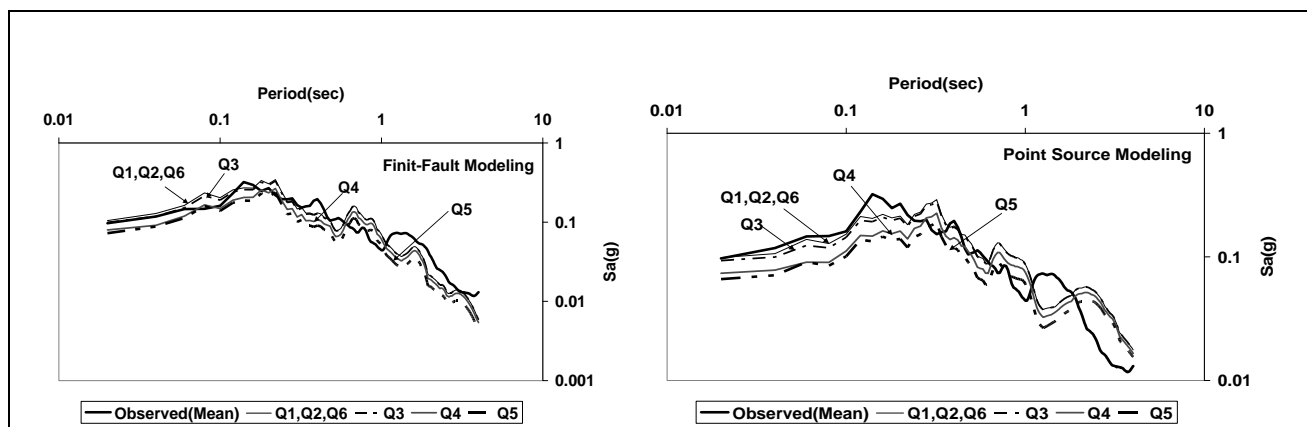**Fig 6. Observed horizontal acceleration time history (L and T component) and simulated (for Q6) in ST1**

Fig 7. Simulated and observed 5%-damped pseudo-acceleration response spectra for St2
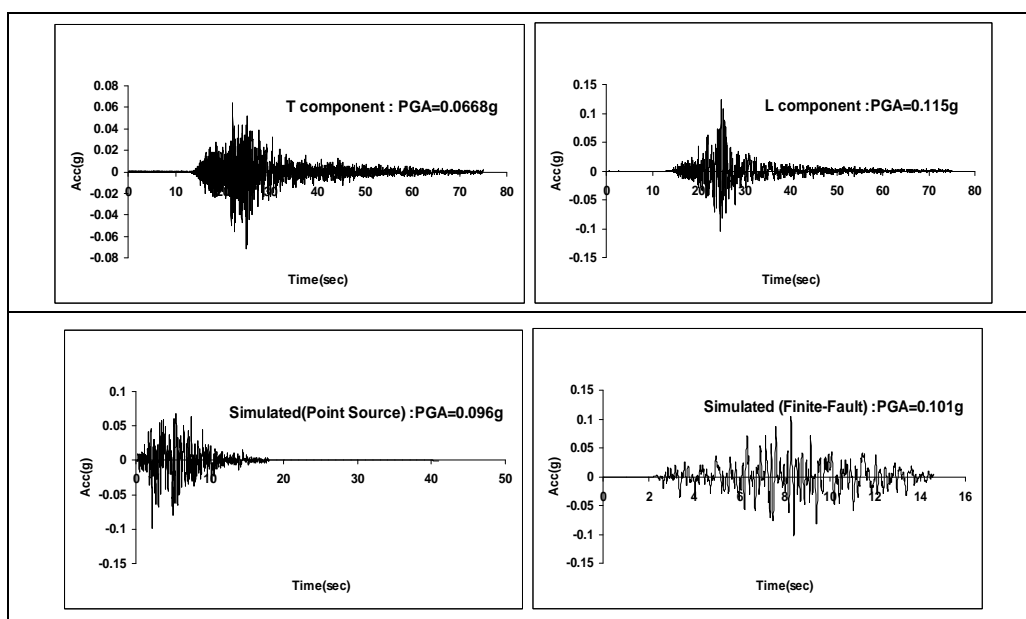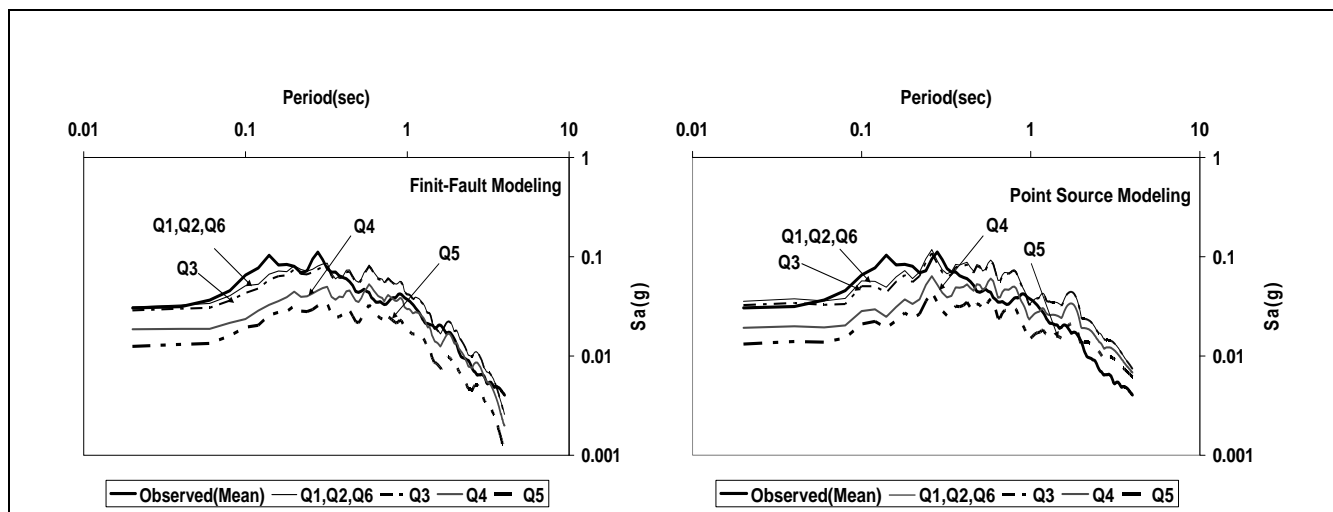

Fig 8. Observed horizontal acceleration time history (L and T component) and simulated (for Q6) in ST2

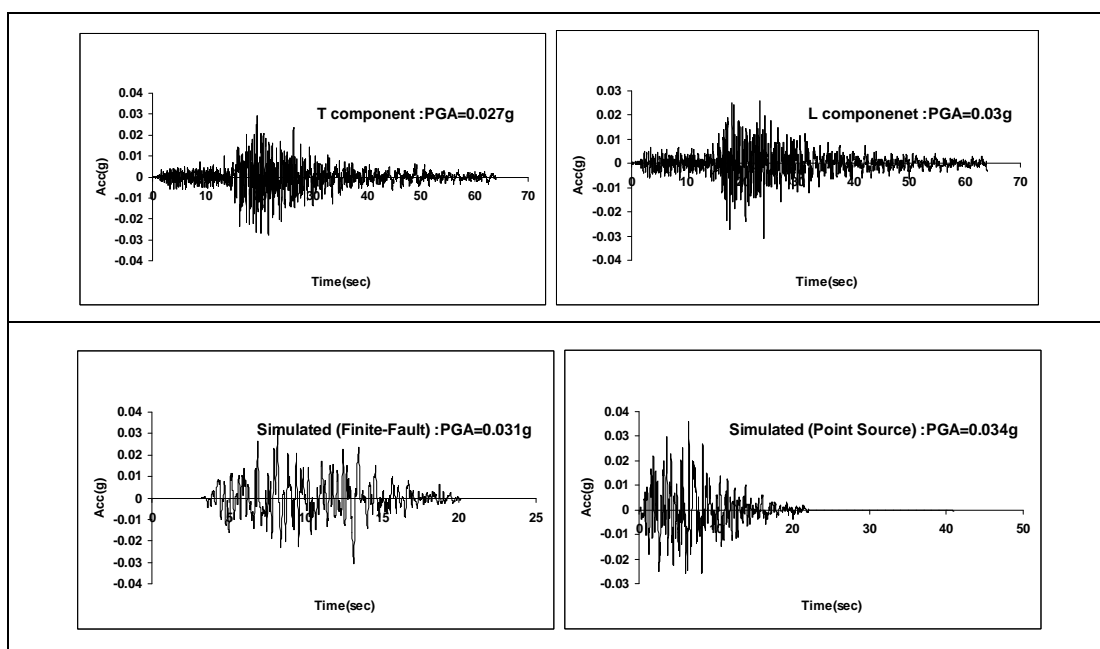**Fig 9. Simulated and observed 5%-damped pseudo-acceleration response spectra for St3**

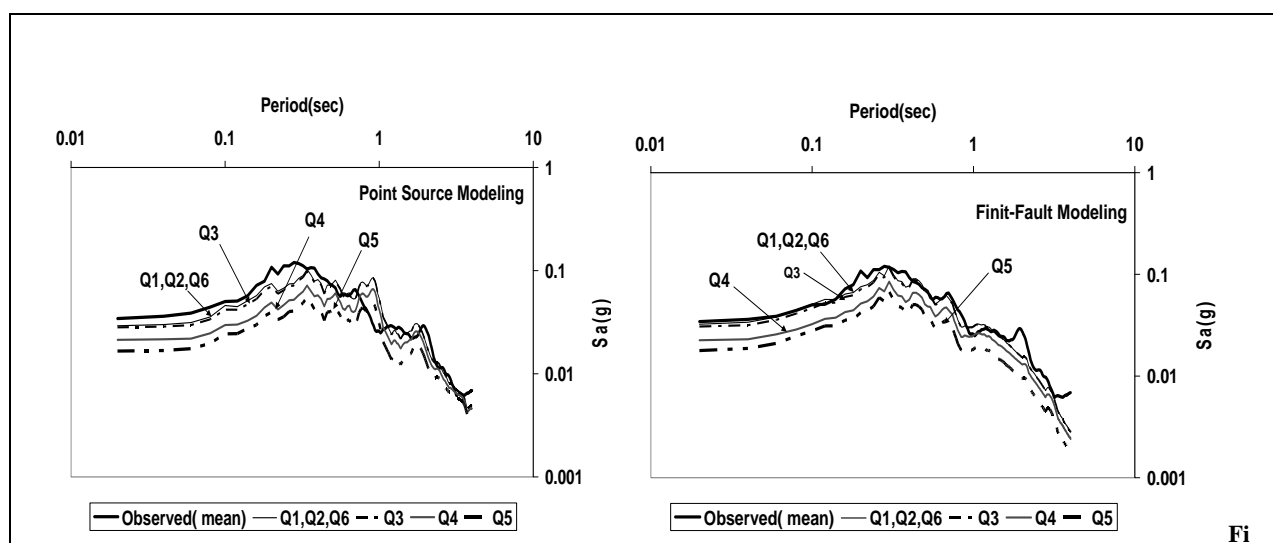**Fig 10. Observed horizontal acceleration time history (L and T component) and simulated (for Q6) in ST3**

Fig 11. Simulated and observed 5%-damped pseudo-acceleration response spectra for St4
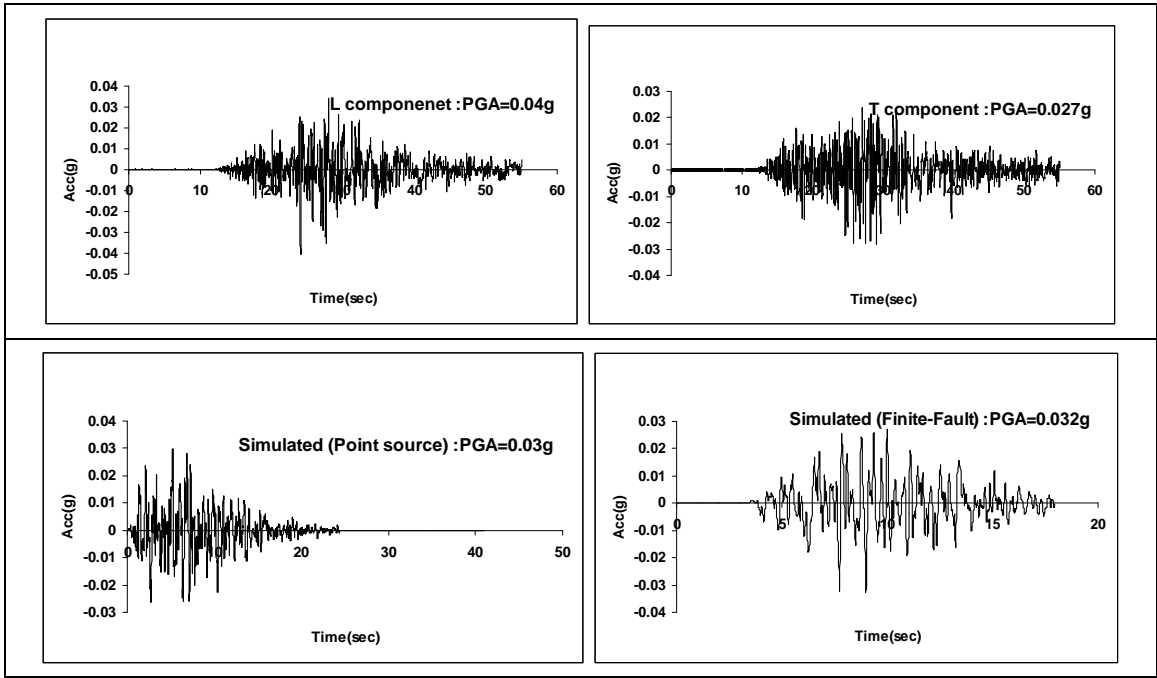
Fig 12. Observed horizontal acceleration time history (L and T component) and simulated (for Q6) in ST4
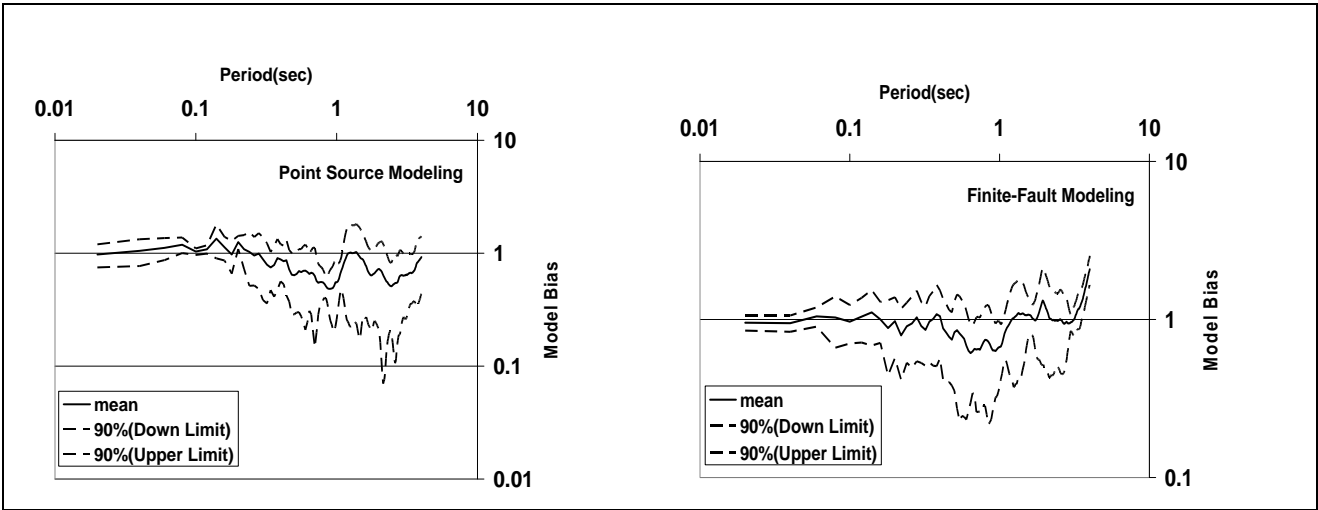

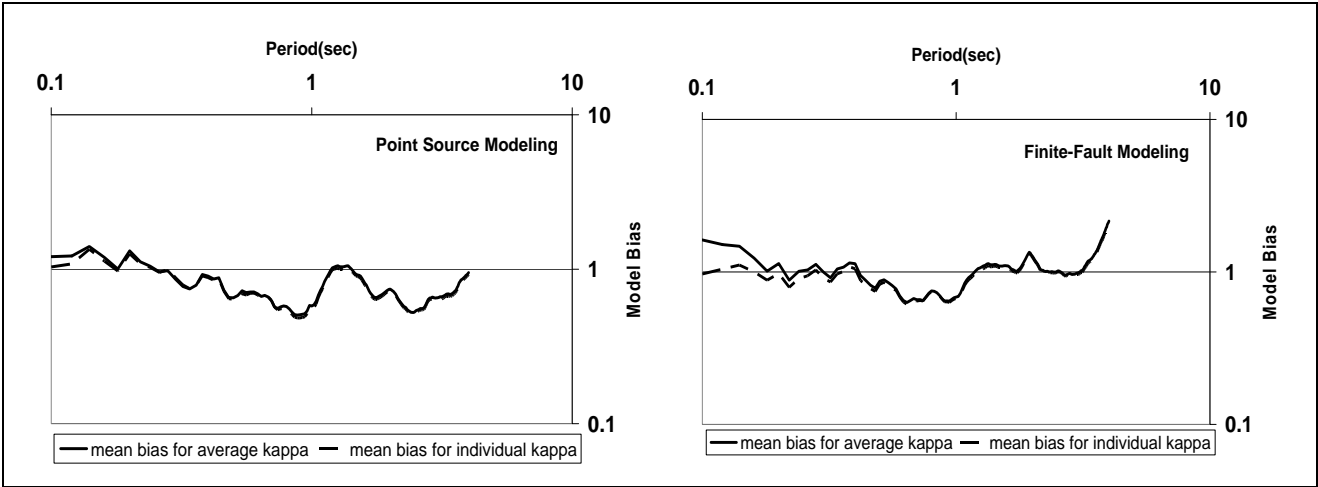**Fig 13. Model bias showing the ratio of observed spectrum, averaged over 4 stations**

Fig 14. Comparison of mean bias results for average value and individual value of kappa in point source and finite-fault modeling

References

[1] Hutchings, L., *"Prediction of Strong Ground Motion for the 1989 Loma Prieta Earthquake Using Empirical Green's Functions,"* Bul. Seis. Soc. Am. 81, 1991, PP. 88–121.

[2] McCallen, D.B., Hutchings, L.J., *"Ground Motion Estimation and Nonlinear Seismic Analysis"*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-JC-121667. Proceedings: 12th Conference on Analysis and Computation of the American Society of Civil Engineers, Chicago, 1996.

[3] Beresnev, I.A., Atkinson, G. M., *"Source Parameters of Earthquakes in Eastern and Western North America Based on Finite-Fault Modeling,"* Bull. Seism. Soc. Am. 92, 2002, PP. 695 – 710.

[4] Boore, D.M., and Atkinson, G.M., *"Stochastic Prediction of Ground Motion and Spectral Response Parameters at Hard–Rock Sites in Eastern North America,"* Bull. Seism. Soc. Am. 77, 1987, PP. 440–467.

[5] Beresnev, I.A., Atkinson, G.M., *"Modeling Finite–Fault Radiation from the ωn Spectrum,"* Bull. Seism. Soc. Am. 87, 1997, PP. 67 – 84.

[6] Beresnev, I.A., Atkinson, G.M., *"FINSIM–a FORTRAN Program for Simulating Stochastic Acceleration Time Histories from Finite Faults,"* Seism. Res. Let. 69,1998a, PP. 27 – 32.

[7] Beresnev, I.A., Atkinson, G.M., *"Stochastic Finite-Fault Modeling of Ground Motion from 1994 Northridge Acceleration, California, Earthquake. I-Validation on Rock Sites,"* Bull. Seism. Soc. Am. 88,1998b, 1392 – 1401.

[8] Earthquake Engineering Research Institute (EERI) *"Preliminary Observations on the Bam, Iran, Earthquake of December 26 2003,"* EERI Special Earthquake Report — April 2004.

[9] International Institute of Engineering Earthquake and Seismology (IIEES) *"Preliminary Report on the Bam Earthquake,"*2003.

[10] United State Geological Survey (USGS), 2003. Websites: http://earthquake.usgs.gov.htm.

[11] Eshghi, S., Zare, M., *"Bam (SE Iran) earthquake of 26 December 2003, Mw6.5: A Preliminary Reconnaissance Report,"* International Institute of Engineering Earthquake and Seismology (IIEES) report, 2003.

[12] Talebian, M., et al. *"The 2003 Bam (Iran) Earthquake: Rupture of a Blind Strike-slip Fault,"* Geophys. Res. Lett., 31, L11611, 2004, doi: 10.1029/ 2004GL020058.

[13] Funning, G.J., Parsons, B.E., Wright, T.J., Jackson, J.A., Fielding, E.J., *"Surface Displacements and Source Parameters of the 2003 Bam (Iran) Earthquake From Envisat Advanced Synthetic Aperture Radar Imagery"*, J. geophys. Res., Vol. 110, B09406, 2005.

[14] Berberian, M., *"Contribution to the Seism Tectonics of Iran, Part II., Materials for the Study of the Seism Tectonics of Iran",* Rep. 39, Geol. Surv. of Iran, Tehran,1976.

[15] Jackson, J., Bouchon, M., Fielding, E., Funning, G., Ghorashi, M., Hatzfeld, D., Nazari, H., Parsons, B., Priestley, K., Talebian, M., Tatar, M., Walker, R., Wright, T., *"Seismotectonic, Rupture Process, and Earthquake-Hazard Aspects of the 2003 December 26 Bam, Iran, Earthquake"*, Geophys. J. Int. (2006) 166, 1270–1292, 2006.

[16] Fielding, E.J., Talebian, M., Rosen, P.A., Nazari, H., Jackson, J.A., Ghorashi, M., Walker, R., *"Surface Ruptures and Building Damage of the 2003 Bam, Iran Earthquake Mapped by Satellite Synthetic Aperture radar Interferometer Correlation"*, J. geophys. Res., 2004,110, BO3302.

[17] Jafari, M.K., Ghayamghamian, M., Davoodi, M., Kamalian, M., Sohrabi-Bidara, A., *"Site Effects of the 2003 Bam, Iran, Earthquake",* Earthquake Spectra, Volume 21, No. S1, pages S125–S136, 2005.

[18] Hanks, T.C., McGuire, R.K., *"The Character of High Frequency Strong Ground Motion,"* Bull. Seism. Soc. Am. 71, 1981, PP. 2071–2095.

[19] Boore, D.M., *"Stochastic Simulation of High–Frequency Ground Motions Based on Seismological Models of the Radiated Spectra"*, Bull. Seism. Soc. Am. 73, 1983, PP. 1865 – 1894.

[20] Toro, G., McGuire, R., *"An Investigation into Earthquake Ground Motion Characteristics in Eastern North America,"* Bull. Seism. Soc. Am. 77, 1987, PP. 468–489.

[21] Atkinson, G.M., Boore, D.M., *"Ground – Motion Relations for Eastern North America,"* Bull. Seism. Soc. Am. 85, 1995, PP. 17 – 30.

[22] Boore, D., *"Prediction of Ground Motion Using the Stochastic Method"*, Pure and Applied Geophysics, 2003, 160, 635-676.

[23] Toro, G.R., Abrahamson, N.A., Schneider, J.F., *"A Model of Strong Ground Motions from Earthquakes in Central and Eastern North America: Best Estimates and Uncertainties"*, Seismological Research Let.,1997, 68(1), 41-57.

[24] Atkinson, G.M., Boore, D.M., *"Empirical Ground-Motion Relations for Seductions-Zone Earthquakes and Their Application to Cascadia and Other Regions"*, Bull. Seism. Soc. Am. 2003, Vol. 93, No. 4, PP. 1703–1729.

[25] Hartzell, S., *"Earthquake Aftershocks as Green's Functions,"* Geophys. Res. Let. 5, 1978, PP. 1–4.

[26] Anderson, J., Hough, S., *"A Model for the Fourier Amplitude Spectrum of Acceleration at High Frequency,"* Bull. Seism. Soc. Am. 74, 1984, PP. 1969-1993.

[27] Kanamori, H., Anderson, D.L., *"Theoretical Basis of Some Empirical Relations in Seismology,"* Bull. Seism. Soc. Am. 65(5), 1975, PP. 1073-1095.

[28] Building and Housing Research Center (BHRC), 2003, Website: http://www.bhrc.gov.ir/.

[29] Irikura, K., *"Semi-Empirical Estimation of Strong Acceleration Motion During Large Earthquake,"* Bull. Disaster Prevention Res. Ins .Kyoto Univ. 33, 1983, PP. 63-104.

[30] Tumarkin, A.G., Archuleta, R. J., *"Empirical Ground Motion Prediction,"* Ann. Geofis.37, 1994, PP. 1691-1720.

[31] Zeng, Y., Anderson, G., Yu, G., *"A Composite Source Model for Computing Realistic Strong Motions,"* Geophys. Res. Lett. 21, 1994, PP. 725-728.

[32] Atkinson, G.M., Silva, W., *"An Empirical Study o Earthquake Source Spectra for California Earthquakes,"* Bull. Seism. Soc. Am. 87, 1997, PP.97 –113.

[33] Iranian Code of Practice for Seismic Resistant Design of Building (Standard No: 2800), Third Edition 2006, Building and Housing Research Center (BHRC), (in Persian), 2006.

[34] Zare, M., *"Strong Ground Motion Data of the 1994-2002 Earthquakes in Iran: A Catalogue of 100 Selected Records with Higher Qualities in the Low Frequencies,"* JSEE, Vol. 6. No. 2, 2004, PP. 1-17.

[35] Mirzaei, H., Farzanegan, E., *"Specifications of the Iranian Accelerograph Network Stations,"* Building and Housing Research Center (BHRC), Publication No. 280, 1998.

[36] Boore, D.M., Joyner, W.B., *"Site Amplification for Generic Rock Sites",* Bull. Seism. Soc. Am. 87, 1997, PP. 327 – 341.

[37] Brune, J.N., *"Tectonic Stress and the Spectra of Seismic Shear Waves from Earthquakes,"* J. Geophys. Res. 75, 1970, PP. 4997–5009.

[38] Mostafazadeh, M., *"Moment Tensor Solution of 26 December 2004 Bam Earthquake,"* Geophysical Research Abstracts, Vol. 7, 00667, 2005.

[39] Yamanaka, Y., *"Seismological Note,"* No.145, Earthquake Information Center, Earthquake Research Institute, University of Tokyo, 2003.

[40] Boore, D.M., Lamprey, J.W., Abrahamson, N.A., *"Orientation - Independent Measures of Ground Motion,"* Bull. Seism. Soc. Am. V.2.1, 2006.

[41] Beyer, K., Bommer, J.J*., "Relationships Between Median Values and Aleatory Variability's for Different Definitions of the Horizontal Component of Motion"*, Bulletin of the Seismological Society of America, 96,n°4, in press, 2006.

[42] Lam, N., Wilson, J., Hutchinson, G., *"Generation of Synthetic Earthquake Accelerograms Using Seismological Modelling: A Review,"* Journal of Earthquake Engineering., Vol. 4, No.3, 2005, PP. 321-354.

[43] Shoja-Taheri, J., Naseri, S., Ghafoorian, A*., "The 2003 Bam, Iran, Earthquake :An Iterpretation of Strong Motion Records,"* Earthquake Spectra,Vol.21, No.S1, 2005, PP. 181-206.

[44] Atkinson, G.M., Boore, D.M., *"Evaluation of Models for Earthquake Source Spectra in Eastern North America,"* Bull. Seism. Soc. Am. 88, 1998, 917-934.

[45] Atkinson, G.M., Silva, W., *"Stochastic Modeling of California Earthquakes,"* Bull. Seism. Soc. Am. 90, 2000, PP. 255 –274.

[46] Atkinson, G.M., *"The High-Frequency Shape of the Source Spectrum for Earthquakes in Eastern and Western Canada,"* Bull. Seism. Soc. Am. 86, 1996, PP. 102-112.