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Stochastic finite-fault simulation for the 2002 Changureh-Avaj earthquake, NW Iran

Ghasemi, H [*]., Kamalian, N [**]. and Hamzeloo, H [***].

[*] *Building and Housing Research Center, P.O. Box 13145-1696, Tehran, Iran*
[**] *Institute of Geophysics, University of Tehran, P.O. Box 14155-6466, Tehran, Iran*
[***] *International Institute of Earthquake Engineering and Seismology, Tehran, Iran*

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Abstract

Stochastic finite-fault simulation is used to simulate the acceleration time histories of the 22 June 2002 Changoureh-Avaj earthquake. The method generalizes the stochastic ground motion simulation technique, developed for point source, to the case of finite faults, in which the ground motion amplitudes are simulated as a summation of stochastic point source. Geometrical spreading and regional inelastic attenuation are included in the model. The strong motion simulations are performed by adjusting the sub-fault size to calibrate the simulation model against recorded ground motions. In this way the length of the fault is taken as 25 km and its width as 18 km, and the fault plane is divided into 5×3 elements. Considering that site amplification functions play an important role in the simulation process, site specific amplification function is estimated by the horizontal to vertical ratio technique.

A quite satisfactory agreement is found between the simulated amplitude Fourier spectra and the recorded data at frequencies of engineering interest (0.1 to 20 Hz) including the capability of the method to reproduce the salient ground motion characteristics.

Keywords: Finite-fault, Stochastic simulation method, Avaj

1 INTRODUCTION

Predicting the ground motion is one of the most critical stages involved in seismic hazard analysis studies. In this way the most common method is using the attenuation laws determined for the target region or other regions that have similar characteristics as the region studied. But such attenuation laws have been used extensively to predict simple parameters characterizing ground motion intensity such as PGA, and may be not suitable for the case where the entire time history of the ground motion, near its spectrum, is needed (e.g. for simulating a nonlinear multi-degree of freedom systems). Due to such shortcomings, much effort has been made in reliable strong ground motion simulation from finite-faults.

The Stochastic finite-fault method, proposed by Beresnev and Atkinson (1997, 1998a) is one of the simplest, yet powerful methods for predicting ground motions during large earthquakes. The accuracy of the method has been proven during the many attempts that have been made for predicting the ground motion, around the world (e.g. Beresnev and Atkinson (1998b, 1999)). The method generalizes the Stochastic ground motion simulation technique, developed for point source, to the case of finite faults, in which theoretically or experimentally determined characteristics of the source, path and site are included.

In this study the above mentioned method is used for calibrating a model that can be used to simulate strong ground motions obtained during the 2002 Avaj earthquake in which the information needed related to path and site is extracted from Kamalian et al. (2005).

On June 22, 2002, a major earthquake with estimated magnitude M_W 6.5 occurred near Avaj (250 km west of Tehran) in NW Iran at 2:58:27.2 (GMT or 7: 28: 27 local time). The earthquake killed over 226 and injured more than 1300 people. The earthquake was felt at Tehran and affected 373 villages around Ghazvin, Hamedan, Zanjan and Arak cities (Figure 1).

2 DATA

The strong ground motion data, which were used, are related to the 2002 Avaj earthquake with magnitude M_W 6.5. These data have been recorded by 58 stations. All the instruments are of SSA-2 type with threshold of 10 gals. The recordings are digital and of relatively short duration. Therefore, they comprise direct arrival with larger amplitudes.

Through recorded accelerograms during the main shock, 27 accelerograms recorded at Avaj, Abegarm, Shirinsou, Abhar, Bahar, Darsjin, Kabodar-ahang, Razan and Razeghan, stations installed at distances ranging from 28 up to 100 km with respect to the epicenter of the earthquake examined were used to calibrate a model for strong ground motion simulation using the Stochastic Finite-fault Method.

The original digitized accelerograms have been processed following a standard procedure. The corrected acceleration, velocity and displacement were obtained after applying instrument correction, baseline correction and band pass filtering. Table 1 lists the salient features of these stations while their geographical locations are shown in figure 1. Maximum accelerations equal to 429 $cm.s^{-2}$ and 455 $cm.s^{-2}$ for the two horizontal components and 292 $cm.s^{-2}$ for the vertical component were recorded at Avaj station.

Figure 2 shows the uncorrected and corrected traces recorded at the Avaj station.

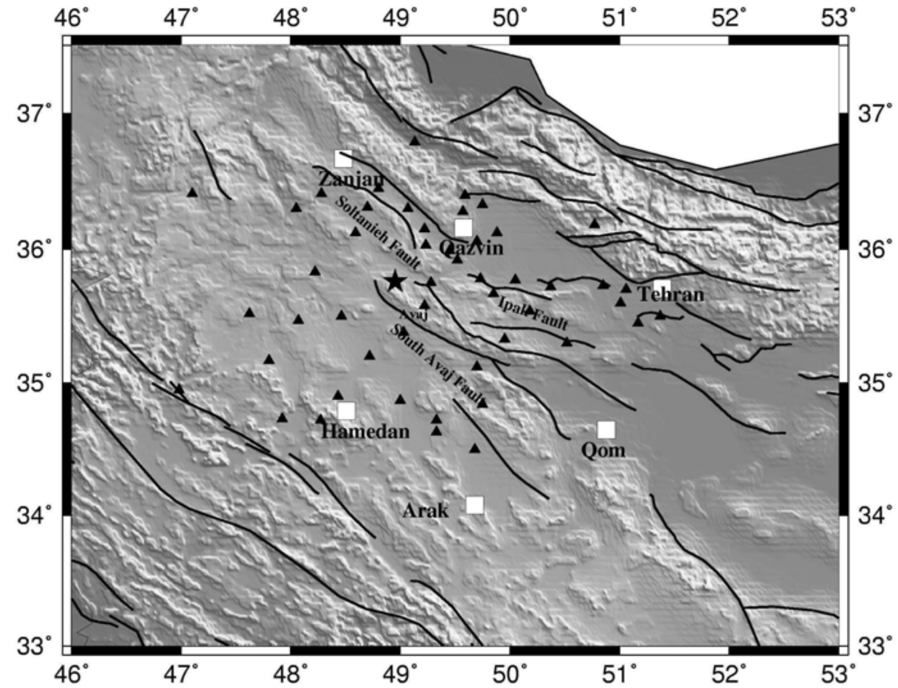

Figure 1. Location of strong ground motion stations and epicenter of Avaj earthquake.

Table 1. The coordinates of recoding strong ground motion used.

STATION	Coordinate		C.P.G.A ($m.s^{-2}$)			C.P.G.V ($m.s^{-1}$)		
	E	N	L	V	T	L	V	T
ABEGARM	49.28	35.75	1.2604	0.4893	1.3163	0.1101	0.0385	0.0978
AVAJ	49.22	35.58	4.6260	2.7112	4.3217	0.2181	0.1003	0.2025
RAZAN	49.03	35.38	1.8688	1.2544	2.0153	0.1099	0.0481	0.0934
SHIRINSO	48.46	35.50	1.7550	0.8726	1.2639	0.0831	0.0397	0.0562
DARSCHIN	49.23	36.03	0.5573	0.4479	0.7569	0.0381	0.0300	0.0402
KABODARAHANG	48.72	35.20	0.8469	0.6899	1.6532	0.0604	0.0310	0.0545
BAHAR	48.43	34.90	0.3318	0.1727	0.3950	0.0157	0.0134	0.0236
KHARAGHAN	49.95	35.33	0.3683	0.1999	0.4724	0.0208	0.0115	0.0209
ABHAR	49.22	36.15	0.3701	0.2820	0.7365	0.0495	0.0419	0.0756

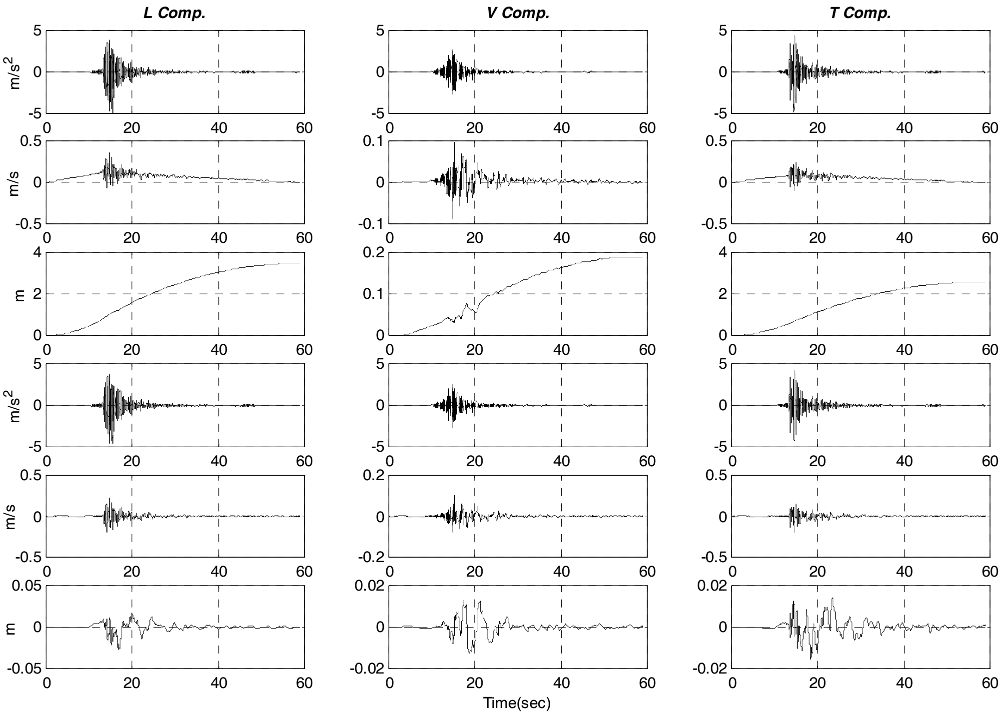

Figure 2. The uncorrected (upper 3 rows) and corrected (lower 3 rows) acceleration, velocity and displacement time histories for Avaj station.

3 METHOD

The basis of the Stochastic method relies on the works of Hanks and McGuire (1981), who combined seismological models of the spectral amplitude of ground motion with the engineering notion that high-frequency motions are basically random (Boore 1983).

In the finite fault method, simulations of some weak earthquakes caused by subfaults, which constitute a major fault, are presented as an approach to predict the near field ground motions.

A major fault is divided into N subfaults, considered as a point source with an ω-square spectrum, which can be fully defined by two parameters: the seismic moment and the corner frequency of the subfault spectrum.

The seismic moment of each subfault, m_0 can be calculated using equation (1).

$$m_0 = \Delta\sigma.\Delta l^3 \tag{1}$$

where $\Delta\sigma$ is the stress parameter and Δl is the subfault size (Beresnev and Atkinson, 1997 and 1998a). The subfault corner frequency, f_c can be obtained using equation (2).

$$f_c = \frac{k.\beta}{\Delta l} \tag{2}$$

Where k is the spectral decay parameter and β is the shear wave velocity.

Ground motions of each subfault are added together considering a proper delay time to obtain the ground motion from the entire fault as:

$$a(t) = \sum_{j=1}^{nw} \sum_{i=1}^{n\ell} a_{ij}(t + \Delta t_{ij}) \tag{3}$$

where nl and nw are the number of subfaults along the length and width of the main fault, respectively, Δt_{ij} is the relative delay time from the radiated wave from the ij subfault to reach the observation point. The heterogeneity of the fault can be considered in the calculation of the seismic moment of each subfault, based on the relative amount of slip of each subfault (Motazedian and Atkinson, 2004).

The Stochastic finite fault simulation contains effects of rupture geometry, heterogeneous slipping distribution, directivity effect, etc (Beresnev and Atkinson, 1998b), in this manner the Fourier amplitude spectrum of ground motion, $A(\omega)$ is represented as:

$$A(\omega) = 2\omega^2.S(\omega).P(\omega).e^{\omega R/2Q\beta} \quad (4)$$

where ω is the angular frequency, R is the hypocenral distance and β is the shear wave velocity. In the above equation, S (ω), accounts for the effects of the seismic source, P (ω) accounts for the spectral cut-off over a certain frequency and the last phrase represents the exponentially decay of the ground motion amplitude by increasing hypocentral distance proportional to quality factor of shear waves, Q_β .

4 MODELING PARAMETERS

In the methodology of Beresnev and Atkinson (1997, 1998a) modelling of the finite source requires information on the orientation and the dimensions of the fault plane, as well as information on the dimensions of the subfaults. Based on spatial distribution of aftershocks, the length of the fault was taken as 25 km and its width as 18 km. According to equation (5) proposed by Beresnev and Atkinson (1998b) for determining subfault size, the fault plane was divided into 5×3 elements.

$$\text{Log}(\Delta l) = 2 + 0.4M \quad (5)$$

where Δl is the subfault size and M is the moment magnitude.
The selected fault model is depicted in figure 3.

Regarding the strike and dip of the causative fault, there is controversy among the articles published as shown in table 2. Nevertheless, the values mentioned in table 2 were tested and the best results were obtained due to the values proposed by Hamzehloo (2005).

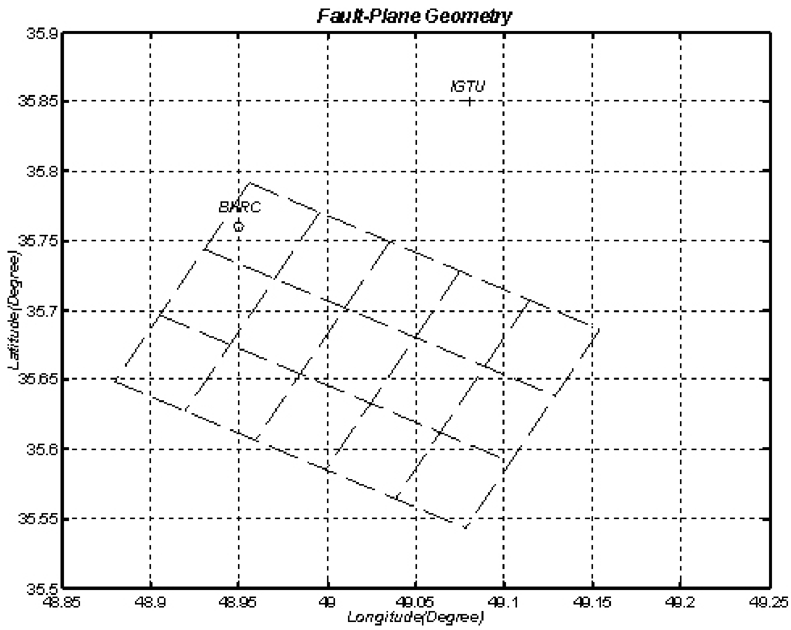

Figure 3. Surface projection of the assumed causative fault with reported epicenters by BHRC and IGTU.

Table 2. Values determined based on several studies for strike and dip for causative fault of 2002 Avaj earthquake.

Strike	Dip	Ref.
100	26	Hosseini et al (2002)
118	53	Hamzeloo (2005)
123	53	ERI (2002)
117	52	USGS

In addition the above method needs information related to attenuation, site characterization and spectral decay parameter, which determines the shape of the Fourier amplitude spectra at high frequencies.

S-wave attenuation is approximated from near field accelerograms, triggered during the main shock of the Avaj earthquake as equation (3) (Kamalian et al. 2005).

$$Q_\beta = 63f^{0.9} \quad (6)$$

It might be worth mentioning that for some regions with a well determined velocity model we can convolve the radiation from the source with theoretically calculated path effects but in the case where we do not have any reliable velocity model we can consider path effect as the multiplication of the geometrical spreading and Q functions (Boore, 1983).

For each of the stations mentioned, the K parameter, which actually controls the level of high-frequency radiation in the simulated time history, was determined based on the Anderson and Quass (1988) proposed method. In this method, the K parameter has been related to the slope of the line fitted to the acceleration spectrum at high frequencies, through relation:

$$a(f) = A_o.e^{-\pi\kappa f} \qquad f > f_E \quad (7)$$

$a(f)$ is the amplitude spectrum of acceleration, f is the frequency, A_0 is the factor depends on source, path and maybe some other factors and K is the spectral decay parameter.

Figure 4. is an example which shows the line fitted to the high frequency portion of acceleration spectra at Abhar station, the whole results related to determining spectral decay parameter and evaluating quality factor for shear wave using accelerographs obtained during the main shock of the Avaj earthquake are given in Kamalian et al. (2005), in addition the K values determined for stations used are listed in table 3.

Regarding that there was no geophysical or geotechnical attempts to determine site classes, the site amplification factor for each of the stations used was approximated using horizontal to vertical spectral ratio (HVSR) or receiver function technique (equation (5)), which can be computed at each j site for the i event at the central frequency f_k from the root mean square average of the amplitude spectral (Field et al. 1995).

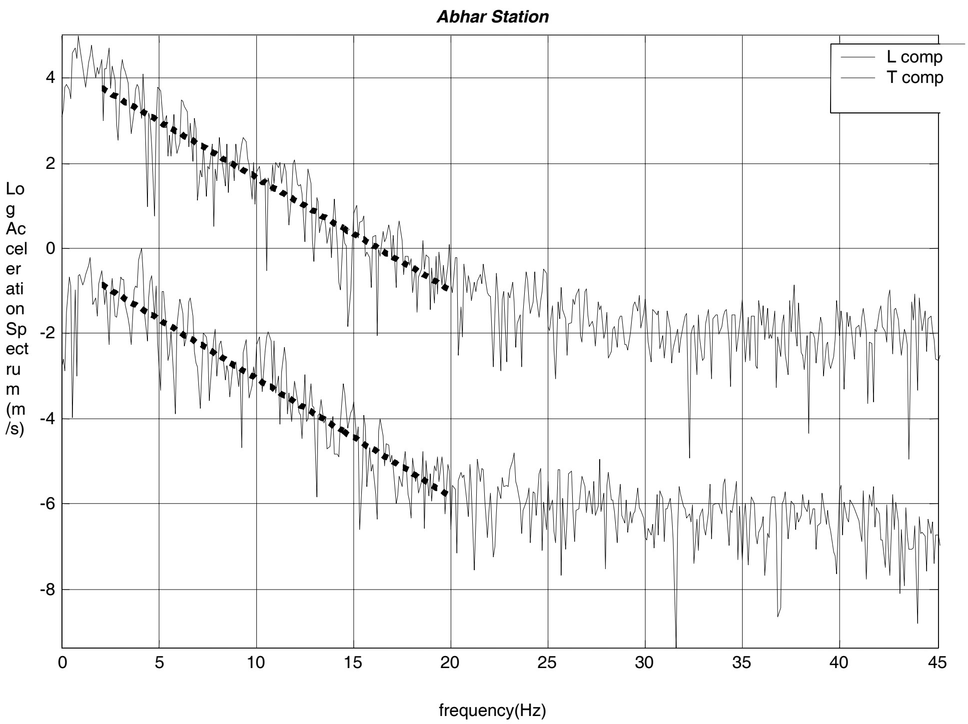

Figure 4. Line fitted to high frequency portion of acceleration spectra at Abhar station.

Table 3. K values determined for stations used in the present study.

STATION	Spectral decay parameter		
	L	T	Ave
ABEGARM	0.098	0.112	0.105
AVAJ	0.059	0.056	0.058
RAZAN	0.046	0.056	0.051
SHIRINSO	0.061	0.053	0.057
DARSCHIN	0.075	0.077	0.076
KABODARAHANG	0.056	0.050	0.053
ABHAR	0.088	0.084	0.086
BAHAR	0.055	0.052	0.054
KHARAGHAN	0.098	0.110	0.104

$$HVSR_{ij}(f_k) = 1/\sqrt{2}\ \frac{sqrt(absH_{ij}(f_k)^2_{NS} + absH_{ij}(f_k)^2_{EW})}{absV_{ij}(f_k)} \quad (8)$$

where:

$H_{ij}(f_k)_{NS}$: Fourier spectra of the NS component,

$H_{ij}(f_k)_{EW}$: Fourier spectra of the EW component

$V_{ij}(f_k)$: Fourier spectra of the vertical component.

Figure 5 shows the specified amplification factor determined for the Shirinsou station using the HVSR method.

Another important input parameter of the methodology employed is the stress parameter $\Delta\sigma$ since $\Delta\sigma$ is known to have very great uncertainties for past events and even greater for future ones (Beresnev and Atkinson, 1998b), its value was kept at 50 bars, following the suggestion of the writers of the simulation code used (Beresnev and Atkinson, 1998a). All of the parameters used are tabulated in table 4.

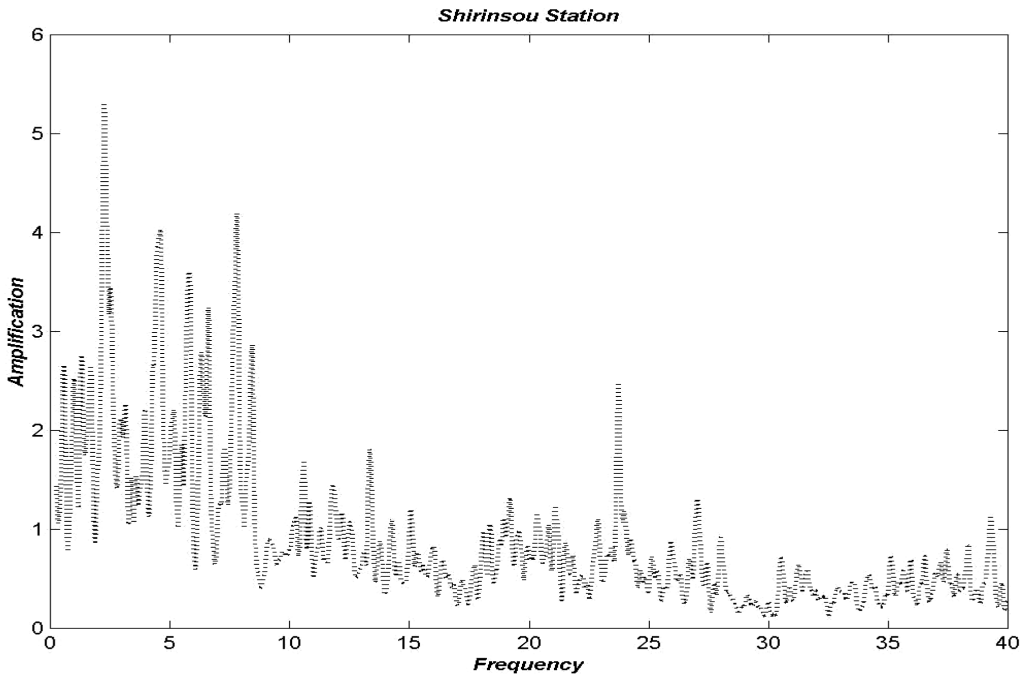

Figure 5. Specified amplification factor determined for Shirinsou station, using the HVSR method.

5 RESULTS

As can be seen in table 4 the only parameter which has no systematic or even empirical approach is the sfact parameter. The sfact parameter accounts for the amplitude of the radiation at frequencies higher than the corner frequency of the subfaults. Expected values of sfact are in the 0.7 to 2 range. We tested different values in the acceptable range and suggest 1.7 for sfact. Low values of the sfact are related to the event with slower slip and vise versa (Beresnev and Atkinson, 1998b).

The installation of a dense temporary network, by IIEES, one day after The Changureh-Avaj main shock gave us the opportunity to derive the fault dimensions, directly from aftershocks. Based on spatial distribution of aftershocks, the length of the fault was taken as 25 km and its width as 18 km, in addition the size of the subfault is derived using empirical relation given by Beresnev and Atkinson (1998b) as 5 km so the fault plane is devided into 5×3 elements.

In figure 6-7 the Fourier spectra of simulated and recorded data at each station are compared, together with the S portion of L and T components, as well as the S part of the simulated one.

The simulated traces consist of random horizontal components and have the same sampling interval as the recorded traces to which they are compared (0.005 sec).

Regarding the observed baseline offset in simulated traces, the PGA values related to correct and uncorrected simulated time histories are compared with real ones and the results are given in table 5. In addition the Fourier spectra of simulated traces are not affected due to baseline correction procedure in frequencies higher than 0.1 Hz as can be seen in table5; it has only negligible effect on obtained PGA values.

Table 4. Modeling parameters used for simulating 2002 Changureh-Avaj earthquake.

Parameter	Changureh-Avaj Earthquake
Fault orientation	strike 118, dip 53
Fault length (km)	25
Fault width (km)	18
Mainshock moment magnitude (M)	6.5
Stress parameter (bars)	50
Subfault dimensions (km)	5
Number of subfaults	18
Crustal shear-wave velocity (km/sec)	3.5
Crustal density (g/cm3)	2.8
Distance-dependent duration term	$1/f_c + 0.05R$
Geometric spreading	$1/R$
Q(f)	$63f^{0.9}$
Windowing function	Saragoni-Hart
sfact	1.7

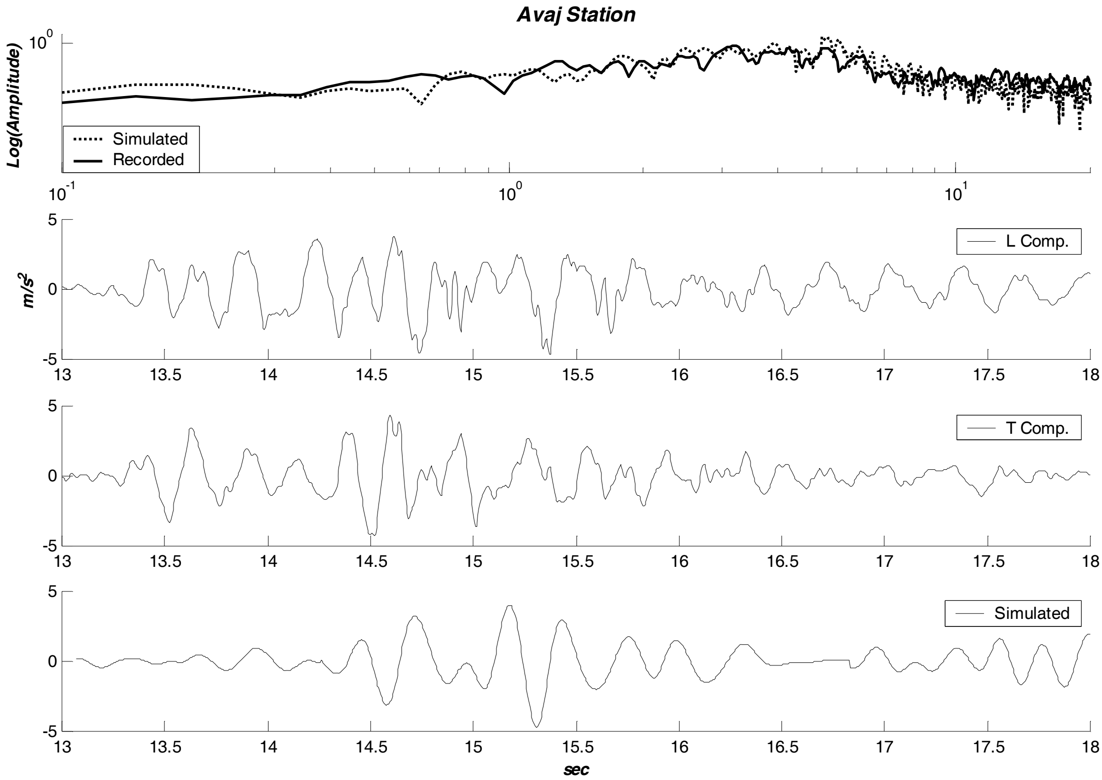

Figure 6. Fourier spectra of simulated and recorded time histories at horizontal components at Avaj station together with the S portion of L and T components, as well as the S part of the simulated one.

Table 5. Estimated error between simulated and recorded time histories.

Station	PGA (g/10)	Sim(Corrected) ($m.s^{-2}$)	Simulated(un) ($m.s^{-2}$)	Error (%)	Site Class
Avaj	4.4738	4.7011	4.697	5	1
Abegarm	1.2883	1.3352	1.3789	3	4
Razan	1.942	1.6991	1.7378	10	4
Abhar	0.5533	0.5007	0.5277	4	4
Bahar	0.3634	0.3889	0.4005	7	1
Darschin	0.6571	0.6144	0.5938	6	4
Razeghan	0.4204	0.4994	0.5056	18	4
Shirinsou	1.5095	1.4435	1.4016	4	3
Kabodarahang	1.25	0.7618	0.8033	35	1

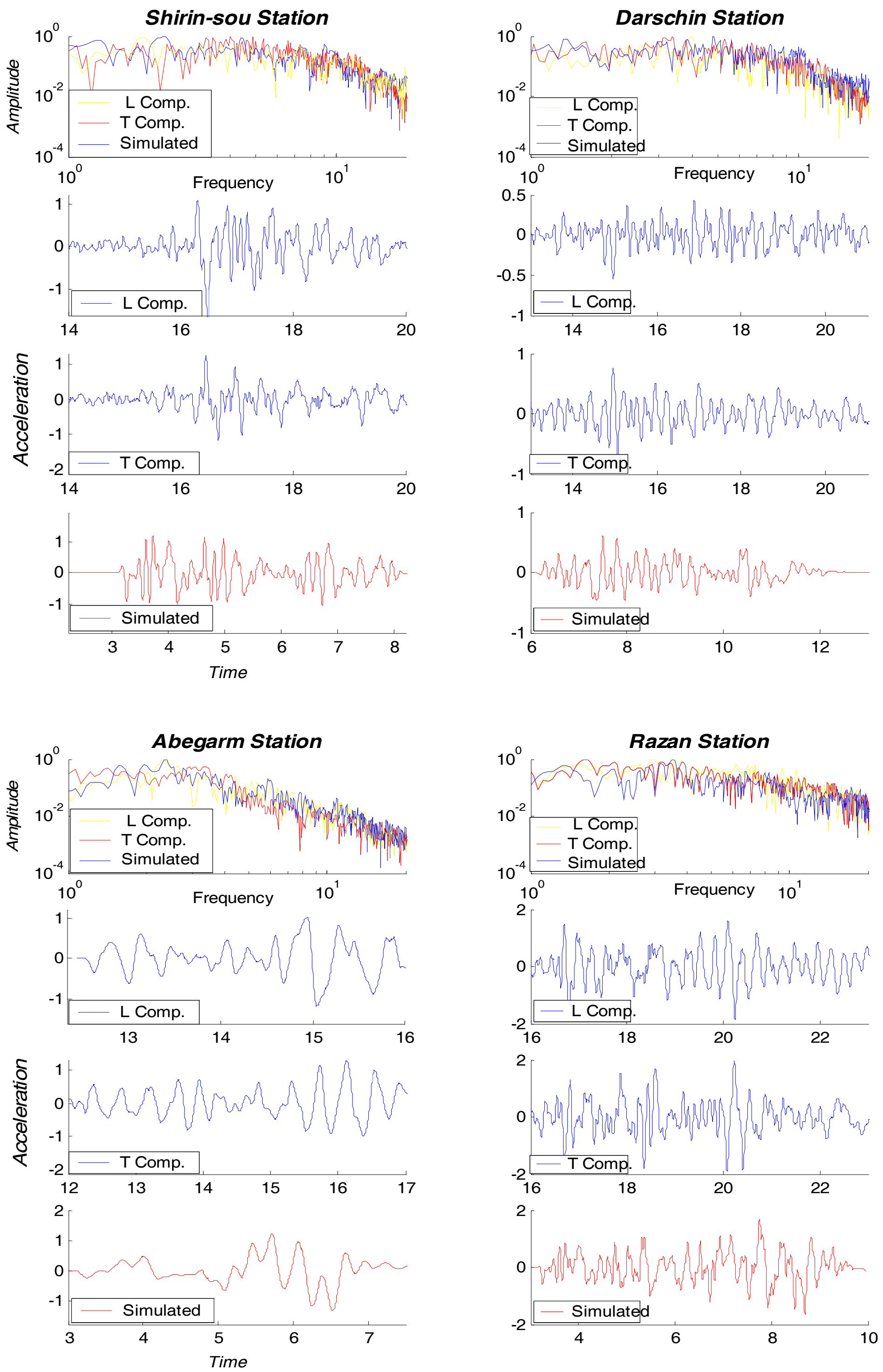

Figure 7. Fourier spectra of simulated and recorded time histories at horizontal components in Abegarm, Razan, Shirinsou, Darschin, Abhar, Razeghan and Bahar stations together with the S portion of L and T components, as well as the simulated one.

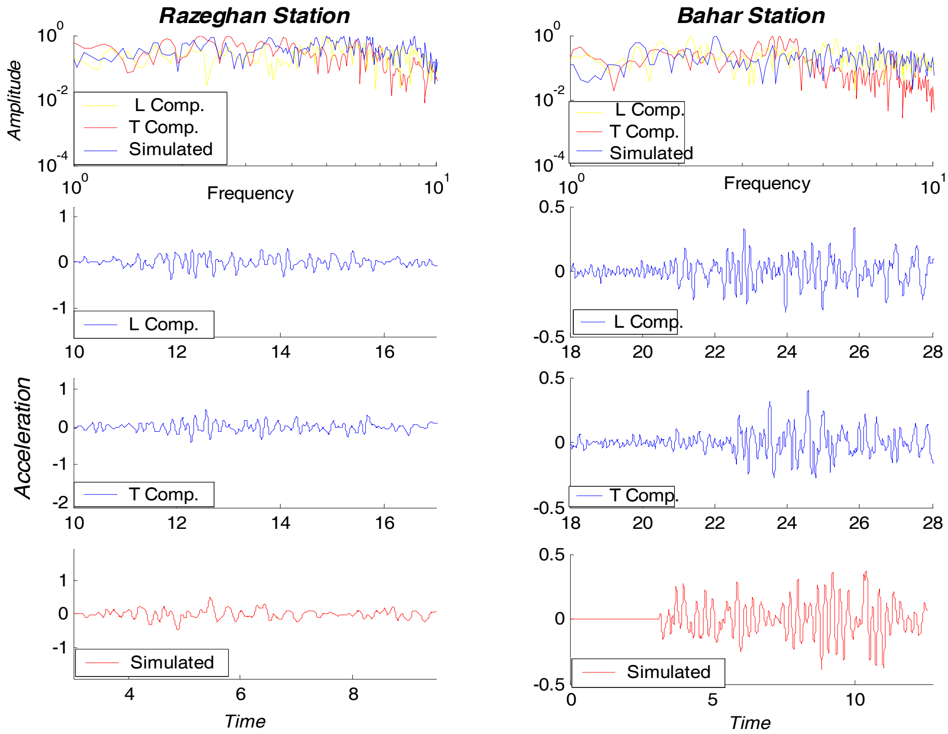

Figure seven continue

6 DISCUSSION

We simulated acceleration time histories and Fourier spectra recorded at Avaj, Abegarm, Razan, Shirin-sou, Darschin, Kabodar ahang, Abhar, Razeghan and Bahar stations, installed at distances ranging from 28 to 100 km with respect to the epicentre of the earthquake examined, during the 2002 Avaj earthquake mainshock. The method used for simulation is the Stochastic finite-fault method proposed by Beresnev and Atkinson (1997). Considering that the site classes for stations used are unknown we employed the H/V ratio technique to estimate site specific amplification function. Based on the attempts made for finding the best element to replace the focal of the earthquake, simulation results proposed that the nucleation start at the northwestern termination of the top of the fault and propagate radially toward southeastern which caused the stations such as Qom, 250 km from the epicenter of the earthquake, to trigger. The proposed nucleation point is in good agreement with the reported epicenter by BHRC determined from strong motion data based on the circle and chord method. The value obtained for sfact, sfact =1.7, shows relatively faster slip on the causative fault of the Changureh-Avaj event. According to the simulation results the amplitude of the spectra observed is generally very well matched in the frequency range (0.5 to 20 Hz), nevertheless large discrepancies are observed in the lower frequency range at most stations. This might be due to representation of the source or the local site amplifications. The overestimation of the simulated spectra at low frequencies observed at Abegarm, Razan and Kaboodar-ahang stations, but not the case at the remaining stations, shows that the source model employed works successfully for them, so the differences observed between simulated and true spectra are attributed to site response. Peak ground accelerations are generally well reproduced (error<10%) except from stations Razeghan and Kaboodar-ahang where estimation errors are 25% and 32% respectively. Nevertheless, considering the error featured using attenuation relationships, they are still quite acceptable.

7 CONCLUSIONS

On the basis of simulation of recorded strong ground motion at 9 stations for the 2002 Avaj earthquake, the following conclusions have emerged:

Results obtained validate the accuracy of the determined attenuation parameter (quality factor) in our previous study.

The assigned model for simulating strong ground motions, could well reproduce the peak ground accelerations of the records studied, in the wide epicentral distance range (28 up to100 km)

The amplitude of the observed spectra is generally very well matched in the frequency range (0.5 to 20 Hz).

Simulation results proposed that the nucleation start at the northwestern termination of the top of the fault and propagate radially toward southeastern caused which stations such as Qom, 250 km from the epicenter of the earthquake, to trigger.

It can be proposed to use the calibrated model for simulating historical or hypothetical earthquakes in the Avaj region for seismic hazard analysis purposes.

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