STUDYING THE IMPORTANT PARAMETERS IN EARTHQUAKE SIMULATION BASED ON STOCHASTIC FINITE FAULT MODELING

H. Moghaddam[1], N. Fanaie[2*] and H. Hamzehloo[3]

[1] *Professor, Dept. of civil Engineering, Sharif University of Technology, Tehran, Iran*

[2] *Ph.d candidate, Dept. of civil Engineering, Sharif University of Technology, Tehran, Iran*

[3] *Assistant professor, International Institute of Earthquake Engineering and Seismology, Tehran, Iran.*

Email: nader.fanaie@mehr.sharif.edu

ABSTRACT:

Opposite to the long period ground motions that can be predicted and estimated, high frequency ground motions have random quality and behave stochastically. Bore stochastic method can be used for modeling high frequency ground motions where there is no accelerograghic record. Stochastic modeling methods are of two kinds: in the first one, seismic source is a point source and in the second, named modeling based on finite fault, seismic source is a rectangular fault plane divided by the same point sources in its longitudinal and traversal directions. Three parameters- quality factor, kappa and stress drop, the important parameters in modeling, are considered in this study. Here, it is found that the main effect of quality factor is on the high frequencies and variation of this parameter has no significant effect on the spectral accelerations in low frequencies. The spectral acceleration and maximum ground acceleration (PGA) decrease when kappa increases; however, the acceleration reduction is higher in high frequencies. Finally, the stress drop increment makes the spectral acceleration increase significantly in high frequencies. In this research the effect of shear wave velocity and density on the modeled accelerations are studied as well.

KEYWORDS*:* Simulation, Finite fault, Spectral acceleration, Quality factor, Kappa, Stress drop.

1. INTRODUCTION

Point source method can not consider ground motion key parameters such as long time duration and amplitude dependence on azimuth of stations (directivity effect) in the large earthquakes. The modeling based on finite fault was presented by Hartzell in 1978 due to the above limitations and strongly accepted in the past two decades [1]. The modeling method based on finite fault combines the aspects of plane source with the ground motion model based on point source and as the mentioned constraints do not naturally exist in modeling based on finite fault, the fracture geometry and directivity effect are considered in this method and good results are obtained. Stochastic finite fault simulation uses time delay method and the summation of accelerograms corresponding to a two dimensional network of subfaults. In This method, applied later experienced by Irikura as well as Beresnev and Atkinson, kinematic source model is applied to describe the fault slip process [2]. Kinematic source model consists of fault fracture geometry (fractured surface area, fault strike and fault dip), nucleation point and rupture velocity. In this method a rectangular plane is considered for the fault and fault plane is divided by rectangular subfaults and it is assumed that the fracture, started from the center of one subfault (hypocenter) is spread radially. The rupture velocity is usually considered as 80% of the shear wave velocity [3]. Each subfault acts as an independent small seismic source when the fracture reaches its center and starts to propagate the seismic energy. The acceleration time history is distributed to the observational point considering the experimental time relation based on the distance, geometrical spreading and Q damping models. The accelerograms, generated by each subfaults based on Brune`s source model are summed, considering their corresponding delay times to be achieved the accelerogram of the total fault plane. In the simulation based on finite fault modeling, each subfault, as a point source, uses the source model presented by Brune with a corner frequency and a constant stress drop. This simulation method is a proper one and used broadly in the assessment of strong ground motions. At the distance, far from the fault plane, the source can be considered as point source and the modeling by point source is more appropriate as it needs fewer calculations. The assessment of point source and plane source results clarify that the plane source model provides more accurate results in the periods over one second comparing to the point source model. Both models provide proper and comparable results in the periods less than one second.

In this article the stochastic finite fault simulation is discussed and the achieved improvements in the programs which use this method are explained. Then, the effects of important parameters, used in the simulation based on finite fault, are analyzed and the effects of these parameters on the modeled accelerograms, the goal of this research, are clarified by changing the quality factor, kappa and stress drop. Moreover, the effects of shear wave velocity and density on the simulation are studied as well. As finite fault modeling is based on the Boore`s stochastic method, first Boore`s stochastic method is interpreted and seismic source spectrum, used in this method, and other factors effective in modeling such as kinds of damping, site effect and amplification phenomenon are studied.

2. BOORE STOCHASTIC METHOD

In Boore stochastic method, the high frequency motions of earthquakes can be presented as the Gaussian noise with limited frequency band having the mean source spectrum w^2. Stochastic modeling method, using the seismic point source was presented by Boore in 1983. The base of this method is that the shape function is applied to a time series of white noise with zero mean, bringing it out of the stationary status, then the Fourier transformation is applied to the noise and the amplitude spectrum of this time series is substituted by a desired spectrum, discussed in the following, and the phase spectrum remains unchanged. The transformation in the time domain results in a time series whose amplitude spectrum is exactly in accordance with a specified spectrum. The graph, used for amplitude spectrum, can represent the motion with limited band in the records [4]. Due to the success of this method in assessing peak ground acceleration, a w^2 spectrum with the inelastic attenuation related to the path and constant stress drop parameter ($\Delta\sigma$) is used in Boore simulation method. It seems that this method can consider all principle aspects of high frequency ground motions for broad band of large earthquakes with different magnitudes. Applying Boore method needs the spectral shape of amplitude as a function of earthquake magnitude. In Boore stochastic method, only the shear wave incorporation in the ground motions is considered and it is known that the shear waves are dominant almost in all cases especially in the horizontal components of ground motions. Boore method constraint is to produce only the shear wave pulses and can not simulate the received phases of surface waves [5].

3. SEISMIC SOURCE SPECTRUM

Fourier amplitude spectrum of ground motion used in Boore stochastic modeling can be expressed as a product of a number of factors in the frequency domain [6]:

$$A_x(f) = S(f).G.A_n(f).P(f).V(f) \quad (3.1)$$

In Eqn. 3.1., S(f) is source factor, G is geometrical attenuation factor, $A_n(f)$ is the inelastic whole path attenuation factor, P(f) is the upper crust attenuation factor and V(f) is the upper crust amplification factor.

3.1. Source factor S(f)

Fourier amplitude spectrum of Brune source model for the acceleration of seismic shear waves generated at the source of an earthquake, S(f), is represented by:

$$S(f)=\frac{CM_0(2\pi f)^2}{1+(\frac{f}{f_c})^2} \qquad (3.2)$$

Where C is a scaling factor, M_0 is the seismic moment, f is the frequency and f_c is the corner frequency. The scaling factor, C, introduced in Eqn. 3.2. is defined as follows:

$$C=\frac{R_{\theta\phi}(Fs)(PRTITN)}{4\pi\rho\beta^3} \qquad (3.3)$$

where, R□□ is the wave radiation factor (55%), F_s is free surface amplification factor [2], PRTITN is the factor partitioning energy into the orthogonal directions (0.707), ρ is the density of the rock at the depth of rupture and β is the shear wave velocity of the rock at the depth of rupture.
The source model, defined in Eq. 3.2. is known as. ω^2 source model (Brune source). f_c which affects the acceleration amplitude and controls the frequency content of earthquake generated in the source, is proportional to the inverse fault fracture time and is obtained by the bellow formula [6]:

$$f_c = 4.9\times10^6\,\beta\,(\frac{\Delta\sigma}{M_0})^{\frac{1}{3}} \qquad (3.4)$$

where, β is expressed in km/s, Δσ in bars and M_0 in dyne.cm.

3.2. Geometrical attenuation factor G

The geometrical attenuation factor, G, which represents geometrical damping is expressed as [6]:

$$G=(\frac{R_0}{R})^n \qquad (3.5)$$

where, R is the distance from the assumed point source (in km), R_o is the distance unit (1km) and the exponent n depends on R. The spherical spreading of these waves results in a 1/R decay in the associated Fourier amplitude (i.e. n=1).

3.3. Inelastic whole path attenuation factor $A_n(f)$

In order to consider the inelastic attenuation, $A_n(f)$ is defined by Boore and Atkinson in 1987 as follows [7]:

$$A_n(f)=e^{-\frac{\pi fR}{Q\beta}} \qquad (3.6)$$

where, f is wave frequency, R is the length of the wave travel path, β is the shear wave velocity and Q is the wave transmission quality factor.

3.4. Upper crust attenuation factor P(f)

For P(f) and $A_n(f)$ similar phrases have been chosen and the P(f) has become as bellow[8]:

$$P(f)=e^{-\pi\kappa f} \qquad (3.7)$$

In the above Eqn. , κ parameter, named kappa, is in second.

3.5. Upper crust amplification factor V(f)

The change in amplitude of seismic shear waves crossing the boundary between two media (from A to B) is in accordance with the principal of energy conservation. The amplification factor, V, has been defined by Boore and Joyner in 1997 as [9]:

$$V(f) = \sqrt{\frac{\rho_A V_A}{\rho_B V_B}} \tag{3.8}$$

where, ρ_A, ρ_B and V_A,V_B are the densities and shear wave velocities respectively, in A and B media.

4. STUDYING THE EFFECTS OF MODELING MAIN PARAMETERS

In order to study the effects of modeling main parameters in EXSIM program, some simulations are done by this program using Parkfield earthquake causative fault in addition to mathematical discussions. In these simulations in order to distinguish the effect of a specific parameter, the amount of that parameter is changed without altering the amount of other parameters and a series of general results are obtained, presented in the following.

Three parameters of quality factor, kappa and stress drop have effects on the high frequency amplitudes, are studied here along with the effects of shear wave velocity and density:

1- Quality factor effect (Q): Quality factor is usually considered as $Q = Q_0 f^{\eta}$ in the articles and Q_0 and η are input parameters in EXSIM program as well. Considering Eqns. 3.1. and 3.6., it is seen that the main effect of quality factor is in the high frequencies and the change of this parameter has no significant effect on spectral acceleration in low frequencies. Three records are simulated by EXSIM using the causative fault of Parkfield earthquake. In these simulations the values of 120, 180 and 240 are used for Q_0 by keeping other parameters constant. Regarding Fig. 1. and concerning Eqns. 3.1. and 3.6., it is observed that spectral accelerations as well as PGA (which is corresponding to the spectral accelerations in high frequencies) are increased by increasing Q_0; of course, the spectral acceleration increasing rate is greater in high frequencies and smaller in low frequencies. To study the η effect, three records are simulated by EXIM as well. In these simulations the values of 0.2, 0.45 and 0.7 are used for η by keeping other parameters constant. According to Fig. 2, it is seen that the spectral accelerations change is low in low frequencies; however, with η increasing the spectral accelerations and also PGA have been increased in high frequencies. In the precise mathematical discuss, it can be said that the spectral accelerations decrease slightly in the frequencies lower than 1 Hz with η increasing, according to the equation $Q = Q_0 f^{\eta}$, because the frequencies lower than 1 Hz become smaller as they reach the greater power and it can be said that the quality factor decreases with ηincreasing for the frequencies lower than 1 Hz. Quality factor increases with η increasing for frequencies over 1 Hz and consequently the spectral accelerations will increase in these frequencies. It is clear that η change has no effect on the spectral acceleration in 1 Hz frequency because 1 by any power remains still 1. For example one simulated accelerogram corresponding to 180 and 0.45 for Q_0 and η is shown in Fig. 3.
2- Kappa effect (κ): To study kappa effect, three records, κ= 0.03, 0.05 and 0.07, are simulated. Considering Fig. 4. and also the Eqns. 3.1. and 3.7., it is seen that the spectral accelerations and peak ground acceleration, PGA, reduce with κ increasing; of course, the decreasing rate of spectral accelerations is higher in high frequencies. Therefore, the effect of this parameter change on the spectral accelerations curve vs. frequency is mostly rotational.
3- Stress drop effect ($\Delta\sigma$):To study the stress drop effect, three records, $\Delta\sigma$ = 60, 90 and 120, are simulated. Regarding Fig. 5, it is seen that the spectral accelerations increase with the increasing in stress drop; of course, this increment is low in low frequencies and considerable in high frequencies. According to the Eqns. 3.2. and 3.4., it is concluded that both seismic moment and stress drop parameters affect on the frequency content of produced shear waves in the earthquake source. The

spectral acceleration is proportional to $M_0 f_c^2$ and consequently to $\Delta\sigma^{\frac{2}{3}} M_0^{\frac{1}{3}}$ regarding Eqn. 3.4. Therefore, it is concluded that the spectral acceleration is basically pertinent to stress drop and at a lower rate to the seismic moment. It is known that peak ground velocity (PGV) is sensitive to the medium frequencies content and peak ground displacement (PGD) to the low frequencies content. Therefore, it is resulted that the effects of stress drop increase on the increment of peak ground acceleration are greater in comparison with the increasing in the peak ground velocity and displacement. Moreover, considering Eqn. 3.4., it is clear that increasing in the stress drop causes the increase of corner frequency of simulated record. It should be mentioned that stress drop is assessed by bar and as this parameter is not measurable directly, there is high uncertainties on this parameter. For example, the peak ground acceleration can be read easily from the recorded accelerogram, but stress drop parameter can not be measured directly.

4- Shear wave velocity effect (β):To study the effect of shear wave velocity, three records, β= 3, 3.3 and 3.6 km/s, are simulated. Regarding Fig. 6, it is seen that the spectral accelerations as well as peak ground acceleration, PGA, decrease with increasing in shear wave velocity. Its mathematical reason is that the C factor decreases in Eqn. 3.3. in which the shear wave velocity of power 3 placed at the denominator is greater than $A_n(f)$ increase in Eqn. 3.6. In the performed simulation, durations of time histories corresponding to 3.0, 3.3, and 3.6 km/sec shear wave velocities are 10.9, 10.54 and 10.22 sec. respectively. It is observed that the duration of simulated accelerograms reduces slightly when shear wave velocity increases. This reduction is explained in the following. It is known that the rupture velocity is usually assumed as percentage of shear wave velocity (between 70% to 80% of shear wave velocity); EXSIM also assumes the rupture velocity equal to 80% of shear wave velocity. As shear wave velocity increases, the rupture velocity increases as well and consequently the fault will be fractured more rapidly; therefore, the delay time of subfault pulses, reaching to the observation point, will reduce. Concerning Eqn. 3.4., it is clear that increasing in shear wave velocity will cause corner frequency of simulated record increase.

5- Density effect (ρ):to study the density effect, three records, ρ =2.0,2.5,3.0gr/cm^3, are simulated. According to Fig.7, it is observed that the spectral accelerations and peak ground acceleration (PGA) values decrease with density increasing. Its mathematical explanation is that C constant has inverse proportion to the density according to Eqns. 3.1., 3.2. and 3.3. Therefore, if the density multiplies by α, then the peak ground acceleration (PGA), spectral accelerations and Fourier amplitude of simulated accelerograms will multiply by 1/α. It should be mentioned that the density is appeared only in Eqn. 3.3.; where, C constant is calculated and will not enter in any other equations.

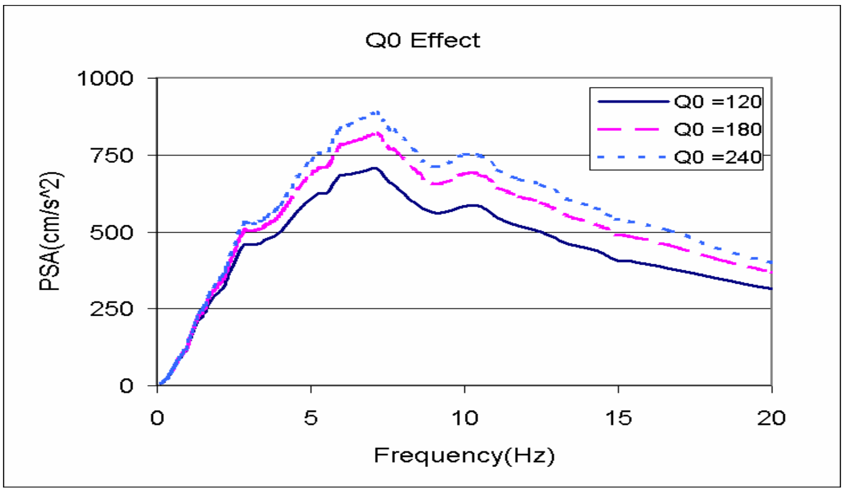

Figure 1 Simulated spectral accelerations for different values of Q_0

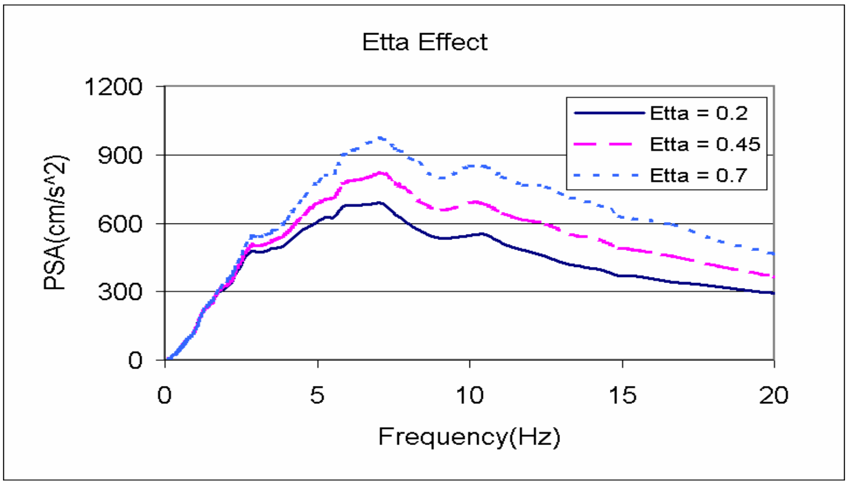

Figure 2 Simulated spectral accelerations for different values of η

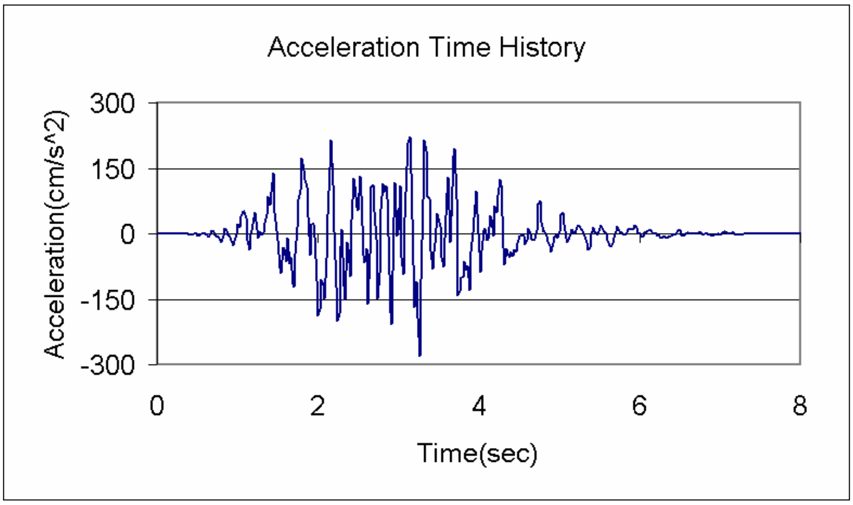

Figure 3 Sample of simulated accelerograms time histories

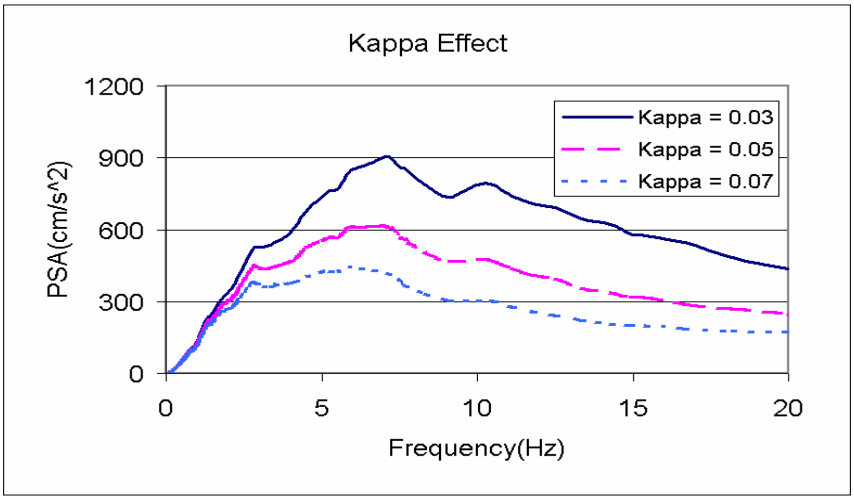

Figure 4 Simulated spectral accelerations for different values of κ

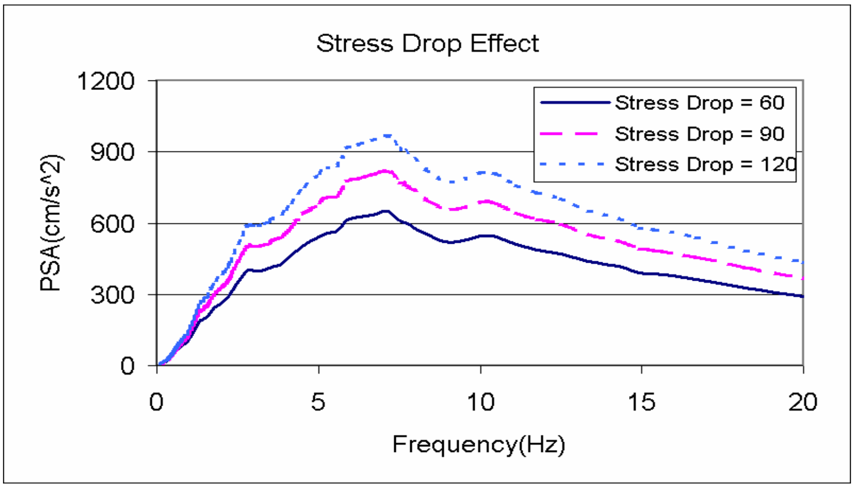

Figure 5 Simulated spectral accelerations for different values of Δσ

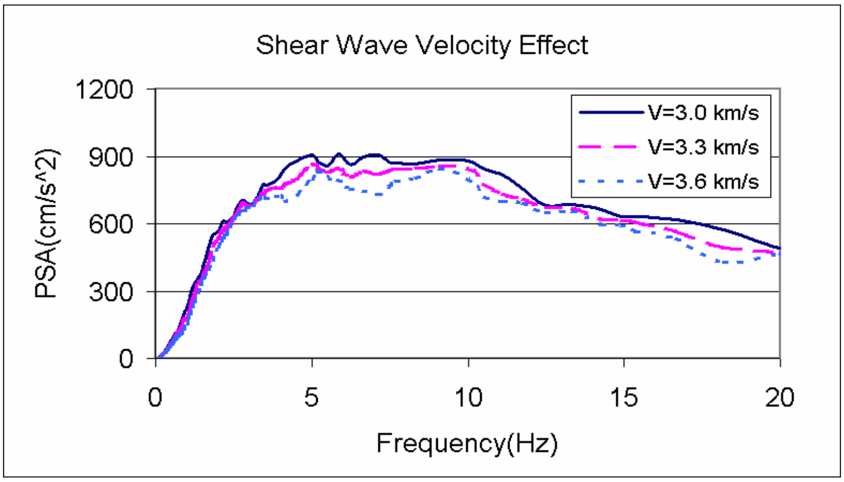

Figure 6 Simulated spectral accelerations for different values of β

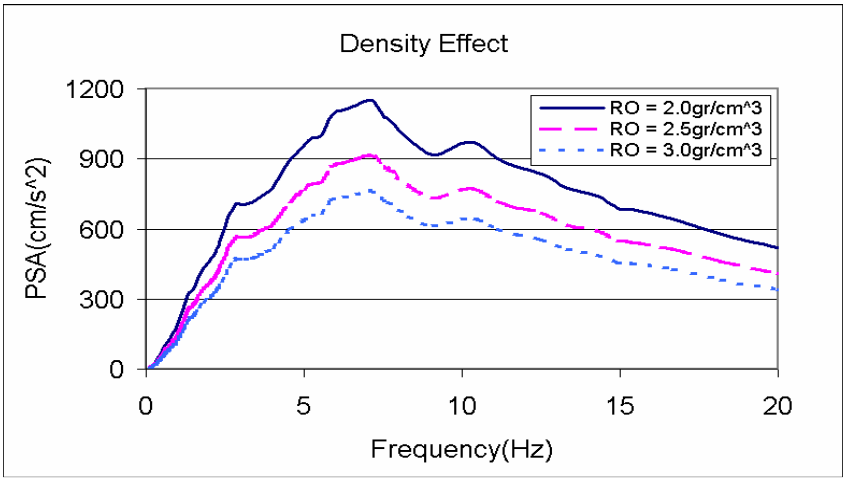

Figure 7 Simulated spectral accelerations for different values of ρ

5. CONCLUSION

The following results are obtained according to the fulfilled simulations:

1) The main effect of quality factor is in the high frequencies and variation of this parameter has no significant effect on the spectral accelerations in low frequencies. With increasing Q_0 in the quality factor $Q=Q_0f^{\eta}$, the spectral accelerations as well as PGA (which is correspondent to the spectral accelerations in high frequencies) will increase; undoubtedly, this increase is greater in high frequencies and lower in the low ones. The spectral accelerations for the frequencies lower than 1 Hz will reduce slightly with increasing in η value as the quality factor values reduce with η increasing in the frequencies lower than 1 Hz. The quality factor values will increase with η increasing in the frequencies greater than 1 Hz and consequently the spectral acceleration values will increase in these frequencies. η change has no effect on the spectral acceleration value in 1 Hz. frequency.
2) The spectral acceleration values as well as peak ground acceleration (PGA) will reduce with kappa increasing; of course the spectral acceleration decreasing value is greater in high frequencies.
3) The spectral acceleration values will increase with stress drop increasing; this amount is low in low frequencies and considerable in the high ones. The effect of stress drop in the increasing of peak ground acceleration is higher than that of peak ground velocity and displacement.
4) The spectral acceleration values as well as peak ground acceleration (PGA) will reduce with shear wave velocity increasing and the duration of simulated accelerogram will decrease slightly as well. Since the fault is fractured more rapidly and the delay time of subfault pulses reaching the observation point will reduce.
5) If the density multiplies by α then the peak ground acceleration value (PGA), spectral accelerations and Fourier amplitude of simulated accelerogram will multiply by $1/\alpha$.

6. ACKNOWLEDGEMENT

The authors are most thankful to Dr. Dariush Motazedian and Dr. Karen Assaturian as the discussion with them about the earthquake simulation based on finite fault modeling as well as EXSIM simulation program has been broadly used here.

REFERENCES

1. Hartzell, S. (1978). Earthquake aftershocks as Green's functions. *Geophys. Res. Lett.* **5**, 1-14.
2. Irikura, K. (1992). The construction of large earthquake by a superposition of small events, Earthquake Engineering. *Tenth world Coference. Balkema. Rotterdam.*
3. Beresnev, I. and Atkinson, G.M. (1998). Stochastic finite-fault modeling of ground motions from the 1994 Northridge, California earthquake. I. Validation on rock sites. *Bull. Seism. Soc. Am.* **88**, 1392-1401.
4. Boore, D.M. (1983).Stochastic simulation of high-frequency motions based on seismological model of the radiated spectra. *Bull-Seism.Soc.Am.* **73(6)**, 1865-1894.
5. Atkinson, G.M. and Silva, W. (2000).Stochastic modeling of California Ground Motions. *Bull.Seism.Soc.Am.* **90(2)**, 255-274.
6. Boore, D.M. (2003).Simulation of ground motion using the stochastic method. *Pure appl.geophys.* **160**, 635-676.
7. Boore, D.M. and Atkinson, G.M. (1987).Stochastic prediction of ground motion and spectral response parameters at hard-rock sites in eastern North America.*Bull.Seism.Soc.Am.* **73**, 1865-1894.
8. Atkinson, G.M. and Silva, W. (1997).An empirical study of earthquake source spectra for California earthquakes. *Bull.Seism.Soc.Am.* **87**, 97-113.
9. Boore, D.M. and Joyner, W.B. (1997). Site amplifications for generic rock sites. *Bull.Seism.Soc.Am.* **87(2)**, 327-341.

995-1010.