Synthesizing the 2006 Silakhor (Darb-e-Astane) earthquake (Iran), using Empirical Green's function method

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Abstract

The main objective of this article is to synthesize the March 31, 2006 Drab-e-Astane earthquake recorded at Chalanchulan station where is located at western part of Iran. The selected station is sufficiently far away from the causative source so as the simulated time series are not influenced by the near source effects such as directivity and fling step. The well known Empirical Green's function is used incorporating a number of recorded aftershocks. The computer software EMPSYN (Hutchings, 1988), is used for simulating the time series thus estimating the seismological model parameters. The Kostrov slip function is used to calculate the slip at a point approximating the shape of slip as a ramp. The three components of simulated strong motions are validated against the observed data in the form of elastic response spectra. Good agreement of the synthesized and recorded time series confirms suitability of the seismological model parameters incorporated. It is concluded that, the model can be used for predicting the strong motion for the region under study to be used in specific site hazard analysis of new and existing important structures.

Keywords: Drab-e-Astane earthquake, Empirical green's function, Kostrov slip function, Simulation.

1. Introduction

Consideration of the post-elastic dynamic response of important structures is of fundamental importance in earthquake engineering as most buildings are expected to deform beyond their linear elastic limit during intense ground shaking. In recent years, the computation of a structure's dynamic inelastic response to an earthquake event has been done more frequently than ever before via time-history analysis. Ideally, the input ground motions to such analyses are past recordings of earthquakes with similar characteristics (e.g. magnitude, distance, and fault mechanism) to the earthquake scenarios that dominate the seismic hazard at the structure's site. Unfortunately, real recordings of ground motions with suitable characteristics are often scarce or non-existent particularly in the region under study Darb-e-Astaneh. This shortage of adequate ground motions has led to the engineering practice of estimating ground shaking based on the regional seismological information.

There are several approaches for modeling earthquake strong motion. Kinematic ω^2 *-based* methods such as those of Boore (Boore ?) and Atkinson (Atkinson ?) through which the rupture process is modeled by postulating a slip function on a fault plane and then using the elastodynamic representation theorem to compute the motion. These Approaches involve the prediction of motions from a fault that has specific dimensions and orientation in a specified geologic setting. As such, this method more accurately reflects the various wave propagation phenomena and is useful for site-specific simulations. Actual ground motion is complicated not only by refraction and reflection due to layer interfaces and ground surface but also by scattering and attenuation due to lateral heterogeneities and anelastic properties in the propagation path. Complete modeling of the wave field in realistic media would be extremely difficult. first successful attempt for theoretical calculation of strong motions was made by Aki (1968) and Haskell (1969), using kinematic source model, given by a propagating dislocation over a fault plane in an infinite homogeneous medium. Their source models are parameterized by five factors, fault length, fault width, rupture velocity, final offset of dislocation and rise time, which are essential for a deterministic fault model (Irikura, 1983).

In many regions, the subsoil medium is not sufficiently known to simulate the wave's propagation in a relevant frequency band for earthquake- engineering purposes (between 0.1 and 25 Hz). An attractive approach to overcome this problem is to sum the recordings of small earthquakes delayed between each other so as to reproduce the rupture propagation effect. Each of the small-earthquake recordings represents all the propagation effects between the source and the receiver and then is regarded as an empirical Green's function (Hartzell, 1978). It is a most advantageous method because the Green functions include complex effects of the dynamical rupture process on the fault as well as heterogeneous structures around the source and an observation site, which are extremely cumbersome to evaluate (Irikura, 1983).

Irikura and Muramatu (1982), and Imagawa and Mikumo (1982) improved Hartzell's method by introducing the phase delayed summation with a specific time function to correct for the difference in the source time function between the main shock and the small events. However, it is important to note that this method does not account for eventual nonlinear soil effects.

The method used in this study only synthesizes linear-soil-response ground motion. Two of the sites studied are on alluvial deposits, and it is possible that nonlinear effects occurred during the main earthquake.

2. Basic of Green's Functions

Empirical Green's functions are defined here as recordings of effectively impulsive point source events (Hutchings and Wu, 1990). The empirical Green's functions have a better accuracy at high frequencies, where geologic in homogeneities are not well modeled, and the synthetic Green's functions have better accuracy at lower frequencies, where empirical Green's functions do not have sufficient energy.

Empirical Green's functions include the actual effects of velocity structure, attenuation, and geometrical spreading. However, it is not possible to record empirical Green's functions from all locations along a fault of interest and with the same focal mechanism solution, so that source locations of empirical Green's functions have also been interpolated to fill in the fault.

The spatial dependence of empirical Green's functions has been researched by Hutchings and Wu (1990) and they 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, and Hutchings (1991), Hutchings (1994), and Hutchings, Jarpe and Kasameyer (1996) found that interpolation for different source locations along a fault works quite well. Also, it is not necessary to have source events fall directly along the fault of interest, but to be located near the fault (Hutchings 1997).

The basic assumptions in this study when using empirical Green's functions are that (1) they are effectively from step-impulsive point-dislocation sources over the frequency range of interest so that spectral shapes and the time series are primarily a result of propagation path and site effects; (2) they can be interpolated for source locations where small earthquakes did not occur or for different focal mechanisms by using equation (2); and (3) their recording site geology has the same linear elastic response for weak ground motion recorded from small earthquakes and strong ground motion from large earthquakes. The first and second assumptions are examined by Hutchings 1991. The third assumption is not analyzed here (Hutchings 1991).

Our synthesis is implemented by the computer code EMPSYN (Hutchings, 1988), which calculates synthetic seismograms by numerically computing the discredited representation relation with empirical Green's functions (EGF). It uses the form (Hutchings & Wu 1990; Hutchings 1991) for synthesized ground motion:

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

Where (X, t) are position and time in space relative to the hypocenter and the origin time of the synthesized earthquake is the number of elements and i refer to values at an element. A_i is an elemental area such that $\sum A_i$ equals the total rupture area. μ_i is the rigidity at an element. $S(t')_i$ is the desired slip function at an element analytically deconvolved with the step function.

$e_n(X, t'-t_r)_i$ 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 rupture time from the hypocenter to the element, which is the integral of radial distance from the hypocenter of the synthesized earthquake divided by the rupture velocity, which can be a function of position on the fault. Me0i is the scalar seismic moment of the source event, and * is the convolution operator. U_n has the same units as e_n (Hutchings, 2007).

EMPSYN uses a summation of step functions to model the Kostrov or Haskell slip functions in the time domain. In this study used Kostrov slip function with Healing Phases proposed by Hutchings. The time delay for the step functions' summation is at the digital sampling rate of the EGFs to ensure that high-frequency artifacts are higher than the frequency range of interest. In the frequency domain, EMPSYN employs a ramp function with all the parameters of the Kostrov or Haskell slip functions. Hutchings (1994) showed that the difference in computed seismograms using the ramp to model the shape of the Kostrov slip function was indistinguishable in the frequency range of 0.5 to at least 15.0 Hz (Hutchings 2007).

3. Site Soil Conditions

The strong motions were synthesized based on linear-soil-response ground motion. The site soil condition of some stations are not be specified. Based on information obtained from BHRC, site soil condition for two stations Dorood and Khoram-Abad are summarized in Table.1. The site soil conditions for other stations have not been specificly cleared.

4. Aftershock data

A number of aftershocks, in the form of three-components, have been reported at some stations during the March 31, 2006 Darb-e-Astane (Silakhor) main shock [29]. Some of these aftershocks were selected to be used for synthesizing strong motions as will be explained later.

Table.1. shows the station names and locations, number of EGFs recorded at each station, references presenting the EGFs information and the site soil condition of some of the stations obtained from BHRC. The site soil conditions, shown in the Table 1, are classified according to the Iranian standard No. 2800, which is compatible with those of NEHRP Code.

Table1. Station names, locations and number of EGFs that recorded at each station in 2006 Darb-e-Astane Earthquake.

Station	Longitude Degree	Latitude Degree	Orient. L,T-90	No of EGF	Geological Classification	
					Standard NO. 2800	NEHRP CODE
Chalanchulan	48.913	33.659	110	8	---	---
Dorood	49.059	33.491	215	2	III-B	D
Khorram-Abad	48.359	33.491	003	5	III-C	D

Clearly, it is not possible to record empirical Green's functions from all locations along a fault of interest and with the same focal mechanism solution, so that source locations of empirical Green's functions have also been interpolated to fill in the fault (Hutchings and Wu, 1990). Also, it is not necessary to have source events fall directly along the fault of interest, but to be located near the fault. In synthesis, we have the option of correcting for different focal mechanism solutions, but Hutchings and Wu (1990) and Hutchings, Jarpe and Kasameyer (1996) found that for high frequencies it does not improve the synthesis. Interpolation is performed by correcting for attenuation, l/R, and P- and S-wave arrival times due to differences in source distance. We include the radiation pattern effect for low frequencies, when we use synthetic Green's functions.

5. Crustal Model

The crustal velocity model proposed by Haddon (1995), is used for calculating synthetic Green's functions. Program EMPSYN utilizes a linearly increasing velocity model that approximates the model listed to determine rupture and healing velocity during rupture for interpolation of empirical Green's functions. The velocity model is approximated by:
$V_p = 5.38 + 0.047*Z$, and $V_p = 7.1$ at 36.0 km; where Z is depth.

6. Modeling and result

The well known EGF approach was used for estimating the three components of strong motions at Chalanchulan station, using the FORTRAN program “EMPSYN” originally written by Hutchings (1988).

Some investigators have previously reported source parameters information of the causative main shock. In this study, we carried out a sensitivity study to obtain the most suitable model parameters such as epicenter location, focal depth, focal mechanism (strike, deep and rake), rupture length and width. In that, we changed one of these parameters by scaling its values while keeping constant the others. Finally, we selected the parameters corresponding to the average scaling factors and incorporated into the model. Table 2 shows the final seismological parameters together with those of other investigators. The seismological parameters of main shock, such as epicenter location, focal depth, focal mechanism (strike, deep and rake), rupture length and width, obtained from the final values of model parameters, were incorporated in the model and the three components of main shock in the form of acceleration time histories were simulated at Chalanchulan Station using the aftershocks recorded at the above mentioned station.

The simulated time series were validated against recorded data at stations sufficiently far away from the causative source aimed at not being influenced by the near source problems such as directivity and fling step effects. Figure 1 demonstrates the observed and simulated acceleration time histories at Chalanchulan station (L., T. and V. Components). Figure 2 shows the comparison of simulated elastic response spectra at this station with those of observed data. Good match of synthesized and recorded data confirms the reliability of model used and appropriateness of the selected model parameters. It is notable that, we do not claim that, a) the two well known uncertainties, aleatoric and epistemic, inherently existing in the model parameters are quite minimized and b) the substitution of aftershocks in corresponding sub-faults on the plane source are completely correct, rather, we believe that more research works are required for selecting suitable aftershocks and modifying delay times of the waves radiated from sub-faults to the desired stations.

Finally, Table 3 shows the obtained Hypocenter location and Fault dimensions.

Table 2. Source Parameters of 2006 Darb-e-Astane Earthquake proposed and Used in this study

Epicenter			Main Event		Reference
Longitude Degree	Latitude Degree	Depth (Km)	Moment M_W,M_L,M_n	Focal mechanism (Strike, Dip, Rake)	
44.09	33.69	5.0	6.1 (M_L)	------	BHRC
48.800	33.583	10	5.7 (M_n)	314 , 54 , 180	NEIC
48.91	30.76	14.1	6.1 (M_L)	307 , 67 , -148	IEES
---	---	---	6.1 (M_L)	315 , 61 , -164	Hamzeloo et al
48.81	33.69	18	6.1(M_L)	306 , 63 , -176	This study

Table 3. Fault Characteristics and Hypocenter location used in this study.

Fault dimension (Km)				Hypocenter location		
Up	Right	Down	Left	Longitude	Latitude	Depth (Km)
3.62	4.17	5.81	3.83	48.81	30.69	18

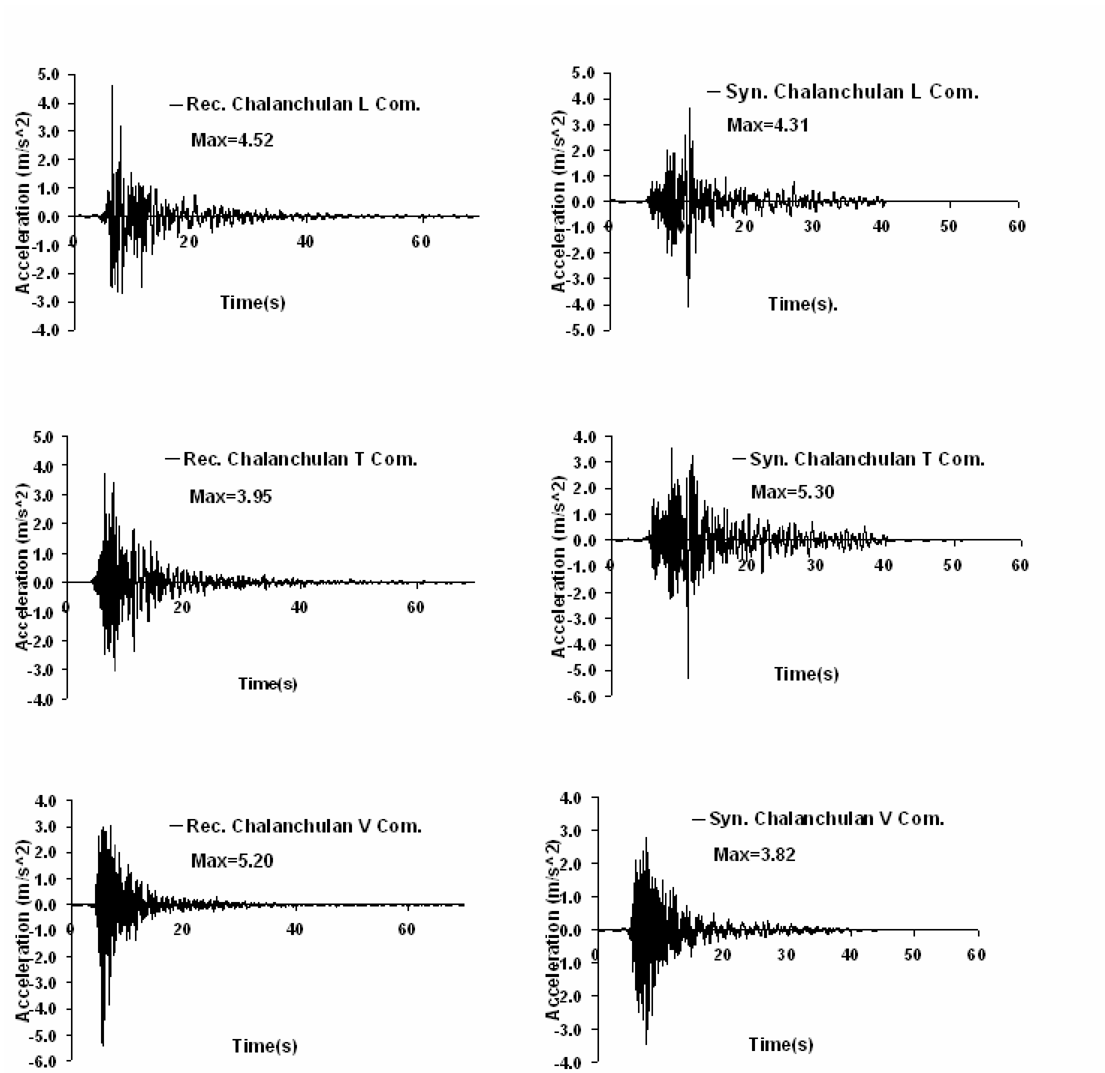

Figure 1. Comparison of synthesized strong motions at Chalanchulan st. with those of recorded data.

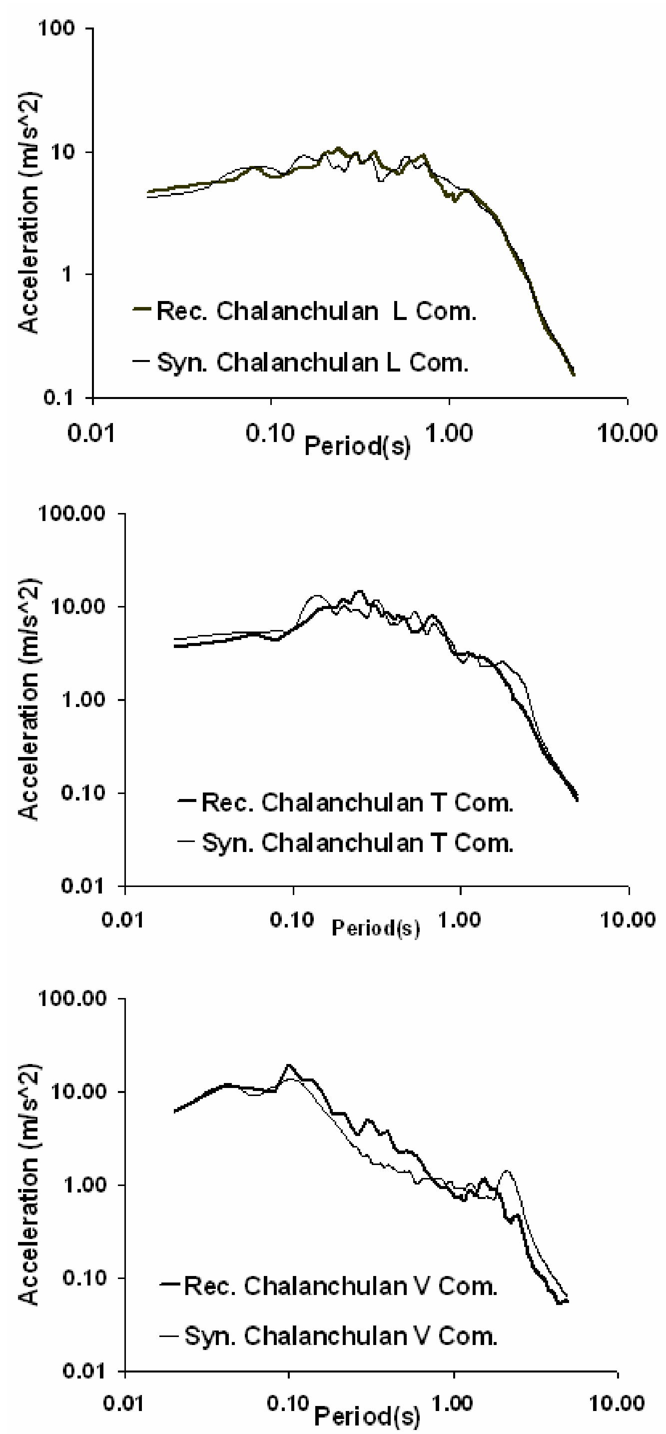

Figure 2. Comparison of synthesized elastic response spectra at Chalanchulan station with those of recorded data.

7. Discussion and conclusion

We used the EMPSYN computer software (Hutchings, 1988), to simulate the ground shaking recorded at Chalanchulan station during the March 31, 2006 Drab-e-Astane earthquake, aimed at estimating the seismological model parameters of the causative fault. The predicted parameters are; epicenter location, focal depth, focal mechanism (strike, deep and rake), rupture length and width, hypocenter location, input rupture and healing velocities, stress drop, rise time and average slip. The estimated synthesized ground motion is compared with those of recorded data at a station far away from the source so as the would not be influenced by the well known near source problems; directivity and fling step . The comparative good agreement of elastic response spectrum with 5% damping ratio corresponding to the simulated ground motion and those of recorded data confirms;

a) The suitability/reliability of estimated aforementioned seismological model parameters.

b) The potentiality of the EGF model in simulating ground motion comparable with observed data and finally.

c) The possibility of proposed technique in generating acceptable ground motions for the region under study, which is faced with the lack of sufficient reliable data to be used in specific site hazard analysis for important structures or those which are supposed to be retrofitted. However, it is not claimed that, the two well known uncertainties, aleatoric and epistemic uncertainties inherently existing in the model parameters are quite minimized in this study rather , the model parameters can be used in currently used simulation approaches such as, kinematic family of omega-squared-based approaches, for example the point source method proposed by of Boore [4, 5], and finite fault technique proposed by Atkinson [31] in which these sort of data are required to be incorporated into the model.

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9. References

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