New source spectral model and strong ground motion simulation of the 1994 M6.7 Northridge earthquake

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ABSTRACT: This paper checked, appended and corrected the strong motion database of Western U.S. on site conditions and so on first, and then recommends a new source spectral model and model parameters depending on the statistical analysis to acceleration Fourier spectra of these strong motion recordings. The new source spectral model has some further improvement to Brune ω^2 model and Atkinson two corners one, which embodies the differences between small and strong earthquakes not only in amplitudes and corner periods, but also in the shapes that were revealed by the recordings.

Based on the new source spectral model, the different ground motion estimating methods, like Finite-fault method, Point-source method and Random Vibration Theory method, have been used in this paper to simulate ground motion of Northridge (M6.7) earthquake as an example. It is certified that the finite-fault effect should be considered in near-source ground motion estimation.

1 INTRODUCTION

The simulation and prediction of strong ground motion has been one of the main research topics in earthquake engineering, many efforts, including theoretical and empirical approaches, have been paid by seismologists and engineers, and some important progresses have been achieved till now. It is indicated in the regions with more recordings that theoretical approaches are valid complement to empirical ones, could be applied in the regions with few or no strong ground motion recordings especially.

The most popular Brune ω^2 source spectral model is more effective to the simulation and prediction of strong ground motion in theoretical approaches now when earthquake magnitudes are lower than 5-5.5, and could model high frequency ground motion (>2Hz) successfully, but might overestimate the ground motion from moderate-to-large earthquakes at low-to-intermediate frequency range (0.1 to 2Hz) (Boatwright and Choy, 1992; Joyner, 1984; Atkinson, 1993; Atkinson and Silva, 1997), some modifications should be made on it. Atkinson (1993) suggested a two-corner source spectral model with a form of superposition of ω^2 model based on empirical regression. It has similar values while magnitude less than 5.5, but gradually get obvious different at low-to-moderate frequency range while magnitudes greater than 5.5 as compared with the results of Brune source spectral model. The estimation of two corner frequencies depends mainly on personal experience.

This paper recommends an new empirical source spectral model depending on theoretical research results, other source spectral models nowadays and statistical analysis to acceleration

Fourier spectra of strong ground recordings in western of U.S. The new model has some obvious improvement to Brune ω^2 and Atkinson two corners source spectral models in full engineering interested frequency ranges.

Some theoretical approaches have been adopted to simulate or predict the strong ground motion besides empirical ones, such as Finite-fault method, Random Vibration theory method and Point-source method, their great potential has been revealed by the successful simulation and prediction of ground motions of some strong earthquakes, even the exact procedures are different among these methods. It is certified that the finite-fault method is more effective in describing the strong ground motion distribution in near source region. By using three methods mentioned above, we simulated the strong ground motion of Northridge earthquake (M6.7) as an example in this paper to illustrate the effectiveness of our new source spectral model by comparing the results of Brune ω^2 and Atkinson two corners source spectral models.

2 DATABASE

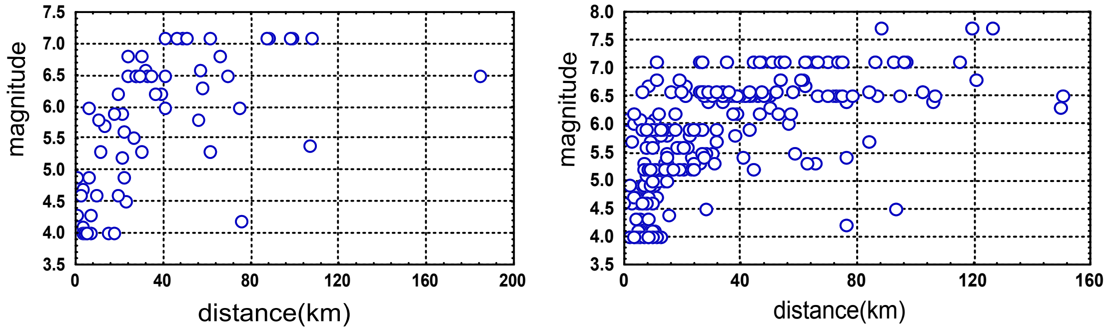
It is known that strong ground motion recordings play an invaluable role in earthquake engineering research. The database in this paper is composed of the recordings in western of US from 1933-1994. The distribution of the total data is listed in table 1.

Table.1 Data Distribution (M≥4.0)

Site Cate.	0<R≤10	10<R≤30	30<R≤100	100<R≤300	R>300	Total No.
S_1	52	182	110	24	9	377
S_2	15	45	155	21	0	236
S_3	23	10	57	0	0	90
S_4	460	466	671	72	3	1672

The data in table 1 include the recordings in horizontal and vertical directions, R is the hypocenter distance (km), and Si (i=1,2,3,4) indicates the site condition. Usually, S_1 represents rock site, S_2 soft rock, S_3 soil and S_4 soft soil respectively.

From the point of view of engineering practice, it wouldn't cause destructive disasters if earthquake magnitudes are lower than 4.0 or when the regional recorded PGA (Peak Ground Acceleration) is lower than 20 cm/s^2, so all of the data we chose should meet the basic requirements, and also recordings should be recorded on free fields or in the basement of structures lower than 3 stories to avoid bias due to soil-stricture interactions. The numbers and distribution of selected data are shown in figure 1.



(a) S_1 and S_2 (b) S_3 and S_4

Fig.1 Data Distribution

In practice, the S_1 and S_2 categories, according to the classification scheme of recording sites, could be combined into one site category, i.e., rock site, and S_3 and S_4 into soil site because of their similarity in properties, this will increase the data number in one site category that would make the results more stable and reliable. We could see from figure 1 that most of the data were recorded within 120km from magnitude 4.0 to 7.7 that is very helpful for us to understand the near source ground motion characteristics.

3 NEW SOURCE SPECTRAL MODEL

The most popular Fourier source spectral model used nowadays is Brune (1970) ω^2 one, but this model was suggested according to the far field recordings, it may not very suitable for application in near field where is very important area to engineering structure design. So we use the above database to check the efficiency of this model in near field first.

Usually, Brune (1970) source Fourier amplitude spectrum of acceleration is represented by:

$$S(M_0, f) = \frac{CM_0 f^2}{1 + (\frac{f}{f_0})^2} \quad (1)$$

where C is a scaling factor, M_0 the seismic moment, f for frequency, and f_0 the corner frequency that could be estimated by the following formula:

$$f_0 = 4.9 \times 10^6 \beta (\frac{\Delta\sigma}{M_0})^{1/3} \quad (2)$$

where $\beta$is the shear wave velocity of near source medium, $\Delta\sigma$ is the stress drop.

It could be easily founded after comparing the spectrum of every strong ground motion recording with the Brune model that there is a “sag” phenomenon within low-to-intermediate frequency range (0.1-2hz) in the source spectrum of recording usually, it is not matched well by Brune source spectral model, and this phenomenon is getting obvious as the increasing of magnitude, which has been mentioned and concerned by some experts, some of them have recommended some modifications to Brune model, such as two corners source spectral model of Atkinson (1993), Joyner (1984) also gave meaningful suggestions.

The authors of the paper believe that Brune source spectral model could represent the earthquake source spectra well for small-to-intermediate with magnitude less than 5.5 in all engineering interested frequency range, even for large earthquakes in lower and higher frequency bands, these typical advantages should be preserved in any modified models. The Brune model would be more effective to estimate ground motion for small-to-large earthquakes if some reasonable modifications are made on it. So we take Masuda (1982) model (equation(3)) as the basic one of our new source spectral model, but ab=2 is assigned in this paper to keep the advantages of Brune source spectral model:

$$S(M_0, f) = \frac{CM_0 f^2}{[1 + (\frac{f}{f_0})^a]^b} \quad (3)$$

where a and b are coefficients. The ratio of a to b could determine the curvature nearby the corner frequency f_0 calculated by equation (2).

The key point is how to determine the coefficient a and b in equation (3) in order to match the recorded spectra well. Naturally, there are some information of sources, paths and site conditions in the strong ground motion recordings, therefore, the Fourier spectra from strong motion recordings on rock site in western of US are utilized in this paper to estimate the values of coefficient a and b of each recording by searching for the best matching between the calculated spectrum from equation (4) and recorded spectrum one by one.

$$F(M_0, f, R) = S(M_0, f)G(R)D(R, f)A(f)P(f) \quad (4)$$

where $E(M_0,f,R)$ is the Fourier amplitude spectrum of ground motion at a position with distance R, $S(M_0,f)$ is the source spectrum, A(f) is near surface amplification factor and could be estimated by a transfer function of regional crust velocity gradient, P(f) is a high-cut filter, G(R) accounts for the geometrical attenuation caused by the changing of wave component along the distance, D(R,f) represents anelastic attenuation, which are expressed in equation (5) and (6) respectively.

In estimation of coefficient a and b for each recording, the stress drop of each earthquake is

$$G(R) = \begin{cases} \dfrac{1}{R} & R < 70\ \text{km} \\ \dfrac{1}{70} & 70 \le R \le 130\ \text{km} \\ \dfrac{1}{70}\sqrt{\dfrac{130}{R}} & R > 130 \end{cases} \qquad (5)$$

$$D(R,f) = \exp\left(-\frac{\pi f R}{Q\beta}\right) \qquad (6)$$

taken as if it was indicated, otherwise 100bar for a reasonable approximation from the results of some researchers (Kanamori and Anderson, 1975; Hough and Dreger, 1995; Hanks and McGuire, 1981; Boore, 1983); G(R) is adopted by equation (5); D(R,f) is expressed as equation (6) with quality factor $Q=150f^{0.5}$ (Hartzell et al, 1996); P(f) is taken as $P(f)=\exp(-\pi fk)$ with k=0.05 (Anderson and Hough, 1984; Atkinson and Silva, 1997; Boore and Joyner, 1997). A(f)=2, a mean value in the western part of US, is selected. Other parameters are the medium density ($2.8g/cm^3$) and shear velocity (3.7km/s) near the source.

After coefficient a and b of every recording spectrum were estimated, the statistic relation between coefficient a (or b) and magnitude (M) is fitted as follows:

$$a = 3.05 - 0.33M \qquad b = \frac{2.0}{a} \qquad (7)$$

It is should be mentioned that the coefficient a and b are estimated by strong ground motion recordings on rock site, so they are only proper to the estimation of ground motion on rock site principally. The curves of new model and other two source spectral models, i.e. Brune (1970) and Atkinson (1993), are shown in figure 2 with magnitude 4, 5, 6 and 7 respectively from the bottom to the top in order to show the difference among different models, and the stress drop 100bar is assumed.

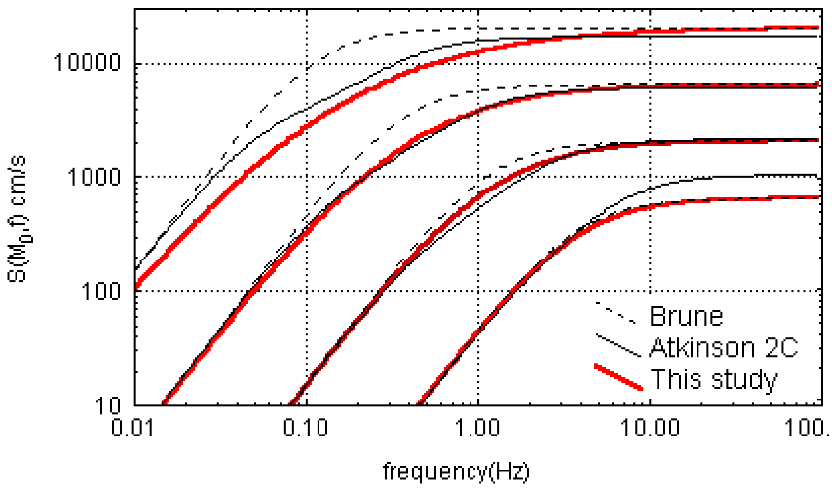


Fig.2 Source spectra curves of three models

It is found from figure 2 that the new model is similar with Brune one while magnitudes are lower than 6.0, but has some differences with Atkinson's two corner model when magnitudes lower than 5.0. Both Our new model and Atkinson's could embody the "sag" phenomenon obviously as the magnitudes stronger than 6.0. So it can be certified that our new model could represent the source spectra well not only in low-to-moderate magnitudes, but also stronger.

4 STRONG GROUND MOTION SIMULATION

As an example of strong ground motion simulation, we take the Northridge M6.7 earthquake to illustrate the efficiency of new source spectral model and also compare with others. In simulating the ground motion of Northridge M6.7 earthquake in US, we use the popular finite fault stochastic approach. The procedure of this method was mentioned before in many papers (Silva et al., 1990; Beresnev et al., 1997; Atkinson et al., 2000).

The full fault dimension of Northridge earthquake (M6.7) in US was estimated as 18km×15km along strike and dip respectively (after Wald et al., 1996). The parameters of the source are listed in table 2. The subevent magnitude is chosen as 5 in this paper, the fault is discretized into subfaults, each 3 km×3 km (Wang, 2000), and the individual slips are derived based on the counters from the model of Wald et al. Totally, there are 30 subfaults on the mainshock rupture plane that are indicated in figure 3.

Table.3 Source Parameters

Fault orient. Strike/dip	Fault L.×W. (km)	Fault depth (km)	Seismic Moment (dyne-cm)	Stress drop (Bar)	S. Vel. (km/s)	Med. Dens. (g/cm^3)	Rup. Vel. (km/s)
122°/40°	18×15	5—21	$1.1\pm0.2\times10^{26}$	50	3.7	2.8	0.8×3.7

0.4	0.6	0.4	0.8	0.8	0.4
1.0	2.4	2.4	1.0	1.0	0.4
1.2	2.4	2.4	1.6	1.2	0.4
0.4	1.0	0.8	1.0	1.6	0.6
0.4	0.6	0.8	0.8	0.8	0.4

5
8
11
14
17
20km

Fig.3 Finite-fault model

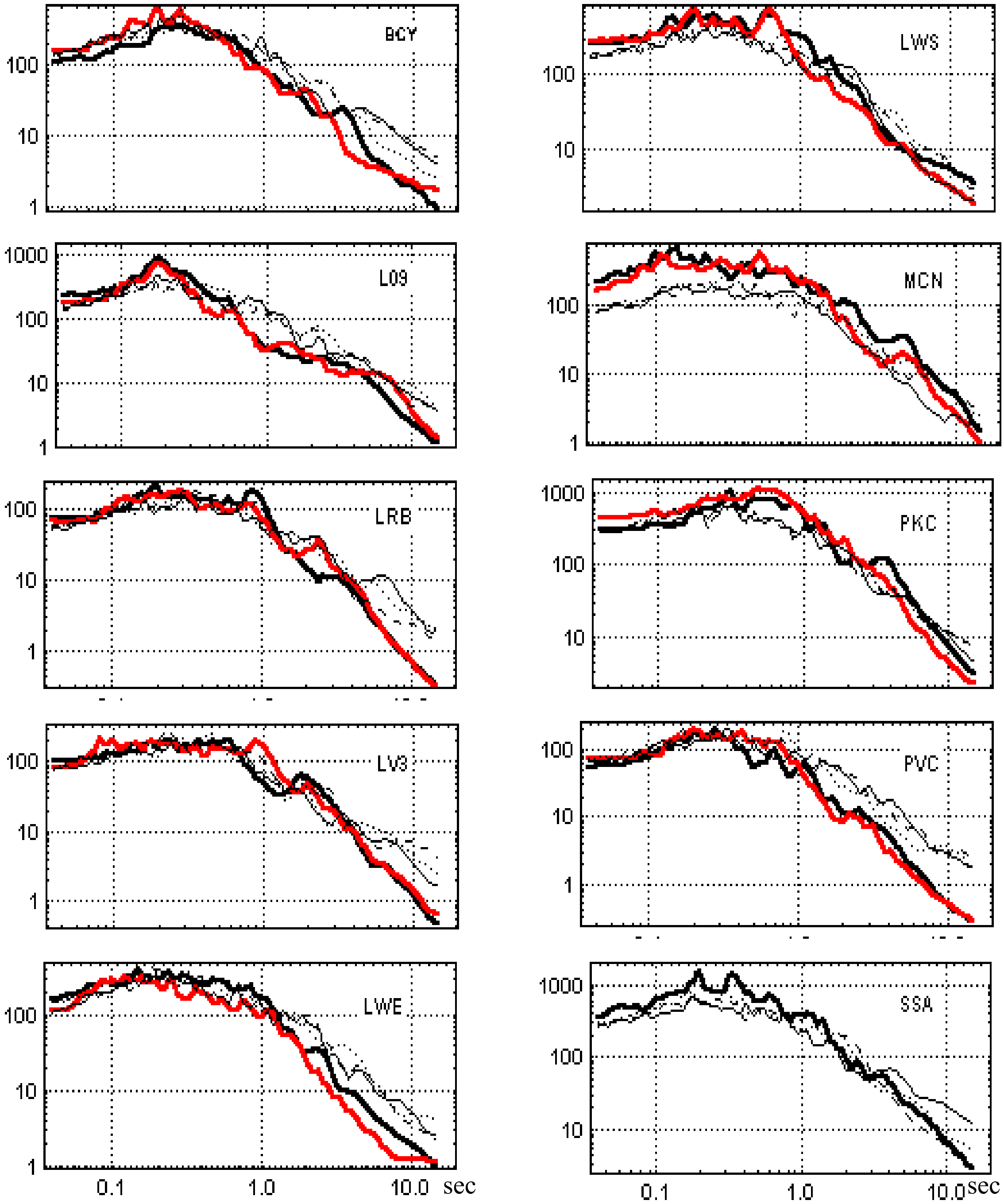
The acceleration Fourier spectrum radiated from each subevent could be calculated by equation (4), and the acceleration time history could be generated by Fourier inverse transform. A powerful procedure is developed successfully to keep the Fourier spectra of the enveloped time history be exact same as the estimated one. The time history a(t) at every station could then be superposed by:

$$a(t) = \sum_{k=1}^{N_L} \sum_{m=1}^{N_W} \sum_{n=1}^{N_S} a_{km}(t - t_{kmn}) \tag{8}$$

where N_L, N_W is the number of subfaults along fault length, width respectively, N_S is the number of subevents, and a_{km} is the time history generated by the k^{th}-m^{th} subfault, t_{kmn} represents the time lag from the difference between the triggerings of the subevents, and from the difference between the paths from the subfaults to the site.

5 RESULTS AND CONCLUSION

Acceleration response spectra (with damping ratio 5%) of recordings and spectra from three random simulated time histories are calculated at 22 rock stations with the farthest hypocenter distance less than 90km and 10 of them are presented in figure 4 because of the page limitation. The two solid lines in figure 4 are spectral curves of the recordings; the three thin lines are random simulated results.



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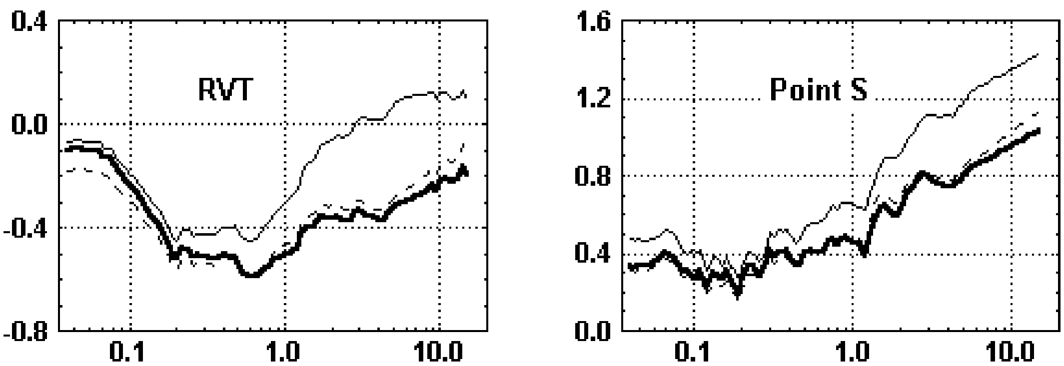

three models could be seen in figure 5, in which the bias is defined as the logarithm of ratio of simulated spectral amplitudes to recorded ones, the solid lines represent the results of using our new spectral model, the thin solid lines are from Brune's model, the dash lines from the Atkinson 2C model. One could find that the bias of the our new model is the lowest in all frequency range, and the Brune's and Atkinson's is the highest at lower and higher frequency range respectively among the three source spectral models.

Fig.5 Model bias for all 22 stations

A series of results and comparisons of model biases are also shown in figure 5, such as dividing the fault into 5km×5km subfaults as Beresnev did (1998), the results of Point-source simulation (Boore, 1983) and Random Vibration Theory (RVT) (Hanks and McGuire, 1981). It is obvious that the finite fault approach is a very effective method to simulate the strong ground motion in near source field, and could reveal the affections of fault size, angle and asperity on fault plane, the other two methods are very simple to use, but have bigger biases in full frequency range because they couldn't describe the source complexity well as compared with finite-fault method. The presented new source spectral model and model parameters based on strong ground motion recordings could reflect the obvious and obscure information included in the sources, paths and site conditions properly, and some of information are very difficult to be described well by other theoretical models nowadays, this new model is more suitable for the practical application.

The results of this paper indicate that the not only the analysis methods and the form of source spectral models have distinctive influence upon the simulation accuracy of strong ground motion in near source field, but also any other factors, such as local response, topography, and basin effects, may significantly affect the ground motion simulation at individual sites, which could be incorporated into further work.

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