ISET Journal of Earthquake Technology, Paper No. 471, Vol. 43, No. 3, September 2006, pp. 65-74

ESTIMATION OF NEAR-FAULT STRONG GROUND MOTIONS FOR KEY ENGINEERING STRUCTURES

Guoxin Wang*, Hongnan Li*, Dongsheng Wang* and W.K. Chow**

*State Key Laboratory of Coastal and Offshore Engineering
Dalian University of Technology, Dalian 116024, China
**Research Centre for Fire Engineering
The Hong Kong Polytechnic University, Hong Kong, China

ABSTRACT

The strong motion database of Western US for different site conditions is reviewed in this paper. A new source spectral model is developed from Brune's ω^2 model and Atkinson's two-corners model. Associated parameters are estimated by statistical analysis on the Fourier spectra of the recorded strong motions. The spectral differences between small and strong earthquakes are described not only in amplitude and corner periods, but also in the shapes that were revealed by the recordings. Based on this new source spectral model, different ground motion estimation methods including finite-fault method, point-source method, and the method based on random vibration theory are applied to simulate ground motions of the Northridge (M_w = 6.7) earthquake. It is concluded that the finite-fault effect should be considered in the near-source ground motion estimation.

KEYWORDS: Ground motion, Source spectra, Acceleration

INTRODUCTION

The estimation of strong ground motion parameters (peak acceleration, velocity, amplitude and frequency content of response spectra) of moderate-to-large earthquakes is the key process for the seismic analysis of key engineering structures. This provides information on the most probable seismic hazard that structures might suffer in the future. Necessary action can be taken to protect them. These structures, like dams, bridges, antenna towers, and high-risk facilities such as chemical or nuclear power plants, should continue to function properly. Any disturbance to their normal operation would lead to severe consequences. They must remain reasonably safe during and after the earthquakes. Their seismic performances should be studied carefully by combining different ground motions excited by the surrounding hazard sources with earthquake potential.

Usually, critical ground motions can be obtained from the records for previous earthquakes. More records have become available in recent years for the structural seismic analyses. However, as learnt from the seismic characteristics of recent strong earthquakes such as the 1994 Northridge (M_w = 6.7), 1995 Kobe (M_w = 6.9), and 1999 Chi-Chi (M_w = 7.6) earthquakes, different earthquakes may have different characteristics and factors including earthquake source parameters, surface topography, and soil conditions. All these would affect the structural response characteristics in different ways, inflicting very different types of damage to the structures. The present records do not have similar seismological conditions to which the structures are exposed. In studying the structural seismic response performances, ground excitations were estimated by theoretical methods in many previous studies on near earthquake source regions. Theoretical relationships between strong motion and earthquake source parameters were reported and improved gradually in the literature (Aki, 1968; Haskell, 1969; Boore and Zoback, 1974; Levy and Mal, 1976; Israel and Kovach, 1977; Hartzell, 1978; Bouchon, 1979, 1980; Olsen and Archuleta, 1996). Effects of the rise time of particle displacement, rupture velocity and its directivity, as well as the effect of sedimentary layers were analyzed. Currently numerical methods for simulating the ground motion field radiated during the rupture process along extended faults (Cotton and Campillo, 1995; Gariel and Campillo, 1989; Beroza and Spudich, 1988; Fäh and Suhadolc, 1994) are carried out by including the effects of source and propagation complexity. Recent studies of crustal events have suggested that heterogeneous patterns of final slip distribution and rupture velocity on the fault plane as inferred from the inversion of accelerograms, teleseismic and geodetic data are rather complicated at high frequencies (Hartzell and Heaton, 1983; Heaton, 1990).

In this paper, the finite-fault approach will be applied to model the strong motion acceleration records close to the earthquake faults where the complex rupture process dominates the seismic radiation. This may have distinguished features from the far-field waves, implying its importance in engineering structural safety. Further, a new empirical source spectral model based on some theoretical results will be recommended in simulating the motions. This new model is better than the traditional Brune's ω^2 model and Atkinson's two-corners source spectral model in covering the full range of frequency of engineering interest.

It is known that some theoretical approaches have been adopted to simulate or predict strong ground motions besides the finite-fault method (Boore et al., 1993; Boore, 2003; Atkinson and Silva, 2000; Lam et al., 2000; Panza and Suhadolc, 1987; Panza et al., 2000), such as the random vibration theory method and the point-source method. The great potential of these methods has been revealed by the successful simulation and prediction of ground motions of some strong earthquakes, even though the exact procedures are different among these methods. It will be demonstrated that the finite-fault method is more effective in describing the strong ground motion distribution in the near-source region. To compare this new source spectral model with the finite-fault method, the strong ground motion of Northridge earthquake (M_w = 6.7) is taken as an example in this paper. Three source spectral models are used with the three different methods as mentioned above.

DATABASE

It is known that strong ground motion records play an invaluable role in earthquake engineering research. Most of the available records, especially the more valuable near-fault ones, were obtained during the earthquakes in USA, Japan and Taiwan. All these are useful in understanding the ground motion characteristics for deducing information for engineering structural design.

The database for this paper is selected carefully from the records in the western part of US from 1933 to 1994 as published by USGS on CDs in 1996. The earthquake magnitudes for these records are higher than M_s = 4.0 (the most common magnitude in these CDs) and peak ground acceleration (PGA) over 20 cm/s^2. There are 126 records distributed in the 0 to 200 km distance range from the sources. Most of them were recorded within the hypocentral distance of 60 to 70 km. They were recorded on rock or soft rock sites as free-field motions or in the basement of structures lower than three stories to avoid bias due to soil-structure interaction.

The records include two horizontal components at each station. It can be seen from Figure 1 that most of the data are distributed around the near-source region for M_s = 4.0 to 7.7. This information is very helpful for studying the near-source ground motion characteristics.

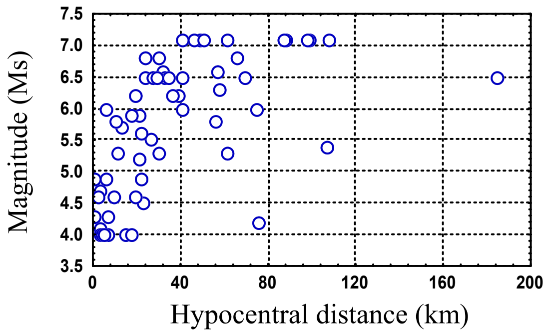

Fig. 1 Data distribution

NEW SOURCE SPECTRAL MODEL

Brune's ω^2 Fourier source spectral model (Brune, 1970) has been most widely adopted to predict strong ground motions by both engineers and seismologists around the world. However, this point source model was developed on the basis of far-field and small earthquake records which is not exactly suitable for simulating near-source strong ground motions from moderate-to-large earthquakes at low-to-intermediate frequency range (0.1 to 2 Hz) because it would over-predict the results for the practical situations (Boatwright and Choy, 1992; Joyner, 1984; Atkinson, 1993; Atkinson and Silva, 1997); so further modifications in this model are required. The above database could be applied to check and modify the performance of Brune's model while applying to the near-field motions.

Atkinson (1993) proposed a two-corner source spectral model with a form involving the superposition of ω^2 model based on empirical regression. It predicts similar values as Brune's model for earthquake magnitudes less than 5.5. However, values different from those in the records were predicted at the low-to-moderate frequency range for the magnitudes greater than 5.5. The estimation of two corner frequencies depends mainly on the experience of the model-users themselves.

The source Fourier acceleration amplitude spectrum $S(M_0, f)$ proposed by Brune (1970) is represented in terms of seismic moment M_0 and frequency f as

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

where C is a scaling factor; and f_0 is the corner frequency estimated via the shear wave velocity β of near-source medium and stress drop $\Delta\sigma$ as

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

In comparing the spectrum of every strong ground motion record with the Brune's model, a "sag" phenomenon was identified within the low-to-intermediate frequency range (0.1-2 Hz), which cannot be represented by Brune's source spectral model. This "sag" phenomenon is very obvious as the magnitude increases, as reported by many seismologists and engineers, such as Gusev (1983, 1989, 1991). Brune's model will be modified here to include this feature. This is similar to the two-corners source spectral model by Atkinson (1993) and recommendation by Joyner (1984).

In this paper, Brune's source spectral model is believed to be capable of predicting the earthquake source spectra well for small-to-intermediate earthquakes with magnitudes less than 5.5 in all frequency ranges of engineering interest. This model has to be modified for large earthquakes within lower and higher frequency bands. Brune's model may be more effective in estimating ground motions for small-to-large earthquakes for all frequency ranges if reasonable modifications are made. To achieve the modification of Brune's model, the Fourier spectrum of every record is calculated first. Results are then converted to the spectrum at 1 km from the hypocenter by using the attenuation term, and by taking it as the source spectrum. In this way, several source spectral curves are deduced from different records. After comparing these curves with that by Brune (1970) under the same conditions, a new source spectral model is suggested through coefficients a and b:

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

The ratio of a to b would determine the curvature to the corner frequency f_0 calculated by Equation (2). These two parameters are restricted to keep the nice and realistic characteristics of Brune's model intact in the lower and higher frequency bands and to modify in the low-to-intermediate frequency range (0.1 to 2 Hz), by setting

$$ab = 2 \tag{4}$$

The key point now is to determine the coefficients a and b in order to match with the recorded spectra. The database mentioned above has been used for carrying out a statistical analysis. The best match is searched for between the model and the following amplitude spectrum of ground motion at distance R (in km):

$$E(M_0, f, R) = S(M_0, f) G(R) D(R, f) A(f) P(f) \tag{5}$$

where $S(M_0, f)$ is the source spectrum; $A(f)$ is the frequency-dependent near-surface amplification factor 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 (Kanamori and Anderson, 1975); and $D(R, f)$ represents an elastic attenuation given by

$$G(R) = \begin{cases} \frac{1}{R} & R < 70 \text{ km} \\ \frac{1}{70} & 70 \le R \le 130 \text{ km} \\ \frac{1}{70}\sqrt{\frac{130}{R}} & R > 130 \text{ km} \end{cases} \tag{6}$$

and

$$D(R, f) = \exp\left(-\frac{\pi f R}{Q\beta}\right) \tag{7}$$

In estimating coefficients a and b for each record, the stress drop of each earthquake is taken same as the published one. Else, 100 bar is taken as a reasonable approximation based on the results available in the literature for earlier earthquakes (Kanamori and Anderson, 1975; Hough and Dreger, 1995; Hanks and McGuire, 1981; Boore, 1983). Further, $G(R)$ is adopted as in Equation (6); and $D(R, f)$ is expressed as in Equation (7) with quality factor $Q = 150 f^{0.5}$ (Hartzell et al., 1996). $P(f)$ is taken as $P(f) = \exp(-\pi f k)$ with $k = 0.05$ (Anderson and Hough, 1984; Atkinson and Silva, 1997; Boore and Joyner, 1997). $A(f)$ is taken from the results of Boore (1986) as a factor of 2 over a wide range of frequencies in the western crusts of US. This is an approximation for the site amplification and results might be biased due to this. Other parameters are the medium density (2.8 g/cm^3) and shear velocity (3.7 km/s) in the near-source area.

After estimating the coefficients a and b for every recorded spectrum, statistical correlation between the coefficient a (or b) and the magnitude (M) is fitted by trial and error as follows:

$$a = 3.05 - 0.33M \tag{8}$$

It may be noted that $ab = 2$ as given by Equation (4) and the coefficients a and b are estimated using the strong ground motion records on rock sites. These values are, therefore, for estimating ground motions on the rock sites. The curves of the new model and the other two source spectral models by Brune (1970) and Atkinson (1993) are compared in Figure 2 for the earthquake magnitudes of 4, 5, 6 and 7, respectively. The stress drop is assumed to be 100 bar.

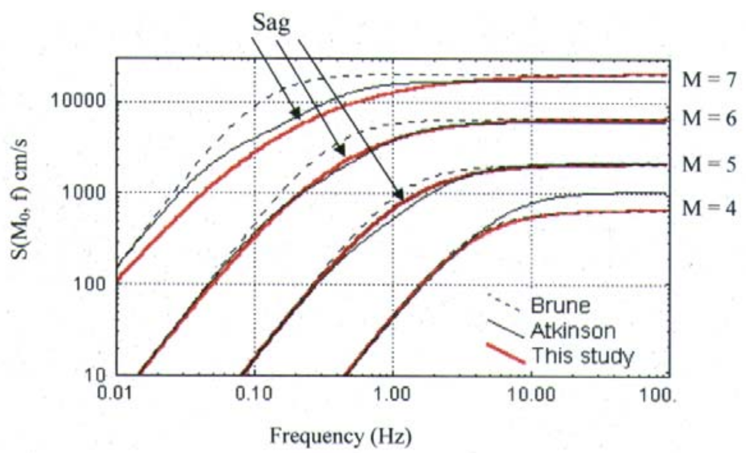

Fig. 2 Source spectral curves for the three models

It is observed from Figure 2 that the new model is similar to Brune's model for earthquake magnitudes lower than 6.0. There are some differences between the new model and Atkinson's two-corners model for magnitudes lower than 5.0. Both the new model and the model of Atkinson obviously show the "sag" phenomenon for magnitudes greater than 6.0. It is a good demonstration that the new model can simulate source spectra well for large magnitudes. On the other hand, the new model is also applicable to any other region with different stress drop and source parameters.

SIMULATION OF STRONG GROUND MOTIONS

The 1994 Northridge earthquake ($M_w = 6.7$) is taken as an example to study the efficiency of different source spectral models. Many near-fault records were reported on rock sites for this earthquake. The accelerograms have been simulated first by using three source spectral models and the finite fault stochastic approach, with the procedures as reported in the literature (Silva et al., 1990; Beresenv and Atkinson, 1997, 1998; Atkinson and Silva, 2000). By comparing the synthetic accelerograms and their response spectra (for 5% damping ratio) with the actual ones, differences among them could be observed. Finally, two kinds of sub-sources are utilized to analyze the uncertainty of the sub-source size. The other two methods are similarly used to study the differences with the results predicted by the three models.

The source parameters of the Northridge earthquake are listed in Table 1. The slip distribution on the main shock rupture plane is shown in Figure 3 (Wald et al., 1996). The subevent magnitude is taken as 5. The entire fault is discretized into 30 subfaults, each of 3×3 km size (Wang et al., 2001). The individual slip on each subfault is derived primarily based on the contours of Figure 3, but probably with area adjustment in some measure as compared with the original on account of the uncertainty in determining the slip distribution by different means and in discretizing the slip fault. The 30 subfaults and their slips are shown in Figure 4.

Table 1: Source Parameters

Fault Orientation (Strike/Dip)	Fault $L \times W$ (km)	Fault Depth (km)	Seismic Moment (dyne-cm)	Stress Drop (bar)	Shear Velocity (km/s)	Medium Density (g/cm^3)	Rupture Velocity (km/s)
122°/40°	18×15	5-21	$1.1 \pm 0.2 \times 10^{26}$	50	3.7	2.8	(0.8 × 3.7 =) 2.96

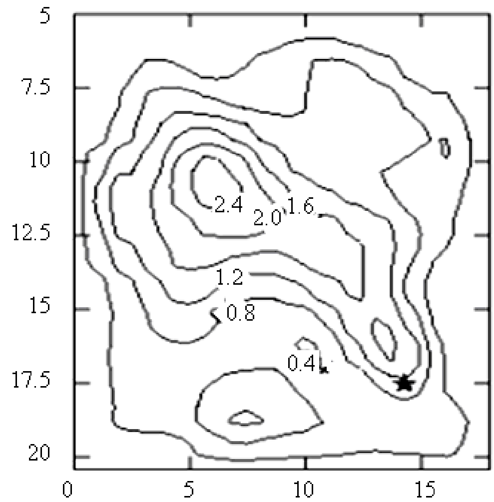

Fig. 3 Main shock slip distribution

The acceleration Fourier spectrum radiated from each subevent is calculated by Equation (5). The acceleration time history is then generated by Fourier inverse transform. An efficient numerical procedure has been developed successfully to keep the Fourier spectra of the enveloped time history to be exactly the same as the estimated one. The time history $a(t)$ at each station is obtained as

$$a(t) = \sum_{k=1}^{N_L} \sum_{m=1}^{N_W} \sum_{n=1}^{N_S} a_{km}\left(t - t_{kmn}\right) \tag{9}$$

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

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 20 km

Fig. 4 Subfault slip distribution

RESULTS AND DISCUSSION

The accelerograms are synthesized by the above method at 22 stations near the fault, whose distances are less than 90 km. The acceleration response spectra (for 5% damping ratio) at 10 selected typical stations with different azimuths around the fault rupture plane, which could identify the characteristics of hanging (and foot) wall and directivity, are shown in Figure 5. The two solid lines in Figure 5 are spectral curves from the recordings, and the three thin lines are from the random simulated results with each subfault of 3×3 km size.

It is observed from Figure 5 that most simulated response spectra match the recorded ones reasonably well within the short-to-intermediate period range (normally less than 1.0 s) despite deviations for several stations. This suggests that the new source spectral model is a reasonable modification to Brune's and Atkinson's models.

The biases from the three models can be seen in Figure 6, where bias is defined as the logarithm of the ratio of simulated spectral amplitudes to recorded ones. The solid lines represent the results for the new spectral model, the thin solid lines for Brune's model, and the dashed lines for Atkinson's two-corners model. The bias of the new model is the lowest in all frequency ranges. The models due to Brune (1970) and Atkinson (1993) give bigger biases at lower and higher frequency ranges.

A series of results and comparisons of model biases are also shown in Figure 6. These include dividing the fault into 5×5 km subfaults (Beresnev and Atkinson, 1998), results of the 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 the near-source field. This model could reveal the effects of the fault size, angle and asperity of the fault plane. The other two methods are very simple to use, but have bigger biases in the full frequency range. This is because these models cannot describe the source complexity well as compared with the finite-fault method. The proposed source spectral model and the model parameters based on strong ground motion recordings could reflect the obvious and obscure information included in the sources, paths and site conditions properly. Some information was very difficult to be described well by the other theoretical models. The proposed model is, therefore, more suitable for the practical applications.

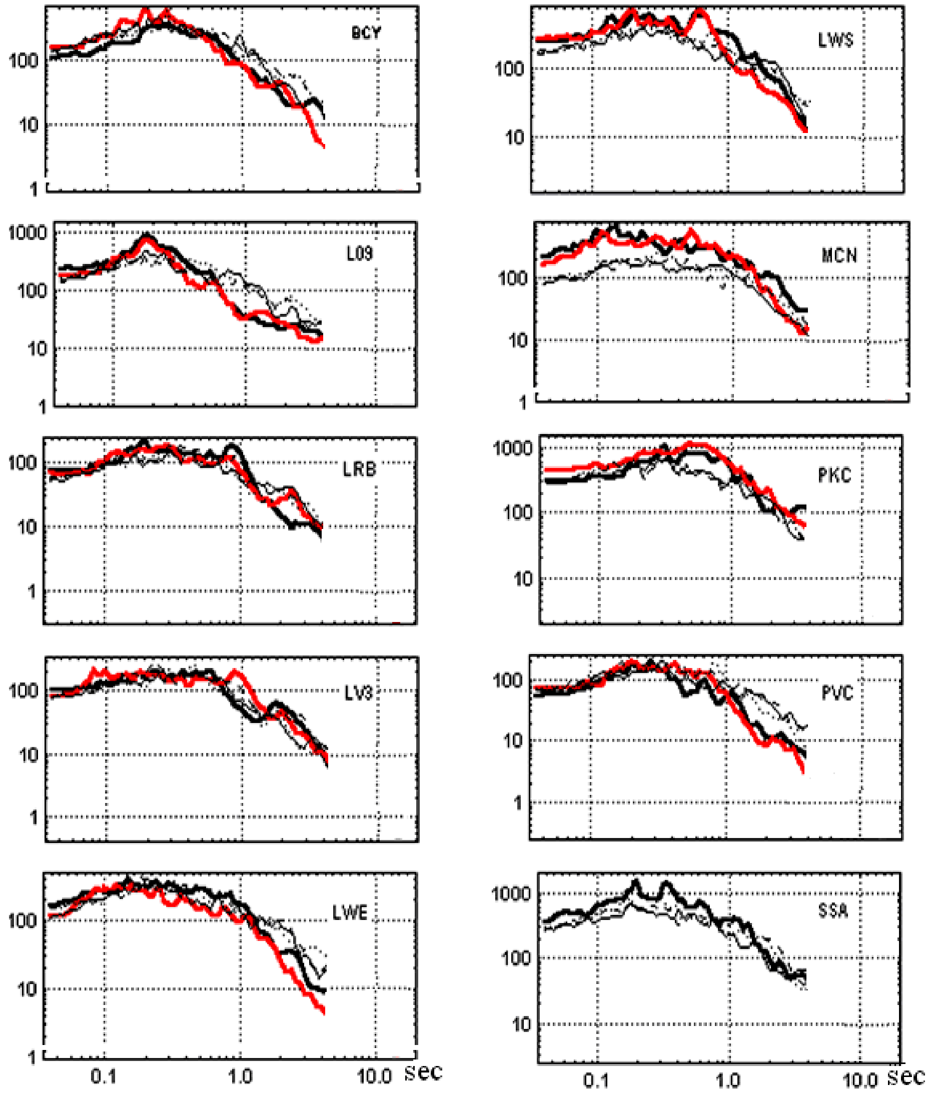

Fig. 5 Comparison of acceleration response spectra for 5% damping ratio

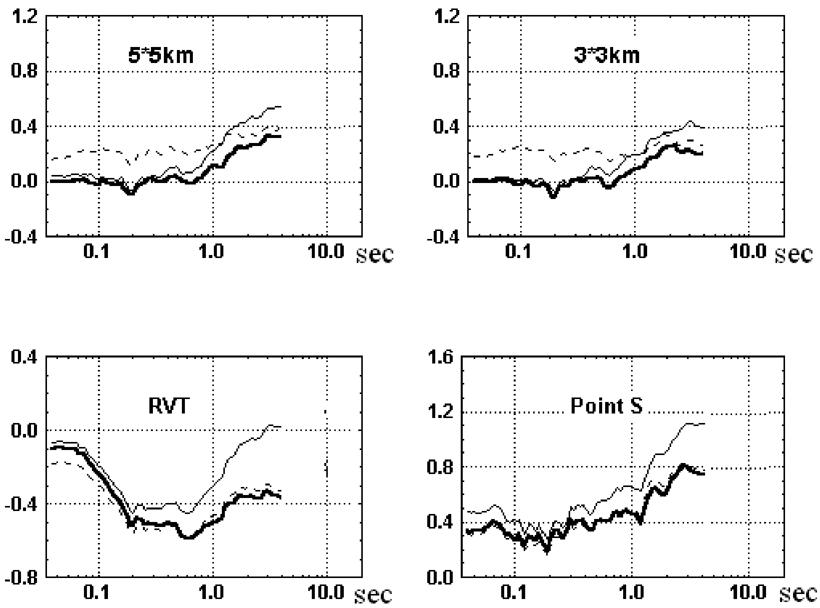

Fig. 6 Model bias for all 22 stations

CONCLUSIONS

The results of this paper have indicated that not only the theory concerned, but also the form of the source spectral model would affect the accuracy of simulations for strong ground motions in the near-source field. Other factors such as local response, topography, and basin effects may significantly affect the ground motion simulations at individual sites. All these would be incorporated in future works. At the moment, the proposed model is applicable to the estimation of ground motions as inputs for important engineering structural design. This is particularly the case for the structures located in the near-fault regions.

REFERENCES

1. Aki, K. (1968). “Seismic Displacement near a Fault”, Journal of Geophysical Research, Vol. 73, pp. 5359-5376.
2. Anderson, J.G. and Hough, S.E. (1984). “A Model for the Shape of the Fourier Amplitude Spectrum of Acceleration at High Frequencies”, Bulletin of the Seismological Society of America, Vol. 74, No. 5, pp. 1969-1993.
3. Atkinson, G.M. (1993). “Earthquake Source Spectra in the Eastern North America”, Bulletin of the Seismological Society of America, Vol. 83, No. 6, pp. 1778-1798.
4. Atkinson, G.M. and Silva, W. (1997). “An Empirical Study of Earthquake Source Spectra for California Earthquakes”, Bulletin of the Seismological Society of America, Vol. 87, No. 1, pp. 97-113.
5. Atkinson, G.M. and Silva, W. (2000). “Stochastic Modeling of California Ground Motions”, Bulletin of the Seismological Society of America, Vol. 90, No. 2, pp. 255-274.
6. Beresenv, I.A. and Atkinson, G.M. (1997). “Modeling Finite-Fault Radiation from the ω^n Spectrum”, Bulletin of the Seismological Society of America, Vol. 87, No. 1, pp. 67-84.
7. Beresenv, I.A. and Atkinson, G.M. (1998). “Stochastic Finite-Fault Modeling of Ground Motions from the 1994 Northridge, California, Earthquake. I. Validation on Rock Sites”, Bulletin of the Seismological Society of America, Vol. 88, No. 6, pp. 1392-1401.
8. Beroza, G.C. and Spudich, P. (1988). “Linearized Inversion for Fault Rupture Behavior: Application to the 1984 Morgan Hill, California, Earthquake”, Journal of Geophysical Research, Vol. 93, No. B6, pp. 6275-6296.
9. Boatwright, J. and Choy, G.L. (1992). “Acceleration Source Spectra Anticipated for Large Earthquakes in Northeastern North America”, Bulletin of the Seismological Society of America, Vol. 82, No. 2, pp. 660-682.
10. Boore, D.M. (1983). “Stochastic Simulation of High-Frequency Ground Motions Based on Seismological Models of the Radiated Spectra”, Bulletin of the Seismological Society of America, Vol. 73, No. 6A, pp. 1865-1894.
11. Boore, D.M. (1986). “Short-Period P- and S-Wave Radiation from Large Earthquakes: Implications for Spectral Scaling Relations”, Bulletin of the Seismological Society of America, Vol. 76, No. 1, pp. 43-64.
12. Boore, D.M. and Zoback, M.D. (1974). “Near-Field Motions from Kinematic Models of Propagating Faults”, Bulletin of the Seismological Society of America, Vol. 64, No. 2, pp. 321-342.
13. Boore, D.M., Joyner, W.B. and Fumal, T.E. (1993). “Estimation of Response Spectra and Peak Accelerations from Western North American Earthquakes: An Interim Report”, Open-File Report 93-509, United States Geological Survey, Denver, U.S.A.
14. Boore, D.M. and Joyner, W.B. (1997). “Site Amplifications for Generic Rock Sites”, Bulletin of the Seismological Society of America, Vol. 87, No. 2, pp. 327-341.
15. Boore, D.M. (2003). “Simulation of Ground Motion Using the Stochastic Method”, Pure and Applied Geophysics, Vol. 160, No. 3-4, pp. 635-676.
16. Bouchon, M. (1979). “Predictability of Ground Displacement and Velocity near an Earthquake Fault: The Parkfield Earthquake of 1966”, Journal of Geophysical Research, Vol. 84, No. B11, pp. 6149-6156.

17. Bouchon, M. (1980). "The Motion of the Ground during an Earthquake: 1. The Case of a Strike Slip Fault; 2. The Case of a Dip Slip Fault", Journal of Geophysical Research, Vol. 85, No. B1, pp. 356-376.
18. Brune, J.N. (1970). "Tectonic Stress and the Spectra of Seismic Shear Waves", Journal of Geophysical Research, Vol. 75, pp. 4997-5009.
19. Cotton, F. and Campillo, M. (1995). "Frequency Domain Inversion of Strong Ground Motions: Application to the 1992 Landers Earthquake", Journal of Geophysical Research, Vol. 100, No. B3, pp. 3961-3976.
20. Fäh, D. and Suhadolc, P. (1994). "Application of Numerical Wave-Propagation Techniques to Study Local Soil Effects: The Case of Benevento (Italy)", Pure and Applied Geophysics, Vol. 143, No. 4, pp. 513-536.
21. Gariel, J.C. and Campillo, M. (1989). "The Influence of the Source on the High-Frequency Behavior of the Near-Field Acceleration Spectrum: A Numerical Study", Geophysical Research Letters, Vol. 16, No. 4, pp. 279-282.
22. Gusev, A.A. (1983). "Descriptive Statistical Model of Earthquake Source Radiation and its Application to an Estimation of Short-Period Strong Ground Motion", Geophysical Journal of the Royal Astronomical Society, Vol. 74, No. 3, pp. 787-808.
23. Gusev, A.A. (1989). "Multiasperity Fault Model and the Nature of Short-period Subsources", Pure and Applied Geophysics, Vol. 130, No. 4, pp. 635-660.
24. Gusev, A.A. (1991). "Intermagnitude Relationships and Asperity Statistics", Pure and Applied Geophysics, Vol. 136, No. 4, pp. 515-527.
25. Hanks, T.C. and McGuire, R.K. (1981). "The Character of High-Frequency Strong Ground Motion", Bulletin of the Seismological Society of America, Vol. 71, No. 6, pp. 2071-2095.
26. Hartzell, S.H. (1978). "Earthquake Aftershocks as Green's Functions", Geophysical Research Letters, Vol. 5, No. 1, pp. 1-4.
27. Hartzell, S. and Heaton, T.H. (1983). "Inversion of Strong Ground Motion and Teleseismic Waveform Data for the Fault Rupture History of the 1979 Imperial Valley, California, Earthquake", Bulletin of the Seismological Society of America, Vol. 73, No. 6A, pp. 1553-1583.
28. Hartzell, S., Leeds, A., Frankel, A. and Michael, J. (1996). "Site Response for Urban Los Angeles Using Aftershocks of the Northridge Earthquake", Bulletin of the Seismological Society of America, Vol. 86, No. 1B, pp. S168-S192.
29. Haskell, N.A. (1969). "Elastic Displacements in the Near-Field of a Propagating Fault", Bulletin of the Seismological Society of America, Vol. 59, No. 2, pp. 865-908.
30. Heaton, T.H. (1990). "Evidence for and Implications of Self-Healing Pulses of Slip in Earthquake Rupture", Physics of the Earth and Planetary Interiors, Vol. 64, No. 1, pp. 1-20.
31. Hough, S.E. and Dreger, D.S. (1995). "Source Parameters of the 23 April 1992 *M* 6.1 Joshua Tree, California, Earthquake and its Aftershocks: Empirical Green's Function Analysis of GEOS and TERRAscope Data", Bulletin of the Seismological Society of America, Vol. 85, No. 6, pp. 1576-1590.
32. Israel, M. and Kovach, R.L. (1977). "Near-Field Motions from a Propagating Strike-Slip Fault in an Elastic Half-Space", Bulletin of the Seismological Society of America, Vol. 67, No. 4, pp. 977-994.
33. Joyner, W.B. (1984). "A Scaling Law for the Spectra of Large Earthquakes", Bulletin of the Seismological Society of America, Vol. 74, No. 4, pp. 1167-1188.
34. Kanamori, H. and Anderson, D.L. (1975). "Theoretical Basis of Some Empirical Relations in Seismology", Bulletin of the Seismological Society of America, Vol. 65, No. 5, pp. 1073-1095.
35. Lam, N., Wilson, J. and Hutchinson, G. (2000). "Generation of Synthetic Earthquake Accelerograms Using Seismological Modelling: A Review", Journal of Earthquake Engineering, Vol. 4, No. 3, pp. 321-354.
36. Levy, N.A. and Mal, A.K. (1976). "Calculation of Ground Motion in a Three-Dimensional Model of the 1966 Parkfield Earthquake", Bulletin of the Seismological Society of America, Vol. 66, No. 2, pp. 405-423.

37. Olsen, K.B. and Archuleta, R.J. (1996). “Three-Dimensional Simulation of Earthquakes on the Los Angeles Fault System”, Bulletin of the Seismological Society of America, Vol. 86, No. 3, pp. 575-596.
38. Panza, G.F., Romanelli, F. and Vaccari, F. (2000). “Seismic Wave Propagation in Laterally Heterogeneous Anelastic Media: Theory and Applications to Seismic Zonation” in “Advances in Geophysics, Vol. 43 (edited by R. Dmowska and B. Saltzman)”, Academic Press, San Diego, U.S.A.
39. Panza, G.F. and Suhadolc, P. (1987). “Complete Strong Motion Synthetics” in “Seismic Strong Motion Synthetics (edited by B.A. Bolt)”, Academic Press, Orlando, U.S.A.
40. Silva, W.J., Darragh, R.B., Stark, C., Wong, I., Stepp, J.C., Schneider, J.F. and Chiou, S.J. (1990). “A Methodology to Estimate Design Response Spectra in the Near-Source Region of Large Earthquakes Using the Band-Limited-White-Noise Ground Motion Model”, Proceedings of the 4th US National Conference on Earthquake Engineering, El Cerrito, U.S.A., Vol. 1, pp. 487-494.
41. Wald, D.J., Heaton, T.H. and Hudnut, K.W. (1996). “The Slip History of the 1994 Northridge, California, Earthquake Determined from Strong-Motion, Teleseismic, GPS, and Leveling Data”, Bulletin of the Seismological Society of America, Vol. 86, No. 1B, pp. S49-S70.
42. Wang, G.X., Tao, X.X. and Xie, L.L. (2001). “Strong Ground Motion of the 1994 M6.7 Northridge Earthquake Simulated by a Stochastic Approach”, Proceedings of IAGA-IASPEI Joint Scientific Assembly, Hanoi, Vietnam, Paper No. 2367 (on CD).