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State-of-the Art Report
SEISMOLOGICAL SYNTHESIS OF STRONG GROUND MOTION

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SUMMARY

Considerable progress has been made in recent years toward a more quantitative prediction of strong ground motion for a potential earthquake fault by a closer cooperation among geologists, seismologists, and earthquake engineers. There are, however, several outstanding issues about the source, path and site effects on strong ground motion. They are (1) establishing stability of stress drop responsible for strong motion, (2) identification of asperities and barriers on a given fault, (3) origin of f_{max}, (4) regional variation and frequency dependence of Q, (5) characterization of site conditions for capturing the frequency dependent amplification effect and (6) microzonation based on site-specific amplification determined empirically using small earthquakes and artificial sources.

INTRODUCTION

At the annual meeting of the Seismological Society of America in 1980, I gave a presidential address titled "Possibilities of Seismology in 1980's," in which I discussed several goals for seismologists during the decade of 1980. One of the goals that I thought we would accomplish in the present decade was the strong motion prediction based on fault models of earthquakes, namely, to synthesize seismic motion at a specific site of an engineering structure when a potential earthquake fault mapped by geologists breaks. In a recent joint meeting of Seismological Societies of America and Japan in Hawaii, the president of SSJ, Dr. Tatsuo Usami picked up my address in 1980, and questioned if the goal of strong motion prediction would be achieved in this decade, now that we are approaching its end. In the present paper, I shall try to respond to Dr. Usami's question.

It has been almost 80 years since Reid proposed the elastic rebound theory for explaining the origin of an earthquake, and a quarter century since Maruyama (Ref. 1), and Burridge and Knopoff (Ref. 2) derived a mathematical framework for relating observed seismic motion with the earthquake rupture process along a fault in the earth. The mathematical framework enabled seismologists to bridge geologists' observations on earthquake faults directly with strong ground motion concerned by engineers designing earthquake resistant structures.

This new approach has been gaining momentum as an increasing amount of high-quality strong motion records have been digested by the use of various models of earthquake sources. In fact, successful predictions of observed strong ground motion using both deterministic and stochastic models were considered as one of major scientific achievements in the U.S. National Earthquake Hazards Reduction Program in a report published by the U.S. Geological Survey in 1985.

Quantitative modeling of earthquake source processes is of the fundamental interest to seismologists, and its output is of the practical importance to earthquake engineers. Thus, this new approach naturally promoted stronger interaction between seismologists and earthquake engineers, as witnessed, for example at the workshop on "Strong ground motion simulation and earthquake engineering" held April 30 - May 3, 1984 in Los Altos, California, by the EPRI, the National Science Foundation, the U.S. Nuclear Regulatory Commission, and the U.S. Geological Survey. The Proceedings of the Workshop (Ref. 3) concluded that geologists, seismologists, and engineers must work together to develop ground-motion time histories for engineering design, and that the workshop was a step in the right direction.

During the Los Altos workshop, I felt an acute need for more active participation of geologists in helping seismologists to assign parameters of their source models for a given potential earthquake fault and/or seismotectonic province. This problem was addressed in a recent workshop on "fault segmentation and controls of rupture initiation and termination" March 7-9, 1988 in Palm Springs, California, and seismologists and geologists began productive interaction for a more quantitative prediction of strong ground motion.

So, we are gaining momentum in this approach among the broad community of geologists, seismologists, and earthquake engineers. Let us now review briefly its state-of-the-art.

Earthquake Source Modeling   The subject of earthquake source modeling relevant to strong ground motion has been reviewed by several authors (Refs. 4,5,6, and 7) and here we shall limit ourselves to general statements, minimizing reference to individual works.

The ultimate goal of seismologists in earthquake source modeling is so called "dynamic modeling", in which we predict strong ground motion for a potential earthquake fault using laws of physics of rock failure and seismic wave generation under a given tectonic stress condition. The dynamic modeling approach has been extended to the 3-dimensional case of heterogeneous fault plane with asperities and barriers (e.g.,Ref. 8). This approach has been useful as a guide for developing more practical kinematic modeling, in which fault slip or stress drop is prescribed in an ad hoc manner by a small number of parameters. For example, Yomogida (Ref. 9) compared the near-source strong motion records for the Michoacan, Mexico, earthquake of 1985 and California earthquakes, and found that the former can be explained by smooth growth of a crack, while the latter involves irregular rupture propagation.

A variety of kinematic models have been applied to observed strong motion records. They are divided into two broad groups, namely, deterministic and stochastic models. The deterministic model has a more restricted range of applicability than the stochastic model in terms of distance to the earthquake source and the frequency of seismic motion. The limiting distance and frequency depends on the earthquake size. Ground motion with relatively long period can be simulated with a meaningful accuracy for engineering purposes using the known fault slip in a previous major earthquake and the known crustal structure entirely deterministically. For example, Bouchon and Aki (Ref. 10) simulated the displacement and particle velocity for periods longer than 5 sec due to the 1857 great California earthquake using the distribution of slip along the San Andreas fault estimated by Sieh (Ref. 11) completely analytically. The simulation of the same earthquake was made also by Kanamori (Ref. 12) and Butler and Kanamori (Ref. 13) using Hartzell's(Ref. 14) method of empirical Green's function, in which actual records of small earthquakes sharing the common source location and mechanism are used in place of analytical Green's function.

In general, the analytical approach has an advantage of simulating strong motion records for an arbitrary choice of parameters of earthquake source, propagation path, and recording site. Thus, it is most useful for the parameter sensitivity study and for evaluating the range of uncertainty in the predicted motion due to the uncertainty in model parameters.

On the other hand, the empirical Green's function method is practically useful because it eliminates the need for specifying the propagation path and recording site effect. For example, Irikura (Ref. 15) was able to synthesize a strong motion record of the Izu-Hanto-Oki earthquake (M=6.7) in an excellent agreement with the observed for frequencies lower than about 1 Hz.

At present, any practical simulation of high-frequency acceleration requires a stochastic model because of our ignorance of the details of fault zone and rupture process. A simple but useful model was proposed by Hanks and McGuire (Ref. 16) to explain the observed root mean square acceleration. Their model brought out one of the most encouraging results of strong ground motion seismology for California earthquakes, namely the stability of "dynamic stress drop" within a factor of 2, although the physical meaning of the dynamic stress drop is unclear within the context of Brune's model used as the starting point (see Papageorgiou and Aki (Ref. 17)). The specific barrier model of Papageorgiou and Aki (Ref. 18), a hybrid of deterministic and stochastic models, on the other hand, clearly distinguishes the local stress drop responsible for high-frequency generation from the global stress drop corresponding to the average over the entire fault plane. They also found the stability of local stress drop among major California earthquakes. The stability of local stress drop apparently is not restricted to California, because Kamiyama (Ref. 19) obtained a similar result for Japan by applying the specific barrier model to the velocity response spectra equalized to a rock site, a reference distance (77.7 km) and a reference focal depth (43 km) by the regression analysis of many strong motion records obtained in Japan. Furthermore, Boore and Atkinson (Ref. 20) found that the Hanks-McGuire model with constant stress parameter independent of magnitude also applies to small to moderate earthquakes in the eastern North America.

Further studies are needed for establishing the stability of stress drop worldwide, because there are conflicting reports on the dependence of stress drop on depth and fault types (McGarr (Ref. 21); Crouse, et al. (Ref. 22)).

The specific barrier model of Papageorgiou and Aki is a rather extreme model of expressing a heterogeneous fault plane in which barriers are assumed to be unbroken after the passage of rupture. Strong patches on a fault plane which break during an earthquake are called asperities, and used in a deterministic model of Kanamori and Stewart (Ref. 23) and in a stochastic model of Izutani (Ref. 24) based on Hirasawa's (Ref. 25) idea.

If we know the characteristics and distribution of asperities and barriers, we can specify the parameters of these models, and predict strong ground motion using these models. At present, However, we don't have a well established and widely accepted means of identifying asperities and barriers on the fault plane.

One approach to resolve this outstanding problem is to determine the asperities and barriers by the inversion of observed seismograms, and relate the result with available geological and geophysical features of the fault plane. The deterministic inversion of both near-source and far-field seismic data for defining asperities and barriers has been pursued by many seismologists (e.g. Kikuchi and Kanamori (Ref. 26), Olson and Apsel (Ref. 27), Ruff and Kanamori (Ref. 28), Archuleta (Ref. 29), Hartzell and Heaton (Refs. 30, 31), and Mendoza and Hartzell (Ref. 32) among others), and is clearly a promising direction for the future development of strong motion seismology. I am optimistic about the future cooperation of geologists in this effort judging from their enthusiastic participation in the workshop mentioned earlier.

Another important unresolved problem concerns with the so called f_{max},coined by Hanks (Ref. 33), beyond which the acceleration spectrum decays sharply. The primary cause of f_{max} is probably not due to the propagation path effect, because it depends only weakly on the propagation distance. In many cases of small earthquakes, it is related to the presence of a surficial layer with very low Q as demonstrated by Anderson and Hough (Ref. 34) among others. For major earthquakes in California, however, f_{max} may be due to the smoothing affect of finite breakdown zone of a fault. Papageorgiou and Aki (Ref. 18) and Aki (Ref. 35) combine various observations on large and small earthquakes associated with a given fault zone in arguing for the validity of f_{max} being due to the source effect. f_{max} is important for engineering structures sensitive to high frequencies such as a unclear power plant. I feel that we should be broad-minded in this issue in order to explore possible f_{max} effects due to source, path and site conditions.

Attenuation with Distance The state-of-the-art in predicting attenuation relations for strong ground motion has been reviewed recently by Campbell (Ref. 36) and Joyner and Boore (Ref. 37). In the present paper, therefore, I shall briefly touch some of the more controversial seismological aspects of strong motion attenuation. An accurate and reliable measurement of attenuation for sismic waves with high frequencies and over travel distances relevant to strong ground motion has been a difficult problem for seismologists for various reasons. Among numerous attempts made in the past two decades to overcome the difficulties, two approaches appear to have endured a long successful developments. One is the single station method using S waves from many local earthquakes at relatively short epicentral distances first applied by Fedotov and Boldyrev (Ref. 38) to the Kuril Island area. The other is the use of Lg waves measured at relatively long epicentral distances, first applied by Nuttli (Ref. 39) to Eastern North America.

The method of Fedotov and Boldyrev avoided the problem of recording site effects on attenuation measurements by using only a single station. It also greatly simplified the geometrical spreading effect by the use of deep seismic sources, for which the wave path will be nearly straight and the assumption of geometrical spreading being inversely proportional to hypocentral distance may be justified. Fedotov and Boldyrev, however, had to assume that the source spectrum is the same for all earthquakes with the same magnitude. This assumption was later discarded by Aki (Ref. 40), who eliminated the source effect on S waves by normalizing to the coda waves at a reference lapse time. The elimination of source effect does not depend on the validity of a specific model of coda waves such as the single-scattering model (as some people misunderstand), but only based on the observed fact that the coda wave amplitude shows a common decay curve with time independent of location of source and receiver. The method was applied to the Kanto area with a further test by two different choices of the single station in the same area. Two stations, Tsukuba and Dodaira (nearly 100 km apart), gave results in an excellent agreement with each other.

The attenuation of seismic waves is usually expressed in terms of Q^{-1}, where Q is called the quality factor. The total attenuation of amplitude with distance is expressed as a product of geometrical spreading factor and exp $(-\pi fx/Qv)$, where f is the frequency, x is the travel distance, v is the wave velocity. Both Fedotov and Boldyrev (Ref. 38) and Aki (Ref. 40) found that Q increases with frequency in the form of $Q_o f^n$ for the frequency rang 1 to 25 Hz, and n is from 0.5 to 0.8 for the Kuril island area and the Kanto area.

On the other hand, the refinement of Nuttli's method for Lg wave attenuation was done by Campillo et al. (Refs. 41 and 42). In the first paper, they calculated exact synthetic seismograms for realistic models of crustal structure and confirmed the approximate validity of Nuttli's assumption on the geometrical spreading. In the second paper, they determined Q using the geometrical spreading obtained from synthetic seismogram and allowing for frequency dependent site amplification for each recording site. There result again showed that Q increases with frequency in the form of $Q=Q_of^n$, with $Q_o=290$ and n=0.52 for central France.

In the meantime, much simpler methods of estimating Q were devised using coda waves under the assumption of single back-scattering (Refs. 43, 44, and 45), and have been applied to many regions of the world. Frequency-dependent Q values obtained by these coda methods in general agreed well with those obtained by the single station method (e.g. Ref. 40) or by the Lg method (e.g. Ref. 46). On the whole, active tectonic provinces like stable regions such as central North America are characterized by low values (0.1-0.2).

The above result has a direct consequence on engineering seismology, because if n=1, the shape of response spectrum will be independent of distance (as in California), but the relative content of low frequency will increase with distance if n is small (as in the central U.S.).

In their state-of-the-art report mentioned earlier, however, Joyner and Boore (Ref. 37) brought up a recent paper by Frankel and Wennerberg (Ref. 47) who questioned the reality of frequency dependence of Q discussed above. They suggested that the geometrical spreading of 1/r may not be justified in many cases, and the apparent frequency dependence of Q may be simply the consequence of underestimating the effect of geometric spreading. I feel that the correct geometrical spreading was assigned carefully in the works of Aki (Ref. 40) and Campillo et al. (Ref. 42), but it is clear that further work is needed to extend their methods to other areas before the frequency dependence of Q may be widely accepted.

According to a recent study by Sato (Ref. 48) on the attenuation of seismic waves in a medium with a fractal distribution of point absorbers or scatterers, the geometrical spreading factor will depend on the fractal dimension. Clearly, there is a need also for further theoretical work on seismic attenuation.

Local Site Effects The state-of-the-art in evaluating local site effects on strong ground motion has been reviewed recently by Aki (Ref. 49) in a recent special conference of the American Society of Civil Engineers titled "Earthquake Engineering and Soil Dynamics II" held in June, 1988 at Park City, Utah. In the following, I shall present a brief summary of my findings and recommendations.

Remarkably consistent results have emerged from various studies of site effects on strong ground motion in both U.S. and Japan by classifying a given geological condition broadly into soil and rock sites. All of them show that soil sites have greater amplification factors than rock sites for long period, but the relation tends to be reversed for short periods. The crossover period is around 0.2 sec for both U.S. and Japan.

With regard to the magnitude of amplification factor, soil sites show up to a factor 2 to 3 greater amplification than rock sites for periods longer than the crossover period, while the amplification at rock sites relative to soil sites for shorter periods is less than a factor of 2.

The above frequency dependence of site effect is reflected in the difference in site effect among peak ground acceleration, velocity, and displacement. For example, Trifunac (Ref. 50) concluded that the influence of geological conditions at the recording site appeared to be insignificant for peak acceleration but become progressively more important for peaks of velocity and displacement. This statement is consistent with the frequency dependent site effect, because the predominant period in peak acceleration is in the general range shere the crossover occurs, and there may be roughly equal chance for amplification and deamplification, while the predominant period in peak velocity and displacement is probably longer than the cross-over period.

The above results seemingly suggest that the variation in the site effect from a site to another may be at most a factor of 3, and the effect may decrease with decreasing period, becoming insignificant for short periods that prevail in the peak acceleration. A review of recent empirical studies on site-specific amplification using regression analysis of earthquake data, however, clearly indicates that the above suggestion is not right. The correct interpretation is that the broad classification of geologic conditions into soil and rock sites fails to capture the essential factor controlling the site effect for shorter periods.

Observations in Japan by Kamiyama and Yanagisawa (Ref. 51) indicate that the geographic variation of site-specific amplification factor obtained by regression analysis ranges over a factor of about 10 for frequencies between 1 to 10 Hz. Since the standard error of the observed variation of amplification factor for different directions of incident waves is less than a factor of 2, we may conclude that a very meaningful microzonation map predicting the amplification factor can be constructed for the frequency range at least from 1 to 10 Hz.

There are two alternative approaches toward the meaningful microzonation. One is to measure the site-specific amplification factor empirically using the data from large and small earthquakes (Ref. 52). The other is to improve the characterization of site conditions to capture the physics of frequency dependent amplification effect.

The microtremors are easier to observe than earthquakes and useful for a broad classification of site conditions, but cannot give accurate estimation of amplification factor because of the unknown source effect.

Numerous observations (e.g. Ref. 53) exist to support that the amplification factors for weak and strong motions are similar to each other to the first order, except for the obvious case of liquefaction.

In order to improve the site characterization, it is essential to understand the causes of local variations in ground motion. There have been considerable progresses in this respect by numerous theoretical studies on the causes of local variations in ground motion including the effects of flat free surface, topography, flat soft surface layer, and sediment-filled valley. Successful comparisons of observation and theory suggest that we may have an adequate state-of-the-art in predicting the site effect on ground motion for many realistic situations, if we know (1) input motion, (2) velocity and density distribution, (3) topography, (4) sediment thickness, and (5) damping of sediment. The analysis method still need development for application to more general 3-D, heterogeneous and anisotropic cases, but the real difficulty lies in gaining information about input motion and structural parameters mentioned above.

The most realistic approach to the microzonation is then to determine empirical site-amplification factors for as many sites as possible by the regression analysis of earthquake data, and correlate them with various geotechnical parameters of the site which are relatively easier to measure. Analytical studies on the causes of site effects will give helpful insight to the search for effective parameters.

Integration of Source, Path and Site Effects Damage in Mexico City by the earthquake of 19 September 1985 has been attributed to a double resonance, namely, the resonance of building and that of lake sediment at the same period of 2 to 3 seconds. Recently revealed seismological evidence suggests that it might have been due to a triple resonance with an additional resonance at the earthquake source. The evidence comes from (1) the vertical component motion observed at several sites in Mexico City, (2) teleseismic P wave-form, and (3) strong motion velocity record at Caleta de Campos.

The vertical component displacement record observed in Mexico City showed a very similar wave form at all stations whether it is on the lake sediment or not, and it showed ripples of period 2 to 3 seconds. Since ripples are observed at the site without the lake sediment, they are not due to the resonance of lake sediment, but due to incident wave field. The same ripples were observed on the strong motion velocity record at Caleta de Campos (Ref. 54) as well as on the record of broad-band stations at Grafenberg, Germany and other distant stations (Ref. 55). Since the path effects are widely different among the above three types of records, we must conclude that the ripple is caused by some resonance phenomena at the source such as regularly spaced asperities.

The above example clearly illustrates the importance of simultaneously considering the source, propagation path, and site effects for understanding the damage caused by strong ground motion.

Hopefully, Dr. Usami is now convinced that we are approaching the goal I promised in 1980.

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REFERENCES

1. Maruyama, T., On the Force Equivalents of Dynamic Elastic Dislocations with Reference to the Earthquake Mechanism, Bull. Earthq. Res. Inst., Tokyo University, 41, 467-468, 1963.
2. Burridge, R. and L. Knopoff, Body Force Equivalents for Seismic Dislocations, Bull. Seis. Soc. Am., 54, 1875-1888, 1964.
3. Scholl, R.E. and J.L. King, editor, Strong Ground Motion Simulation and Earthquake Engineering Applications, EERI, Publication No. 85-02, 1985.
4. Aki, K., Strong Motion Prediction Using Mathematical Modeling Techniques, Bull. Seis. Soc. Am., 72, S29-41, 1982.
5. Aki, K., Strong Motion Seismology, in Earthquakes: Observation, Theory and Interpretation, H. Kanamori and E. Boschi (eds.), 223-250, 1983.
6. Boore, D.M., The Prediction of Strong Ground Motion, M.O. Erdic and M.N. Toksoz (eds.), Strong Motion Seismology, 109-141, 1987.
7. Heaton, T.H. and S.H. Hartzell, Earthquake Ground Motions, Ann. Rev. Earth Plant. Sci. 1988, 16, 121-145, 1988.
8. Das, S., Comparison of the Radiated Fields Generated by the Fracture of a Circular Crack and a Circular Asperity, Geophys. J. R. Aster. Soc., 85, 601-615, 1986.
9. Yomogida, K., Dynamic Rupture Processes Infered from Near-fault Observations, abstract, EOS, 68, p. 1354, 1987.
10. Bouchon, M., and K. Aki, Simulation of Long-period, Near-field Motion for the Great California Earthquake of 1857, Bull. Seis. Soc. Am., 70, 1609-1682, 1980.
11. Sieh, K.E., Slip Along the San Andreas Fault Associated with the Great 1857 Earthquake, Bull. Seis. Soc. Am.,68, 1242-1448, 1978.
12. Kanamori, H. A semi-empirical approach to prediction of long-period ground

motions from great earthquakes, Bull. Seis. Soc. Am., 69, 1645-1670, 1979.
13. Butler, R. and H. Knamori, Long-period ground motion from a great earthquake, Bull. Seis. Soc. Am., 70, 943-961, 1980.
14. Hartzell, S. H., Earthquake aftershocks as Green's functions, Geophys. Res. Lett., 5, 1-4, 1978.
15. Irikura, K., Semi-empirical Estimation of Strong Ground Motions During Large Earthquakes, Bull. Disas. Prev. Res. Inst., Kyoto Univ., 33, 63-104, 1983.
16. Hanks, T.C. and R. McGuire, The Character of High Frequency Strong Ground Motion, Bull. Seis. Soc. Am., 71, 2071-2096. 1981.
17. Papageorgiou, A.S. and K. Aki, Scaling Law of Far-field Spectra Based on Observed Parameters of the Specific Barrier Model, PAGEOPH, 123, 353-374, 1985.
18. Papageorgiou, A. and K. Aki, A Specific Barrier Model for the Quantitative Description of Inhomogeneous Faulting and the Prediction of Strong Motion, Part 1, Bull. Seis. Soc. Am., 73, 693-722, Part 2, Bull. Seis. Soc. Am., 73, 953-978, 1983.
19. Kamiyama, M., A Scaling Law of Source Parameters Associated with Strong Motion Accelerograms, in Ground Motion and Engineering Seismology, A.S. Cakmak, editor, Elsivier, 595-607, 1987.
20. Boore, D.M. and G.M. Atkinson, Stochastic-prediction of Ground Motion and Spectral Response Parameters at Hard-rock Sites in Eastern North America, Bull. Seis. Soc. Am., 77, 440-467, 1987.
21. McGarr, A., Scaling of Ground Motion Parameters, State of Stress, and Focal Depth, J. Geophys. Res., 89, 6969-6979, 1984.
22. Crouse, C.B., Y.K. Vyas, and B.A. Schell, Ground Motions from Subduction-zone Earthquakes, Bull. Seis. Soc. Am., 78, 1-25, 1988.
23. Kanamori, H. and G.S. Stewart, Seismological Aspects of the Guatemala Earthquake of February 4, 1976, J. Geophys. Res., 83, 3427-3434, 1978.
24. Izutani, Y., Source Parameters Relevant to Heterogeneity of a Fault Plane, J. Phys. Earth, 32, 511-529, 1984.
25. Hirasawa, T., Prediction of Maximum Acceleration Due to a Stochastic Source Model, Rep. Special Research on National Disaster (in Japanese), No. A-54-3, 35-45, 1979.
26. Kikuchi, M. and H. Kanamori, Inversion of Complex Body Waves, Bull. Seis. Soc. Am., 72, 491-506, 1982.
27. Olson, A.H. and R.J. Apsel, Finite Faults and Inverse Theory with applications to the 1979 Imperial Valley Earthquake, Bull. Seis. Soc. Am., 72, 1969-2001, 1982.
28. Ruff, L. and H. Kanamori, The Rupture Process and Asperity Distribution of Three Great Earthquakes from Long-Period Diffracted P-waves, Phys Earth. Planet Interiors, 31, 202-230, 1983.
29. Archuleta, R., A Faulting Model for the 1979 Imperial Valley Earthquake, J. Geophys. Res., 89, 4559-4585, 1984.
30. Hartzell, S.H. and T.H. Heaton, Inversion of Strong Ground Motion and Teleseismic Waveform Data for the Fault Rupture History of the 1979 Imperial Valley, California Earthquake, Bull. Seis. Soc. Am., 73, 1553-1583, 1983.
31. Hartzell, S.H. and T.H. Heaton, Rupture History of the 1984 Morgan Hill, California, Earthquake from the Inversion of strong Motion Records, Bull. Seis. Soc. Am., 74, 1969-1994, 1984.
32. Mendoza, C. and S.H. Hartzell, Inversion for Slip Distribution Using Teleseismic P Wave Forms: North Palm Springs, Borah Peak, and Michoacan Earthquakes, Bull. Seis. Soc. Am., 78, 1092-1111, 1988.
33. Hanks, T.C., f_{max}, Bull. Seis. Soc. Am., 72, 1967-1980, 1982.
34. Anderson, J.G. and S.E. Hough, a Model for the Shape of the Fourier Amplitude Spectrum of Acceleration at High Frequencies, Bull. Seis. Soc. Am., 74, 1969-1994, 1984.
35. Aki, K., Magnitude-frequency relation for small earthquakes: A clue to the origin of f_{max} of large earthquakes, J. Geophys. Res., 92, 1349-1355, 1987.
36. Campbell, K.W., Strong Motion Attenuation Relations: A Ten-year Perspective, Earthquake Spectra 1, 799-804, 1985.

37. Joyner, W.B. and D.M. Boore, Measurement and characterization of Strong Ground Motion on a Regional Scale, Proceedings of an ASCE Conference on "Earthquake Engineering and Soil Dynamics II", Park City, Utah, June, 1988.
38. Fedotov, S.A. and S.A. Boldyrev, Frequency Dependence of the Body Wave Absorption in the Crust and the Upper-mantle of the Kuril-Island Chain, Izv. Akad. Sci. USSR, Phys. Solid Earth, No. 9, 17-33, 1969.
39. Nuttli, O.W., Seismic Wave Attenuation and Magnitude Relations for Eastern North America, J. Geophys. Res., 78, 876-885, 1973.
40. Aki, K., Attenuation of Shear-waves in the Lithosphere for Frequencies from 0.05 to 25 Hz, Phy. Earth Planet. Interiors, 21, 50-60, 1980.
41. Campillo, M., M. Bouchon, and B. Massinom, Theoretical Study of the Excitation, Spectral Characteristic and Geometrical Attenuation of Regional Seismic Phases, Bull. Seis. Soc. Am., 74, 79-90, 1984.
42. Campillo, M., J.-L. Plantet, and M. Bouchon, Frequency-dependent Attenuation in the Crust Beneath Central France from Lg Waves: Data Analysis and Numerical Modeling, Bull. Seis. Soc. Am., 75, 1395-1411, 1985.
43. Aki, K. and B. Chouet, Origin of Coda Waves: Source Attenuation and Scattering Effects, J. Geophys. Res., 80, 3322-3342, 1975.
44. Herrmann, R. B., Q Estimates Using the Coda of Local Earthquakes, Bull. Seis. Soc. Am., 70, 447-498, 1980.
45. Aki, K., Scattering and Attenuation of Shear Waves in the Lithosphere, J. Geophys. Res., 85, 6496-6504, 1980b.
46. Singh, S.K. and R.B. Herrmann, Regionalization of Crustal Coda Q in the Continental United States, J. Geophys. Res. 88, 527-538, 1873.
47. Frankel, F. and L. Wennerberg, On the Frequency Dependence of Shear-wave Q in the Crust from 1 to 15 Hz, EOS, Trans. Am. Geophys. Union, 68, 1362, 1987.
48. Sato, H., Amplitude Attenuation and Coda Excitation in Fractal Structure (abstract) Seis. Res. Let., 59, 38, 1988.
49. Aki, K., Local Site Effects on Strong Ground Motion, Proceedings of an ASCE Conference on "Earthquake Engineering and Soil Dynamics II", Park City, Utah, June, 1988.
50. Trifunac, M.D., Preliminary Analysis of the Peaks of Strong Earthquake Ground Motion Dependence of Peaks on Earthquake Magnitude, Epicentral Distance and Recording Site Conditions, Bull. Seis. Soc. Am., 66, 189-219, 1976.
51. Kamiyama, M. and E. Yanagisawa, A Statistical Model for Estimating Response Spectra of Strong Ground Motions with Emphasis on Local Soil Conditions, Soils and Foundations, 26, 16-32, 1986.
52. Phillips, W.S., and K. Aki, Site Amplification of Coda Waves From Local Earthquakes in Central California, Bull, Seis. Soc. Am., 76, 627-648, 1986.
53. Rogers, A.M., J.C. Tinsley, and R.D. Borcherdt, Predicting Relative Ground Response in Evaluating Earthquake Hazards in the Los Angeles Region, ed. J.I. Ziony, U.S.G.S., Prof. Paper 1360, 221-248, 1985.
54. Anderson, J.G., P. Bodin, J.N. Brune, J. Prince, S.K. Singh, R. Quass, and M. Onate, Strong Ground Motion from the Michoacan, Mexico Earthquake, Science 233, 1043-1049, 1986.
55. Singh, S.K., E. Mena, R. Kind, and F. Kruger, Evidence for Anomalous Body Wave Radiation Between 0.4 and 1 Hz from 19 September 1985 Michocan, Mexico Earthquake, Union Geofisica Mexicana Meeting, Ensenada, Nov. 1987.