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STRONG-MOTION SEISMOLOGY

David M. Boore

U. S. Geological Survey, 345 Middlefield Road, Menlo Park, CA 94025

Although this is the first review on this topic to appear in a quadrennial report, the roots of strong-motion seismology extend back to at least 1932, when far-sighted engineers in the Seismological Field Survey of the U. S. Coast and Geodetic Survey installed rugged, fieldworthy instruments designed to make on-scale recordings of large earthquakes (Carder, 1964); these instruments are called accelerographs, for their output closely mimics ground acceleration (Hudson,1979). The original instruments and their offspring have provided a wealth of information about ground motions of direct use to engineers. Due in large part to the continued devotion of the Seismological Field Survey (now part of the Branch of Engineering Seismology and Geology at the U. S. Geological Survey), the number of recordings has increased substantially, particularly in the last two decades, and multiple recordings of a few California earthquakes have provided the data necessary to begin to unravel the complexities of the ground motions and to predict these motions on an empirical basis. Although seismologists used accelerograph records in studies of earthquake energy and ground motion attenuation as long ago as 1942 (Gutenberg and Richter, 1942, 1956), widespread seismological use of the records began with Aki's (1968) analysis of the 1966 Parkfield earthquake. The field of strong-motion seismology has been especially vigorous since 1971, when the San Fernando, California, earthquake produced close to 100 on-scale records of the ground motion within 150 km of the faulting. The rapid growth of the field in the last decade was helped by the social concern with earthquake hazard reduction and by regulatory processes intended to protect the environment and the population from the failure of such engineered structures as nuclear power plants and large dams.

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A major task of strong-motion seismology is the study and prediction of potentially damaging ground shaking; practically speaking, this means predictions of ground motion within several tens of kilometers from earthquakes with moments larger than about 3×10^{23} dyne-cm. To do this requires a truly interdisciplinary approach, with contributions from both seismologists and engineers working on subjects as diverse as theoretical models of crack propagation and experimental nonlinear soil behavior. Because so many different areas of research pertain to strong-motion seismology, this review has been difficult to organize and has resulted in a voluminous bibliography, of which only a fraction of the papers will be specifically cited. The paper begins with a review of data acquisition and processing, followed by studies based on empirical analyses of strong-motion data. These include investigations of the character of strong motion, such as the correlation between components and the prediction from regression studies of strong ground motion as a function of source size and distance from source to site. After this will be a number of topics related to the prediction of strong ground motion, following the usual order of source, propagation path, and site response. Consideration of these topics forms the bulk of the review. The final section deals briefly with the important and difficult problem of prediction of ground motion in the central and eastern United States, where few recordings of motions from damaging earthquakes are available. Because the emphasis in this review is on the prediction of strong ground motion, references to modeling studies using accelerograms from specific earthquakes are not given in a separate section but are distributed throughout the text when their conclusions are relevant to the topic under consideration. In fact, most of them are collected in the subsection of source studies dealing with estimation of source properties.

Because my charge was to review the field from 1979—1982, I have ignored the many contributions made previously (the bulk of which were made between 1971 and 1979). An excellent guide to the earlier literature (and the current literature as well) is the ***Abstract Journal of Earthquake Engineering*** (R. C. Denton, ed.), published by the Earthquake Engineering Center of the University of California at Berkeley.

This review has ignored seismological work related to the estimation of rupture length, magnitude, and recurrence times for future earthquakes. Although of great importance in the reduction of earthquake hazards, these topics more properly belong in a review of risk and seismicity (to have been included in this volume).

Data Acquisition and Processing

Instrumentation and arrays

Of the more than 2700 strong motion accelerographs distributed throughout the United States, most are in buildings and dams in California (Iwan, 1981). About 630 instruments are deployed for the purpose of measuring ground motions that are as free as possible from structural effects (Rojahn and Borcherdt, 1982). About 40% of these are part of the strong-motion instrumentation program of the California Division of Mines and Geology (Wootton, 1980). The most important data to be gathered from these instruments during the reporting period were from the 1979 Coyote Lake, 1979 Imperial Valley, and 1980 Livermore Valley earthquakes, all in California (Porcella *et al.*, 1979; Brady *et al.*, 1980; and McJunkin and Ragsdale, 1980a, 1980b). A good source of data availability is the series of Seismic Engineering Program reports published as U. S. Geological Survey Circulars—e. g., Porcella (1982). Compilations of many data are given by Crouse *et al.* (1980) and Lee *et al.* (1980). Information about accelerograph stations within the western hemisphere is contained in Switzer *et al.* (1981).

Although accelerograms are a rich source of seismological data, full use of the records was hampered by the lack of absolute time and the few number of recordings from any one earthquake. During the last decade, these concerns have been ameliorated to a large extent. Radio time or crystal clocks are being incorporated into the instruments, and increasing attention is being paid to installation (McJunkin, 1979), array or network design from a seismological perspective, and digital recording. Although a number of these matters were considered before 1979 (e.g., Dielman *et al.*, 1975), some important developments have taken place since then. A network of 94 accelerographs has been installed in and around the Los Angeles Basin. This network—a cooperative venture of the University of Southern California (funded by the National Science Foundation) and the California Division of Mines and Geology—will augment existing stations for source studies and provide information about wave propagation in laterally heterogeneous materials (Anderson *et al.*, 1981). On a different scale, recordings have been obtained from small, special purpose arrays. A linear, 300-m long array composed of 6 digital accelerographs near El Centro, California (Bycroft, 1980) produced valuable records of the 1979 Imperial Valley earthquake that are being used to infer the rupture history of the fault (Niazi, 1982a; Spudich and Cranswick, 1982), and an array of 37 digital instruments, installed within a circle of 2 km radius in northern Taiwan, has recorded earthquakes up to magnitude 6.9. Frequency-wavenumber array processing of the data from the Taiwan array indicated that the strong ground motion in the 0.5 to 2 Hz frequency band contained coherent energy propagating at velocities consistent with P, S, and Rayleigh waves (Bolt, Loh, Penzien, Tsai, and Yeh, 1982).

The need for recordings close to large earthquakes can best be met by installing instruments throughout the world. In recognition of this, an international workshop on the deployment of strong-motion arrays was held in Hawaii in 1978 (Iwan, 1979) and special arrays or networks in addition to networks already in existence are now in operation or construction in most seismically active countries, including Italy, China, Japan, Mexico, Turkey, Yugoslavia, India, and Canada.

Record Processing

The 1971 San Fernando, California, earthquake produced a flood of analog records that took several years to hand-digitize and process. This experience and the certainty that with the increasing number of instruments the problem will be worse in future earthquakes has led to the development of automatic digitizing procedures. Two types of digitizers are available, both using film records: a laser-based digitizer that follows a given trace (Brady *et al.*, 1982; Porter, 1982), and a fast-scan drum photodensitometer that uses computer processing to reconstruct a given trace (Lee and Trifunac, 1979; Trifunac and Lee, 1979). Processing of the digital records involves removal of high frequency noise, corrections for instrument response and unknown baselines, integration to produce ground velocity and displacement, and computation of Fourier and response spectra (the latter being a plot of the maximum response of an imaginary single-degree-of-freedom oscillator of fixed damping as a function of the free period of the oscillator; to the extent that a building can be approximated as a simple oscillator, this plot gives a direct estimate of the forces in a building produced by ground shaking with the given acceleration time series.). Although the basic processing techniques were established before 1979, improvements continue to be made. Current research is centered on assessing errors from digitization (Shoja-Taheri, 1980a), and on applying modern signal-processing techniques (Ehrenberg and Hernandez, 1981; Raugh, 1981; Khemici and Shah, 1982; Shyam Sunder and Connor, 1982).

Empirical Studies of Strong Ground Motion

Characteristics

Various ways of characterizing strong ground motion are used for engineering applications and for purposes of comparing with theoretical simulations. For example, Perez (1980, 1982) has characterized the response spectra by the number of cycles sustained above given amplitude levels, and Haldar and Tang (1981) have derived a way of relating an acceleration time history to an equivalent number of uniform cycles. The relations between the three components of recorded motion at a station have been studied by Kubo and Penzien (1979a) and Huang (1982), who constructed a tensor of covariances, and then at every time increment found three orthogonal axes, (the principal axes), such that the covariance between the components was zero. Analysis of the 1971 San Fernando earthquake accelerograms by Kubo and Penzien (1979a) showed a correlation between the major axis and the direction to the fault, indicating more order in the polarization of the accelerograms than might be supposed at first glance. Along the same lines, O'Rourke *et al.* (1982) derived angles of incidence from the polarization of the S-waves and then used this, in combination with a knowledge of local shear velocity, to derive the apparent propagation velocity of S waves at the station. Considering the number of potential problems with this technique, they found very reasonable numbers—2.1 km/s and 3.7 km/s for the 1971 San Fernando and 1979 Imperial Valley earthquakes, respectively. These velocities are consistent with body wave propagation and indicate that even close to earthquakes with faulting near the surface, little of the high-frequency motion is due to fundamental-mode surface waves. For the engineer the measured velocities are important, for they imply that at frequencies of engineering interest, the horizontal wavelengths of the ground motion will greatly exceed the dimensions of most structures. A theoretical study by Luco and Sotiropoulis (1980) arrived at the same conclusion.

Also of interest to seismologists attempting to synthesize strong-motion records are the various studies describing the random-looking acceleration time series in terms of probability distributions. Hanks and McGuire (1981) showed that taken as a whole, the motion has a Gaussian distribution. Mortgat (1979), and following him, Zsutty and DeHerrera (1979) and DeHerrera and Zsutty (1982), found that the peaks could be described by either gamma or exponential probability distribution functions. Given the essentially random ground accelerations, it is perhaps surprising that a strong correlation exists between the peak ground acceleration (that is, the largest extremum in a time series) and the integral-square measure of the motion given by the root-mean-square (McGuire and Hanks, 1980; Hanks and McGuire, 1981). In fact, using the root-mean-square in regression against distance for data from the 1971 San Fernando earthquake leads to no significant reduction of scatter relative to regressions using the peak accelerations as the dependent variable (Bond *et al.*, 1980; McCann, 1980; McCann and Boore, 1982). This could be explained if the scatter in the regressions on distance were due to random, site dependent multiplicative factors.

Attenuation relations

The earthquake loads for which a structure is to be designed are usually specified by one or two measures of the ground motion, the most common being the peak ground acceleration (pga). The estimation of pga almost always is based on attenuation equations derived from regressions of observed motions against earthquake size and distance from source to site. Because of their importance, these regression equations have received much attention and are updated when new data become available. Boore and Joyner (1982) reviewed the techniques used and some of the recent results, while Shakal and Bernreuter (1981) and Toro (1981) discussed some of the biases that might arise if the dependent and independent parameters are not selected with care. In the reporting period of 1979–82, the 1979 Imperial Valley earthquake was an important milestone, for it greatly enhanced the data set for large earthquakes at close distances (i.e., less than 15 km). Boore *et al.* (1980) published a statistical analysis of peak acceleration, velocity, and displacement, and Espinosa (1979) and Boore (1980) derived attenuation curves for peak velocity based on a strong correlation between peak velocity and the peak response of a Wood-Anderson seismograph (thus tying peak velocity to Richter local magnitudes, M_L; see also Luco, 1982). Boore and Porcella (1980) showed that data from the 1979 Imperial Valley earthquake (and a few other recent earthquakes) were well predicted by the earlier study of Boore *et al.* (1980) in the 15 km–100 km distance range. Comprehensive regression analyses including the new data were reported by Campbell (1981b) and Joyner and Boore (1981). Although the basic assumptions regarding the regression model and the constitution of the data set were different, the results of these two studies differed by less than 35% in a range of magnitudes from 5.5 to 7.5 and distances from less than 1 km to 50 km (Boore and Joyner, 1982). In spite of this, controversy exists in the use of the results, especially close to large earthquakes where there are few data to guide the predictions (Bolt and Abrahamson, 1982; Donovan, 1982a,1982b). The key issue is whether the shape of the attenuation curves depends on magnitude. Boore and Joyner (1982) showed that the data cannot distinguish between magnitude-dependent and magnitude-independent shapes. Another issue sometimes raised is whether the spacing between the curves, for equal increments of magnitude, decreases at large magnitudes (an effect known as "saturation"). Campbell's magnitude-dependent shape implies saturation at close distances, but neither Campbell (1981b) nor Joyner and Boore (1981) found evidence for saturation at large distances.

The uncertainties in ground motion predictions can be as large as a factor of two; they are due to many things: variations in source properties, propagation path, and local site response. Several studies have investigated the latter, using ground motion data recorded at several stations in close proximity. Using data from the differential array in El Centro, California, Niazi (1982b) and Smith *et al.* (1982) found that most variation in the peak ground acceleration was due to variations in the high-frequency components, as expected. King and Tucker (1982) found the same thing, and showed that the cross-covariance in the motions deteriorates most rapidly with station spacing for arrays sited in regions with large changes in sediment thickness. McCann and Boore (1982) found variations of a factor of 1.3 in peak ground accelerations recorded within a small (1 km radius) area during the 1971 San Fernando earthquake.

Although the design forces are estimated from peak measures of ground motion, the process is circuitous and involves assumptions about the shape of the response spectrum. A better technique is the direct estimation of response spectra by doing new regressions at a series of incrementally-spaced oscillator frequencies (Cornell *et al.*, 1979). This has been done by Joyner and Boore (1982a, 1982b) for the data set used in their 1981 paper.

The duration of the strong shaking of an earthquake is thought to be an important parameter in structural response and damage and therefore has received some attention. The main difficulty seems to be in agreeing on a definition of duration with engineering significance (McGuire and Barnhard, 1979). Recent definitions are based on cumulative integral-square measures of ground motion (McCann and Shah, 1979; Westermo and Trifunac, 1979; Vanmarcke and Lai, 1980).

Factors in Strong Ground Motion Prediction

As noted earlier, it is logical to separate the many elements needed for the prediction of strong motion into the source, the propagation path, and the site response. These are large categories, however, and so further subdivision is needed.

Source

In this review, three categories of source studies are considered. The first includes modeling studies that determine the source parameters controlling high-frequency motion, such as variations in stress or strength along the fault and rupture velocity determinations. The second category deals with observational and theoretical studies of the effects of finite-size faults relative to the point source approximation commonly used in studies of teleseismic waves. The last category includes mostly theoretical studies aimed at describing the space-time dependence of the slip across the fault surface. (A useful collection of papers on these subjects is U. S. Geological Survey Open-File Report 82-591: Proceedings of Workshop XVI on The Dynamic Characteristics of Faulting Inferred From Recordings of Strong Ground Motion [J. Boatwright, editor and organizer].)

One of the most important developments in the understanding of the earthquake source in the last four years, at least as far as strong motion seismology is concerned, is the documentation of the complexity of earthquake rupture. This complexity can be due to geometrical complexities in the fault plane or heterogenities in the fault strength or tectonic stress. Whatever the cause, an effect is to produce acceleration or deceleration of the rupture front and this in turn radiates high frequencies. Fault complexity has been suspected for some time as the only reasonable explanation of the frequency-magnitude relation, multiple events, and random-appearing ground acceleration (Hanks, 1979a; Nur and Israel, 1980). It has been found in studies of the teleseismic radiation from large earthquakes (Butler *et al.*, 1979; Stewart and Kanamori, 1982) and in studies of recent moderate earthquakes near Friuli, Italy (Cipar, 1981) and California (Hartzell and Brune, 1979; Wallace, Helmberger, and Ebel, 1981; Ebel and Helmberger, 1982; Hartzell and Helmberger, 1982; Olson and Apsel, 1982). All of the studies of the California earthquakes used accelerograph data, sometimes in combination with teleseismic data. A common finding is that small areas of high stress drop are embedded in larger, low stress drop areas. The high-frequency radiation comes from these small areas, although they contribute only a fraction of the total seismic moment.

Even if the rupture were simple, the spread of rupture at a finite speed over the fault surface can lead to destructive interference of the radiated waves and large azimuthal variations in the amplitudes of the waves. This effect, termed "directivity", has been recognized in the long-period radiation from major earthquakes for almost thirty years (see Benioff, 1955). Theoretical and modeling studies show directivity to be an important factor in near-fault ground motions; in general, the predicted amplitudes are much larger in the direction of fault rupture. This apparent focusing of the radiated energy can occur in a narrow range of azimuths, and the azimuthal range and the amplitude of the waves are strong functions of the ratio of the rupture velocity to the shear wave velocity (Hartzell and Archuleta, 1979; Archuleta and Hartzell, 1981). Until recently, observational evidence at frequencies of concern to engineers has been lacking. Now it has been recognized from moderate earthquakes at frequencies from less than 1 Hz to over 10 Hz (Heaton and Helmberger, 1979; Bakun and McEvilly, 1981). Singh (1982) and Niazi (1982a) found directivity in the ground velocities, but not the ground accelerations, produced by the 1979 Imperial Valley earthquakes. Complicated faulting, with corrugations in the fault plane and bilateral rupture on strong patches may destroy the coherence needed to produce a strong directivity effect at higher frequences. This need not always be true, however; Boatwright and Boore (1982) found strong directivity in the ground accelerations radiated by two earthquakes near Livermore Valley, California.

Because of its strong theoretical influence on directivity, rupture velocity is an important source property in the prediction of strong ground motion. Determinations of rupture velocity from a few stations at teleseismic distances are often nonunique—the observed source process time is made up both of the time taken for fault slip to occur and the time it takes for the rupture to propagate along the fault. Analysis of accelerograms distributed around a fault provide a much better experiment for the determination of rupture velocity. For example, the directivity observed by Boatwright and Boore (1982) could only be explained by a rupture velocity greater than about 0.7 times the shear wave velocity. Similar values for the rupture velocity have been reported for the 1971 San Fernando earthquake by Heaton (1982) and, using a variety of techniques, for the 1979 Imperial Valley earthquake by Archuleta (1982a), Niazi (1982a), and Spudich and Cranswick (1982). The latter study is particularly interesting, for it was based on the observed propagation velocity across the short differential array near the fault (Bycroft, 1980, 1982) and is as close as we are likely to come for some time to a direct measurement of the rupture velocity.

Olson and Apsel (1982) also found high rupture velocities for the Imperial Valley earthquake—in fact, they found velocities near the compressional wave speed for propagation over a 20 to 30 km section of fault. Almost all earlier studies of rupture velocity in earthquakes have used an implicit constraint that the rupture velocity was sub-shear. A number of recent theoretical and numerical studies, however, showed that super-shear rupture propagation is possible if the cohesive strength is small. Day (1982b) found that a fault with strength variations may have locally super-shear rupture speeds, but that the stress heterogeneities serve to reduce the average rupture to speeds less than the shear wave velocity. This agrees with the various modeling studies of the Imperial Valley earthquake.

Of possible importance in the prediction of strong motion is the demonstration by Lindh and Boore (1981) and Shoja-Taheri (1980b) that the starting and stopping of the rupture during the 1966 Parkfield, California, earthquake occurred at places corresponding to changes in trend of the surface trace of the San Andreas fault. Furthermore, Bakun (1980) and Bakun *et al.* (1980) have found correlations between seismic activity and surface fault-trace geometry. These studies suggest that surface mapping of fault traces may be used to estimate the degree and location of heterogeneities controlling the radiation of high frequencies in future earthquakes.

Before leaving the realm of modeling earthquake seismograms, I wish to draw attention to Heaton's recent paper on the 1971 San Fernando earthquake (Heaton, 1982). This is his second attempt at modeling records from this event (the first was Heaton and Helmberger, 1979). He found that his previous model, based on accelerograms, did not agree with the teleseismic records, and that his new model is different from one based on teleseismic recordings (Langston, 1978). The lesson is that much nonuniqueness may exist in the source properties derived from a limited data set; it is important to use all available data in the inversion process. Teleseismic records complement near-source accelerograms, for they contain information radiated at different takeoff angles from the source region and at different frequencies.

The realization that heterogeneities in fault properties can significantly influence the high-frequency radiation has led to a number of theoretical and numerical studies of the characterization of the heterogeneities and their influence on the fault slip and radiated energy. These studies range from kinematic or quasidynamic models (Aki, 1979; Andrews, 1981; Boatwright, 1981; Papageorgiou and Aki, 1982a; Swanger, 1982) to models with spontaneous rupture propagation (Das and Richards, 1979; Das, 1980, 1981; Day, 1982b). In agreement with earlier crack studies, Day (1982b) found that abrupt jumps in rupture velocity occur in regions having sharp changes in prestress (i.e., the rupture front has no inertia); high frequencies are radiated by these jumps in rupture velocity (Harris and Achenbach, 1981; Boatwright, 1982a; Madariaga, 1982). Israel and Nur (1979) argued that heterogeneities in faulting are largely due to nonuniform fault strength; variable tectonic stress would be smoothed out by continued faulting.

Predictions of ground motion often requires a knowledge of how source properties or spectra of radiated energy scale with earthquake size. Scholz (1982a) demonstrated that fault slip is proportional to fault length. Two models were proposed to explain this observation, and their predictions of strong ground motion are very different. In one, rise time was fixed and therefore stress drop and peak ground acceleration increase with fault length. The model at the other extreme assumed a constant stress drop and therefore rise times that are proportional to fault length; in this model the peak ground acceleration increases much more slowly than before, going as the square root of the logarithm of fault length (Scholz, 1982b).

In a study using recordings of mine tremors as well as strong-motion records from moderate and large earthquakes, McGarr *et al.* (1981) found that peak velocity scales well with earthquake size and that peak acceleration was not as predictable. The results indicated, for peak velocity at least, that the same scaling can be used for an extremely large range of source sizes—radii from about 8 m to 50,000 m.

The size of earthquakes used in attenuation relations is usually expressed by magnitude. This can lead to confusion, for many magnitude scales exist (Nuttli and Herrmann, 1982) and most reach a limiting value as the physical size (as measured by the moment) of the earthquakes increase. For this reason, among others, the attenuation equations of Joyner and Boore (1981) use the moment magnitude (defined by Hanks and Kanamori, 1979) as one of the independent variables. A criticism of this is that for large earthquakes the seismic moment depends on wave periods much greater than those of engineering interest; implicit in the use of moment magnitude is the assumption that the spectra for most earthquakes scale with moment in the same way. This is not always the case. In some earthquakes the derived moment increases with period for periods considerably beyond the usual corner frequency (Boore *et al.*, 1981; Buland and Taggart, 1981). Furthermore, according to Nuttli (1981b, 1982) the scaling relations, as inferred from various moment-magnitude relations, are different for mid-plate and plate-margin earthquakes. He found, for example, that two earthquakes with a body wave magnitude of 7 can differ in moment by a factor of 100. (Source parameters from recordings within 10 km of small earthquakes in Arkansas and New Brunswick, however, are inconsistent with the parameters from the eastern and central United States earthquakes plotted in Nuttli [1983]—parameters inferred from recordings tens to hundreds of km from the sources. A similar inconsistency has been documented by Munguía-Orozco [1983], for earthquakes in Baja California.)

Several studies have concluded that the type of faulting can influence strong ground motion. Campbell (1981b) reported that accelerations from reverse faults are systematically about 20% to 30% higher on the average than those from other fault types. This conclusion was based on oft-times sparsely recorded events from many geographic regions, and therefore it awaits verification from future recordings. Campbell's findings, however, are consistent with theoretical studies by Anderson and Luco (1982) and McGarr (1982b). The former found an increase in motions above thrust faults, and the latter proposed upper bounds on peak acceleration ($2g$ for reverse faulting; $0.4g$ for normal faulting), from considerations of the state-of-stress in an Earth in which faulting is controlled by the frictional strength of preexisting cracks; these upper limits can be exceeded if local site effects amplify the motion, or if faulting occurs in intact rock.

Propagation path

The studies of propagation path relevant to the prediction of strong ground motion include measurements of the quality factor Q and theoretical wave propagation in heterogeneous media. In a series of papers, Aki has used the direct shear-wave and the coda (later arriving energy not attributed to simple direct, reflected, or refracted energy) to measure the attenuation of waves from small and moderate earthquakes (Aki, 1980a, 1980b, 1981a, 1981b, 1981c, 1982a). At frequencies above about 1 to 3 Hz, he found that attenuation decreases as frequency to a power between 0 and -1, with a peak in attenuation near 1 to 3 Hz. Other studies corroborated the decrease in attenuation with increasing frequency (Mitchell, 1980, 1981; Roecker *et al.*, 1982; Singh *et al.*, 1982). The peak in attenuation is not always seen, however, and Pulli and Aki (1981) suggested that it only exists in tectonically active areas.

The implications of a frequency-dependent attenuation for strong ground motion predictions have not been fully explored. The effort in predicting theoretical wave motions has focused on the effects of layering instead (Bouchon, 1979a, 1979b, 1981; Geller *et al.*, 1979; Herrmann, 1979; Wong and Trifunac, 1979b; Archuleta and Day, 1980; Dravinski, 1980; Harvey, 1981; Herrmann and Goertz, 1981; Kamel and Felsen, 1981; Kausel and Peek, 1982; Niver *et al.*, 1982). Large velocity contrasts can significantly modify the amplitudes of the waves (Bouchon, 1979b) and layering introduces considerable complexity into the waveforms, especially at large distances relative to the source depth (Wang and Herrmann, 1980).

Site response

It has been known for well over a century that local geology can significantly affect the ground motions at a site. Recent work has emphasized the physical understanding of the effects so that quantitative predictions can be made. Site response, usually in the form of amplifications of up to an order of magnitude on soft sediments relative to bedrock motions, have been recognized in waves ranging from small motions at teleseismic distances (Butler and Ruff, 1980), to regional phases (Barker *et al.*, 1981), to strong motions near earthquakes (Joyner *et al.*, 1981; Chang, 1982; Joyner and Boore, 1982a, 1982b; Trifunac and Westermo, 1982). Anomalously large or small ground motion amplitudes are often due to local site conditions. For example, Mueller *et al.* (1982) attributed the peak acceleration of 1.74 *g* recorded during the 1979 Imperial Valley earthquake (the largest strong-motion acceleration ever recorded) to resonance effects due to a thin layer of low velocity sediments—the peak accelerations on nearby stations were 2.5 times less. Campbell (1981b) reported amplifications of peak horizontal acceleration by a factor of 2 at sites underlain by shallow soil as compared to rock or deeper soils.

Empirical studies of the effects of local site geology are often based on the small motions from microseisms, small earthquakes, distant blasts. The energy sources for these motions are fairly common, so specific studies such as detailed mapping of local variations in site response in an area (Hays *et al.*, 1980) and relating the ground response to properties of the underlying soils (Rogers *et al.*, 1979) can be undertaken. A criticism often made of such studies, however, is that because of nonlinear soil response, they are inapplicable to the strong motions from large earthquakes. Hays *et al.* (1979) and Rogers, Covington, Borcherdt, and Tinsley (1981) have looked into this by comparing transfer functions between several stations recording both the 1979 San Fernando earthquake and the weak motions from underground nuclear explosions in Nevada. The observed transfer functions were reasonably similar, implying that the effects of nonlinear soil response may not be as important as once was thought. Joyner *et al.* (1981), studying accelerograms with amplitudes of about 0.25 *g* recorded at two adjacent sites—one on soil and one on rock—reached the same conclusion.

Site response may do more than amplify or attenuate wave motions; Frankel (1982) and Hanks (1982b) concluded that it may be responsible for the commonly-observed sharp depletion of energy in ground accelerations above a certain maximum frequency. Others have attributed this to a source effect (Papageorgiou and Aki, 1982c), with the implication that for small enough earthquakes the stress drop decreases as earthquake magnitude decreases (Archuleta *et al.*, 1982). Estimates of peak accelerations from various source models are directly dependent on the maximum frequency, and therefore this subject will receive increasing attention in the next few years.

Many of the predictions of site response are based on plane wave propagation in vertically-heterogeneous media (Burridge *et al.*, 1980; Kausel and Roesset, 1981), sometimes including nonlinear constitutive behaviour (Wylie and Henke, 1979). Modeling studies by Langston (1981b) and Johnson and Silva (1981) showed that the overall response can be adequately predicted by such models. In their study of accelerograms from the 1979 Coyote Lake, California, earthquake, Joyner *et al.* (1981) found that observed amplifications of 2 to 3 on soil relative to a nearby rock site were well explained by a plane layer model without invoking nonlinear response. They concluded that the amplification of the motion was less a matter of dynamic resonance, as is often assumed, than the simple conservation of energy flux in a tube of rays as it passes through a heterogeneous media. This is not to say that dynamic resonance is nonexistent, only that energy flux may be a good predictor of the amplification of ground motion measures which represent an average over a range of frequencies.

The studies just discussed assumed no variation in material properties in a horizontal direction. This is clearly a poor assumption in many cases; instruments or structures are often sited near the edges of sedimentary basins or near rapid changes in surface topography, such as ridges, artificial cuts, or seacliffs. The influence of these heterogeneities on the seismic ground motion was the subject of a number of papers, some using approximate analytical solutions to idealized problems (Wojcik, 1979; Dravinski, 1982c; Lee, 1982; Wong, 1982). Others used finite element or finite difference methods (Bolt and May, 1979; Drake, 1980; Boore, Harmsen, and Harding 1981; Harmsen and Harding, 1981; May and Bolt, 1982), and one study used a foam rubber model (King and Brune, 1981). The various studies assumed different excitations and geometries, and therefore it is not useful to discuss them in detail. As might be expected, they all showed that lateral heterogeneities have a significant effect on motions whose wavelengths are comparable to the characteristic lengths of the heterogeneities. Boore, Harmsen, and Harding (1981) found that scattering close to a site is a mechanism whereby a significant fraction of vertically traveling energy can be converted into horizontally traveling waves. This may be important for the design of long linear structures such as pipelines and bridges.

Modeling and empirical analysis of data require specific information about the geologic structure and seismic velocities near sites. This has been provided for many strong motion sites in the United States (Silverstein, 1979, 1980a, 1980b; Shannon and Wilson, 1980a, 1980b, 1980c; Fumal *et al.*,1982a, 1982b).

Simulation and Estimation of Strong Ground Motion

I have discussed above many of the elements that go into the prediction of strong ground motion. Studies that combine these elements in various degrees, with the goal of predicting time series or peak parameters, are reviewed here (other reviews can be found in Swanger *et al.*, 1980; Bolt, 1981; Hays, 1980; Swanger *et al.*, 1981; Aki, 1982b). The various studies can be roughly classed into those concerned with predicting intermediate to long period motions (periods greater than about 1 s) and those interested in higher frequencies. The former predictions are often based on computer codes that propagate waves in layered media; the latter recognize that in general the lateral heterogeneities near the Earth's surface make the use of such codes a dubious undertaking (beside which, the cost and complexity of using such techniques is a strongly increasing function of frequency).

A favorite and quite relevent application of the long-period simulation techniques is to compute the motions expected in the Los Angeles area from a repeat of the 1857 earthquake on the San Andreas fault (Kanamori, 1979; Bouchon and Aki, 1980; Butler and Kanamori, 1980; Apsel *et al.*, 1981). The results generally showed that the duration of shaking can be on the order of 6 minutes, and that the maximum amplitudes will be carried by surface waves.

Simulations of high-frequency motion must account for the random-appearing nature of accelerograms, and this is usually done by allowing the source to be complex. The effects of wave propagation are sometimes accounted for by a Green's function technique in which observed records from smaller events are summed to yield the ground motion from a larger earthquake (Kanamori, 1979; Hadley and Helmberger, 1980; Hartzell, 1982). A variation on this theme was given by Hadley *et al.* (1982); they used theoretical wave propagation to obtain the path effect and close-in recordings of a few moderate earthquakes for the source function.

The implications of complex faulting for high-frequency ground motions has been considered by many authors. McGarr (1981) proposed a model of inhomogeneous faulting in which failure occurs in a circular high strength asperity surrounded by an annular, previously failed region. Observations ranging over almost ten orders of magnitude in seismic moment indicated that the ratio of radii of the outer to the inner regions was between 1 and 10, independent of earthquake size. Within the context of his model, this sets upper bounds on near-source ground acceleration and velocity (McGarr, 1982b). (Lower bounds for peak ground motions have been proposed by Luco, 1980, 1982). Further complexities in high-frequency ground motion can be modeled by assuming a distribution of weak and strong patches. Some studies use specific models of the heterogeneities. For example, Joyner and Boore (1980) computed the motions for rupture propagation along a fault on which the dislocation at any point was derived from filtered white noise. Savy (1981) used a fault broken into segments of random lengths, with variable slip and rupture velocity on each segment. The motions computed from these studies account for the finite extent of faults and are appropriate for site-specific predictions of high-frequency ground motions close to large faults. In contrast, Boatwright (1982a) and Papageorgiou and Aki (1982b, 1982c) used a point source representation with random superposition of the radiated field from many circular patches. Their models capture the essence of the high-frequency motions and are appropriate for predictions of the motions over an ensemble of sites surrounding the source. The same can be said for the models of Hanks (1979a), McGuire and Hanks (1980), and Hanks and McGuire (1981): in yet a third way of characterizing the high frequency motion, they showed that a simple spectral representation of the motion (band-limited finite-duration white noise) is justified and that scaling this spectrum according to Brune's simple source-model (Brune, 1970, 1971) gave results in excellent agreement with strong-motion data. McGuire and Toro (1982) have extended the model to the site-specific motions from an extended rupture.

Another class of simulations deals with the motions from what may be called generic models of faulting. Bouchon (1980a, 1980b) has calculated the motion of the ground at many points surrounding both a dip-slip and a strike-slip finite fault. He included a low-velocity layer over the substrate media, and found that this introduces much complexity compared to the motions in a homogeneous halfspace. Anderson and Luco (1982) found an analytical solution for the motions from an idealized propagating fault in a halfspace that allowed them to make extensive parametric studies of the ground motion.

Another type of simulation of use to engineers who need time series for dynamic analyses of structures is based on suitably filtered and windowed random noise (Jurkevics and Ulrich, 1979; Kubo and Penzien, 1979b; Chang *et al.*, 1981; Polhemus and Cakmak, 1981; Nau *et al.*, 1982). These are replicative simulations in that the time series are constrained, on the average, to have certain properties determined from data.

Prediction of Strong Motion in the Central and Eastern U. S.

The design and licensing of the large numbers of nuclear power plants in the eastern half of the United States requires estimates of the strong ground motion from possible earthquakes. Unfortunately, there are few instrumental data available from which to make an empirical estimate of the motions. Instead, two approaches have been used. The first relies on estimates of seismic intensities for future earthquakes and the correlation of intensity with ground motions (Chandra, 1979; Nuttli *et al.*, 1979; Trifunac, 1979; Gupta, 1980; Battis, 1981). Large scatter is often associated with these correlations, however, and therefore methods are being developed for the estimation of ground motions that are less dependent on poorly determined intermediate correlations. These methods generally combine empirical attenuation relations obtained from the low amplitude waves produced by whatever energy sources are available (small earthquakes, explosions) and the scaling of various measures of ground motion obtained from western United States strong-motion data (Campbell, 1981a, 1982). It is clear from studies of Lg waves that attenuation is much less in the eastern United States than in the west (Bollinger, 1979; Chung and Bernreuter, 1979; Apsel and Frazier, 1981; Dwyer *et al.*, 1981). The differences in attenuation should, however, not be important for estimates of motions within several tens of kilometers of the earthquake source. The problem of specifying earthquake size does arise. Nuttli (1981b, 1982) reported that the spectral shapes of midplate and plate margin earthquakes differ. Consequently, earthquakes in the two regions with the same long period measure of magnitude could have different amounts of short period energy. On the other hand, Herrmann and Nuttli (1982) demonstrated an equivalence between magnitudes determined from Lg waves (m_{bLg}) and from the output of a Wood-Anderson seismometer (M_L). Because m_{bLg} is the usual magnitude determined at regional distances for eastern earthquakes, and M_L is used to classify most western earthquakes, they suggested that this establishes a basis for the adoption of the western United States strong motion data base to the east. Herrmann (1981) warned, however that even with the equivalence of m_{bLg} and M_L it may be incorrect to simply replace the attenuation coefficient in regression equations based on western data with that for the east. The problem is that magnitude, peak ground acceleration, peak ground velocity, and peak ground displacement all sample different frequency ranges and, as stated before, the source scaling may differ in the various parts of the country. Clearly, this is an important subject for future work.

Conclusions

As I have attempted to make clear in this review, a great amount of work during the last four years has been put into the prediction of strong ground motion. Seismologists now have a good understanding of this motion over a wide range of magnitudes and distances. Much work remains to be done, however, to reduce the variance in the predictions of the motion. Judging from past experience, the strong motion data set will be considerably enlarged in the next four years. These data will further improve our ability to predict the ground motion. I hope that these additions to the data set will include recordings close to very large earthquakes ($M \geq 7.5$) as well; we have few such records now, and yet it is these earthquakes which govern the design of most important structures and present the greatest earthquake hazard to our population centers.

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References

An introductory remark. Because of the wide range of fields covered in this review, my initial version of this paper grouped the references according to subject matter. I found this to be awkward, for a particular paper could logically fit into several categories, and finding a paper cited in the text often required searching through several groups of references. Thus I have fallen back to the standard alphabetical listing, even though the papers not cited in the text are more likely to escape attention.

In spite of the editor's admonitions not to, I have included many references to the "grey" literature—conference reports, in-house publications, and the like, the engineering community relies heavily on such literature, and much work of importance in strong motion seismology is never published elsewhere.

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SEISMIC STUDIES OF CRUSTAL STRUCTURE

Robert A. Phinney and Robert I. Odom

Department of Geological and Geophysical Sciences
Princeton University, Princeton, NJ 08540

Introduction

During the past four years, seismology has continued its role as the key technique for determination of the structure of the continental and oceanic crust. By and large, however, the field and analysis methods used bear little resemblance to those of ten years ago. A continued push to increase the number of recording channels has led to the routine use of ocean bottom seismometers, sonobuoys, and multichannel streamers in oceanic studies, and to the use of large sets of portable instruments and multichannel seismic reflection strings on land. In studies using earthquakes as sources, local and regional arrays provide a capability for obtaining geologically useful two- and three-dimensional information about the crust. Growth in computing capacity has proceeded in parallel; a substantial number of university and government research groups have hands-on access to superminicomputers with array processors, and handle data libraries containing hundreds of reels of tape. Theoretical advances now make it possible to generate synthetic seismograms for all layered models and for a wide class of nonlayered models, for aid in interpretation of data. Techniques of plane wave decomposition and wavefield migration have opened up many new possibilities for the reduction and interpretation of data collected from arrays without spatial aliasing.

In this review we take up crustal seismology in terms of the major field methods:

1) Explosion studies on land, for crustal and upper mantle structure, with networks of portable stations, and using refractions and wide angle reflections.
2) Deep continental reflection studies, using Vibroseis sources, with dense geophone arrays normally shorter than 10 km, using narrow angle reflections.
3) Marine multichannel reflection studies, using an array of airguns and a towed hydrophone streamer normally shorter than 3 km.
4) Marine long range studies, similar to (1), using ocean bottom seismometers (OBS), or sonobuoys as receivers, with explosions or airguns as sources.
5) Generalized inversion for crust and lithos-

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