REVIEWS OF GEOPHYSICS AND SPACE PHYSICS, VOL. 21, NO. 6, PAGES 1299-1308, JULY 1983
U.S. NATIONAL REPORT TO INTERNATIONAL UNION OF GEODESY AND GEOPHYSICS 1979-1982

SYNTHETICS AND THEORETICAL SEISMOLOGY

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Near Field Synthetics

In the near field, discrete-finite wave number schemes are economic since they involve fewer wave numbers than most wave number integration schemes. The number of wave numbers is determined by the range and the location of artificial reflectors or fictitious sources inherent in discrete wave number techniques. The number and spacing of wave numbers in wave number integration schemes are determined by the desired accuracy.

The vertical integration schemes used in the near field have been either spectral (Apsel,1979,Bouchon,1981) as in the regional techniques or finite-element (Olson,1982) and finite-difference in the time domain as in the Alexseev-Mikhailenko method. The finite element schemes have the disadvantage in that the vertical step size is determined by the desired maximum frequency content, which in turn determines the time step required for stability. This time step is usually many times smaller than the time increment associated with the maximum frequency.

If portions of the vertical velocity and density profile are homogeneous, spectral techniques propagate across the region in one vertical step while the finite element-difference methods reqire many. On the other hand, in the vicinity of moderate vertical gradients the step size or layer thickness of the spectral techniques will be at least as small as the finite element scheme and the number of numerical operations considerably more. Convergence as the number of wave numbers is increased is more straightforward using the spectral schemes and, as one would expect, the number of wave numbers for a given convergence depends on the frequency being evaluated with fewer wave numbers at the lower frequencies.

For the near field and regional synthetic schemes, the wavenumber quadrature of Apsel (1979) and the Fourier Bessel series of Olson (1982) require significantly more wavenumber evaluations than Bouchon's equal interval wavenumber summation. Bouchon (1981) showed that this wavenumber discretization is equivalent to adding an infinite set of specified circular sources about the point source at equal radial intervals. The length of time desired for the point source response governs the minimum distance from these new sources and this determines the wavenumber spacing.

For many problems, a fault is treated as a summation of subfaults which can be considered point sources. Thus there is a need for rapid construction of Green's functions for several different source depths. For codes based on reciprocity, ie. surface source and receiver at depth, such as Apsel (1979) and Olson (1982), the only additional effort for obtaining as many source depth Green's functions as there are vertical integration points is in saving the intermediate values at these points. A similar economy can be obtained using the itrerative reflection and transmission coefficient relations of Kennett.

Kamel and Felsen (1981) presented a hybrid ray-mode formulation for the construction of SH synthetics. Theory, details, and synthetic were given for the complete SH motion at the top of a low velocity surface layer due to a line SH source at depth in the halfspace. The chosen number of ray fields plus the contour of the remainder integral uniquely determine the number of trapped and leaky modes necessary for the complete seismogram. This scheme has the advantage of a generalized or asymptotic ray description for early observation times and of a modal description at later times. A physical interpretation of the formulation is that the constituent local plane waves synthesizing the modes fill the void in spectrum due to take-off angles left vacant at the source by the truncated ray series, and vice versa.

Paper number 3R0666.
0034-6853/83/003R-0666$15.00

Regional Synthetics

At the regional distances, complete seismograms have been calculated by modal and wave number integration techniques. The vertical integration of both techniques have used either propagator matrices or reflectivity formulations for homogeneous layers.

Dunkin (1965), Knopoff (1964), Thrower (1965), and Gilbert and Backus (1966) presented P-SV formulations which allowed the eigenvalues of multilayered systems to be calculated to almost unlimited high frequencies. Abo Zena (1979) presented an alternative method. One of the advantages of Dunkin's formulation was the use of compound matrices for calculating the vertical eigenfunctions. P-SV eigenfunctions using Dunkin's scheme can be calculated entirely with exponential functions whose value is never greater than one.

Another advantage is that these expressions guarantee convergence of the eigenfunctions at depth even at high frequencies. Harvey (1981) pointed out these expressions were self correcting in that they involve both terms representing integration down from the free-surface and integration up from the half-space. And that when evaluating the eigenfunction near the free surface the downward integration terms dominate and at depth near the terminating half space, the upward integration terms dominate. The most stable form of Dunkin's eigenfunction algorithm is to use Thomson-Haskell matrices from the surface down to the desired depth combined with compound matrices from the half space up to the depth. A similar conclusion was reached by Woodhouse (1980) for his form of the algorithm.

Harvey (1981) modified the eigenfunction expressions so that the same self correcting feature could be used with the Thomson-Haskell layer matrices alone. By using a high velocity terminating half space with a shear velocity greater than any apparent horizontal velocity of interest at the synthesis range, Harvey (1981) calculated regional P-SV and SH synthetics by summing all the "locked modes" in the frequency-phase velocity region of interest. The depth of the half-space was chosen so that arrivals from the bottom were separated from the desired signals.

Herrmann (1979) presented a numerical technique for calculating the SH contribution to tangential displacement due to point dislocation sources. The wave number integral was separated into two branch line integrals and the residue contributions of the real axis poles. The relative contributions of each to the total waveform were calculated and it was found that at short distances, the total integral is required to adequately model the low frequency response of the far field. At large distances, the pole contributions are all that is required for a realistic estimate of the solution; the higher the frequency content of the source and the frequency response of the receiver, the better the pole representation. He also discussed the effect of neglecting the near field P-SV contribution to the solution; in particular, the appearance of non propagating, non causal, early arrivals. The far field SH contribution, which does not have these arrivals seemed to be adequate at distances beyond 2 to 5 source depths for the source durations considered.

Wang and Herrmann (1980) extended the Herrmann (1979) SH wave study to both SH and P-SV wave generation. The P-SV near field term contribution to the tangential displacement field could now be calculated and and it was found that a P-SV arrival really arises to cancel out the non causal arrival introduced by the near field term as previously postulated by Herrmann. Similarly, when the near field contribution of the SH wave to the radial displacement field is neglected, a non progating early arrival exists, especially for the vertical dip slip source.

Fryer (1980) presented an alternative to spectral reflectivity techniques. He advocated the use of the time domain reflectivity coefficient with the solution given as an integral of the coefficient over angle of incidence.

Cormier (1980) formulated and synthesized complete seismograms in the high frequency band appropriate for near and regional distances. The procedure combines the zeroth order in frequency asymptotic solutions to the propagator and fundamental matrices of radially inhomogeneous spherical shells with the stable vector-matrix methods of Abo-Zena (1979). The displacement response is evaluated conveniently by separately calculating the response due to the fundamental Rayleigh pole with one complex ray parameter contour and the response of all the other modes with another contour.

Global Synthetics

Ward (1980) presented the moment tensor source description for the elastic wave potentials in a spherically symmetric slowly varying inhomogeneous medium. The formulation uses the propagator matrix method of solution. This technique is contrasted with that of obtaining the inhomogeneous term for the potential wave equations from the body force and then finding the full solution to the inhomogeneous equations.

Chapman and Woodhouse (1981) extend the symmetries of the first order differential system for elastic waves in plane stratified media to the spherically stratified gravitating system. The symmetry between the propagator and its inverse allowed an analogy to be drawn between the nornal mode solutions and solutions obtained by including the source as an inhogeneous term in the differential system.

Ward (1981) used the results of Chapman and Woodhouse (1981) to transform the propagator matrix solution into a form similar to the normal mode solution in that the source terms of both involve combinations of strain with moment tensor and displacement with force.

Recent papers by Dziewonski and Woodhouse (1982) and Woodhouse (1982) substantially move the routine analysis of long period body waves by the method of normal mode summation toward practical utility.

Kinematic Seismic Sources

Boatwright (1980) investigated the far field body wave radiaton for a class of circular rupture models as a function of takeoff angle, rupture velocity and stopping behavior. Although the rupture slip models were kinematic they were made to resemble previously obtained results from numerical models of dynamic stress relaxation. The concept of characteristic frequency as an estimate of source dimension is also evaluated.

Andrews (1980a) used a coherent plus random model of static slip and stress change in the Fourier wave number domain to relate the spectrum of a stress function on a fault surface with average stress drop as a function of earthquake size and with the number-size distribution of earthquakes. Similar results were obtained using the self-similar irregularity concept of fractals.

Andrews (1981) extended the self similar concept to the time dependent case with the assumption that on a fault with self similar geometric irregularities, the slip velocity as a function of space and time is self-affine. This kinematic construction was used to obtain the expected far field and near field spectrum.

Using the discrete wave number technique of Bouchon (1979) Chouet (1982) calculated the dynamic free surface near field of a tensile crack nucleating over a circular and rectangular surface at depth in a homogeneous half-space.

Dynamic Seismic Sources

Replacing the initial value volume integral by a surface integral of the stress pulse, Stevens (1980) easily evaluated the seismic radiation generated by the sudden creation of a spherical cavity in an arbitrarily prestressed elastic medium. The advantage of this technique is that all one needs to know is the stress drop on the cavity surface whereas the initial value method requires the solution of the static problem in order to evaluate the initial value volume integral.

Stevens (1982) formulated the solution for the seismic radiation from an arbitrarily growing spherical cavity in an arbitrarily prestressed medium as a set of coupled Volterra integral equations. Numerical solutions of these equations are used to compute wave forms for several stress fields and growth rates.

Burridge et al. (1979) numerically investigated the integral equation solution to a semi-infinite Mode II shear crack driven at constant speed by a point load on the surface following the tip at a constant distance.

Knopoff and Chatterjee (1982) explored the analytic solutions to the two-dimensional crack problems of antiplane strain rupture initiating at a point in the presence of dynamical friction and studied the influence of cohesion on the rupture process.

Das (1980) presented a numerical scheme for determining source time functions and rupture histories for three dimensional shear cracks. The method is an extension of the boundary-integral method and as applied here is a discretization of the elastodynamic representation theorem using closed form expressions for the Green's function obtained by Richards (1979). These solutions of Lamb's problem for surface displacements due to surface point forces on an elastic halfspace are expressed in terms of simple trigometric functions and square roots.

Das (1981) applied this technique to the spontaneous rupture over crack planes of constant yield strength and constant dynamic stress drop. Slip and rupture histories were obtained for infinite, semi-infinite, and finite rectangular cracks.

Using a finite difference scheme, Virieux and Madariaga (1982) studied spontaneous rupture propagation in two and three dimensions. A maximum stress criteria was used for two types of nucleation; an instantaneously formed crack in a uniformly prestressed medium and the triggering of a preexisting crack.

Using a three dimensional finite difference code similar to Virieux and Madariaga (1982), Day (1982) investigated the effect of fault length and width on slip functions for a simple shear crack model. The rupture velocity was specified as well as the dynamic stress drop. From the numerical results of this driven dynamic model and with comparisons to simpler analytic models, Day was able to develop closed form expressions for static slip, slip rise time, and slip velocity intensity as a function of fault geometry.

Seismic Source Analogues

Israel and Nur (1979), using a one-dimensional continuum model in which stress and strength varied along the fault, numerically investigated their effect on slip histories along the fault with the method of characteristics.

Landoni and Knopoff (1981) numerically investigated the conditions for growing cracks using a one-dimensional model with stress drop a function of relative crack displacement.

Burridge and Moon (1981) simulated numerically a scalar analogue for a rupturing seismic fault plane in a whole space. The rupture spreads with the wave speed and is evaluated by a discretized version of the kernel of the time-areal integral equaton for the displacement on the fault.

Source Path Coupling

Once the displacement and stress fields have been calculated for realistic source models involving processes too complex to be expressed analytically, the usual procedure has been to obtain an equivalent point source by either forming higher order moment tensors for the source displacement field or multipole expansions of the source potentials. The higher order moment tensors or multipole potentials are readily incorporated into codes for forming synthetics on vertically inhomogeneous half-spaces or radially inhomogeneous spherical earth models.

Stump and Johnson (1982) presented the first, second, and third degree moment tensor components for a finite propagating plane shear fault. The convergence of the moment tensor series was investigated in terms of frequency, azimuth, and fault model.

Bache et al. (1982) presented an alternate technique where non-linear explosion calculations are coupled into the propagation medium using the Elastodynamic Representation Theorem. The finite-difference source calculation included non-linear constitutive relations and the interaction with the free surface. The cylindrically axisymmetric displacement and stress calculations were carried out to a cylindrical surface in the linear region surrounding the explosion. The Green's function used in the Representation Theorem surface integration over the cylinder were for Rayleigh waves on a vertically inhomogeneous half-space and the resulting synthetics demonstrated the effects of non-linear explosion phenomena on the generation of Rayleigh waves. This approach has also been used in the excitation of teleseismic body waves from complex explosion calculations involving free surface spallation.

For sources in complex regions where the geometry is such that the strength and time history of the upgoing radiation is distinctly different than that of the downgoing radiaton, but otherwise regular in the linear propagation region, it is simpler to model the propagation effects of upgoing and downgoing source radiation separately and then combine the contributions for a given source. Harkrider (1981) presented the formulation for such a separation of effects for Rayleigh waves generated by underground explosions and calculated synthetics as a function of source depth in a one layer half-space. Other applications proposed for this separation of source effects are propagation models where lateral complexities separately modify the propagation waves generated by the source even though the source radiation is vertically homogeneous.

Lateral Inhomogenities And Transition Zones

Schlue (1979) presented the finite element stiffness and mass matrices for the propagation of spectral Rayleigh and Love wave modes in three-dimensional earth models which are laterally heterogeneous. Schlue (1981) completed the development by giving the boundary stiffness matrix between the laterally homogeneous and inhomogeneous zones.

Using the decomposition of Rayleigh waves into inhomogeneous P and SV waves, Chen and Alsop (1979) gave a procedure for determining the approximate reflection and transmission of obliquely incident Rayleigh waves at a vertical discontinuity between two welded quarter-spaces.

By a generalization of the phase integral method, Frazer and Phinney (1980) presented a technique for computing finite frequency seismograms for a medium whose velocity and density are continuous functions in two or three-dimensions.

Free Oscillations

Dahlen in a series of papers investigated the effect of aspherical splitting on the apparent amplitude, central frequency, and half width of an unresolved isolated multiplet. Using perturbation theory, Dahlen (1979a) determined this effect for both single stations and spectral stacks on a laterally heterogeneous earth model including ellipticity but with anelasticity a function of radius only. Dahlen (1979b) demonstated that for an ellipsoidal earth with no other deviation from sphericity, the appearance of a single or broadened peak as in Dahlen (1979a) is due to cancellation among neighboring singlets. Since the single peak approximation used in Dahlen (1979a,b) breaks down near the epicenter and antipode, Dahlen (1980) obtained an asymptotic formula valid over the entire free surface. Finally, Dahlen (1981) extended his previous results for a smooth laterally heterogeneous earth whose attenuation structure is spherical to an earth whose attenuation structure is laterally variable.

The question of coupling of nearly resonant quasidegenerate multiplets was considered by Woodhouse (1980). The coupling influences considered were those of rotation and ellipticity with a spherically symmetric attenuation structure.

Stifler and Bolt (1981) investigated splitting of low order torsional eigenvibrations using a finite element model of ellipticity and the structural contrasts between oceans and continents.

Chao (1981) using group theory established the eigenfrequency splitting rules for an axisymmetric earth, a rotating earth, and an arbitrary earth. In addition group theory was used to determine the coupling of the unperturbed spherical modes by ellipticity, pear shapedness, and rotation.

Wahr (1981) developed an expansion formalism for the normal modes of a rotating earth by transforming the three-dimensional equations of motion into a six-dimensional system with its own inner product which includes the elastic gravitational operator as part of the inner product definition. This expansion completely decoupled all non-trivial normal modes.

Chao (1982) obtained equivalent results using the method of spectral decomposition for linear operators formulated in Dirac's bra-ket notation first for a non-rotating earth and then, by extending the formulation to operators quadratic in the eigenvalues, to the rotating earth.

Morris and Geller (1982) compared first-order degenerate perturbation theory and Rayleigh-Ritz variational procedures in a calculation of some of the low order toroidal modes of a sphere consisting of hemispheres with different elastic properties.

Seismic Inversion

Silver and Jordan (1982) presented a method for estimating scalar seismic moments from noisy seismic data. The technique also includes the effect of transfer - function errors. The squares of the two scalar moments are related to the squared Euclidian norm and the squared trace of the spectral moment - rate tensor. The basic data function used is the cross-spectrum for seismogram pairs integrated over narrow frequency intervals.

Bolt and Brillinger (1979) present an estimation procedure for determining the amplitudes, frequencies, and damping factors of free oscillations with their variances using complex demodulation and non linear least squares.

Chao and Gilbert (1980) represent a seismogram as an autoregressiive time series and use Prony's method to obtain the complex frequencies from the series. Their algorithm is devised so that spectral peaks can be analysed individually or in small groups. In addition it decouples the problem of estimating amplitude and complex frequency.

Coen (1981) developed an algorithm for inferring the shear modulus and density profiles from the surface displcement field due to an impulsive surface SH line source.

Acknowledgment This research was partially supported by the Advanced Research Projects Agency of the Department of Defense and was monitored by the Air Force Office of Scientific Research under Contract No. F49620-81-C-0008. Contribution No. 3892, Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, California 91125.

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(Received November 8, 1982;
accepted April 29, 1983.)

REVIEWS OF GEOPHYSICS AND SPACE PHYSICS, VOL. 21, NO. 6, PAGES 1308-1318, JULY 1983
U.S. NATIONAL REPORT TO INTERNATIONAL UNION OF GEODESY AND GEOPHYSICS 1979-1982

STRONG-MOTION SEISMOLOGY

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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.

Paper number 3R0397.

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 x 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