Elastic wave radiation from borehole seismic sources in anisotropic media

Wenjie Dong

Submitted to the Department of Earth, Atmospheric, and Planetary Sciences on December 14, 1993 in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

Abstract

This thesis is concerned with wave radiation and propagation from borehole seismic sources in homogeneous and inhomogeneous anisotropic media, with focus on the investigation of borehole influence on downhole source radiation.

First, numerically feasible dynamic and static Green's functions in transversely isotropic media are obtained in dyadic form by evaluating in general a 2-D inverse Laplacian operator involved in previous dynamic Green's function expressions. This evaluation is of particular importance for the later BEM implementation because of off-centered sources. The final dyadic form is similar to that of the isotropic dyadic Green's function, therefore, it lends itself to easy analytical and numerical manipulations. The dynamic Green's function is expressed through three scalar quantities characterizing the propagation of SH, P-SV, and P-SV-SH waves. The static Green's function has the same dyadic form as the dynamic Green's function and the three corresponding scalar functions are derived, From the dynamic Green's function, displacements due to vertical, horizontal, and explosive sources are explicitly given. The singular properties of the Green's functions are addressed through their surface integrals within the limits of coinciding receiver and source. The singular contribution is shown to be -1/2 when the static stress Green's function is integrated over a half elliptical surface. These results are directly applicable to the later BEM implementation.

Following the discussion of Green's functions, analytical radiation patterns of three typical downhole seismic sources in transversely isotropic (TI) media are obtained through asymptotic evaluation of displacement integrals. The radiation patterns are expressed in terms of the slowness components of a particular point on the slowness surface of the medium. This particular point, known as the saddle point of the displacement integrals, is easily determined by geometric arguments based on the slowness and wave surfaces of the TI medium. Since the saddle point determines ray direction,

the radiation patterns can be readily incorporated into existing ray modeling codes to account for borehole source effects. The analytical results show that borehole source radiation patterns are independent of the source frequency if the product of frequency if the product of frequency with borehole radius is much smaller than the sound speed of the borehole fluid. This independence is true for most crosshole experiments with source frequency up to 1 kHz. Numerical test results show that the anisotropy effect on P- wave pattern is relatively moderate. On the contrary, its effect on the S wave pattern is prominent even for low degrees of P and S wave anisotropy. In the isotropic limit, previous analytical results for isotropic medium are recovered. For sources in cased borehole, casing and cement affect both wave amplitudes and radiation patterns.

In chapter 4, a modeling technique based on the boundary element method is established for modeling source radiation from open or cased boreholes in layered TI media. The axis of symmetry of TI layers is assumed to be parallel with the borehole axis. Under this assumption, the problem is significantly simplified because the element discretization of the borehole remains one dimensional. For open boreholes, three equivalent sources on each element are assumed to represent the boundary effects on the inner fluid and the outer solid. Three boundary conditions set up a system of equations for the equivalent sources on all elements. Once the sources are known, displacements in the solid and pressure in the fluid are obtained. For cased boreholes, the method treats borehole fluid, and casing and cement as a cylindrically layered isotropic medium. In this case, the boundary conditions to be satisfied at the borehole wall are four (continuity of the normal and tangential displacements and stresses). Thus, more computation is required to solve the system of equations. The implementation of the method is illustrated through several examples.

Using the technique developed in Chapter 4, a Cross-well hydrophone data set is analyzed in Chapter 5. Two other modelings, one with no boreholes and one with a receiver borehole only, are used for comparison. The results show that synthetic and real data agree with each other very well only when the source borehole stems from the fact that the local geology contains high-contrast sedimentary rocks. Since most of the source energy travels along the source borehole as a tube wave, at high-contrast interfaces tube-to-shear wave conversion is no longer a negligible secondary effect. In fact, as the data and the modeling results suggest, shear waves due to tube wave conversion are even stronger than the primary shear waves. The data and the modeling results also illustrate that, when sandwiched between high velocity layers, a low velocity channel traps tube wave-converted energy and guides it to the receiver borehole to excite tube waves.

Finally, two special borehole sources are modeled analytically and numerically. For the Downhole Orbital Vibrator, actual rotation of a radial force is incorporated into a mathematical expression for the source. By using this source and the Green's functions, the three displacement components in isotropic and TI media are provided. Their numerical evaluation shows that the source may be useful in detecting shear wave anisotropy. For a drill-bit source, the BEM technique of Chapter 4 is extended to model its radiation pattern. Results suggest that the borehole has little effect on drill-bit radiation.