Seismic Guided Wave Propagation in Cracked Thin-Layer Sedimentary Reservoirs and Its Potential Application in EOR Monitoring by Crosshole Surveys

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SUMMARY

This is a theoretical study of the propagation of seismic guided waves in anisotropic sedimentary reservoirs in crosshole surveys. Techniques have been developed for calculating dispersion curves, amplitude-depth distributions, and synthetic seisograms of guided waves in layered structures containing aligned cracks. Based on a gas-sand reservoir waveguide displaying crack-induced anisotropy, a series of dispersion curves, three-component amplitude-depth distributions, and synthetic seisograms have been calculated for different crack parameters: crack density, aspect ratio (crack porosity), crack strike, crack saturation, and level of saturation in gas sand. Modes of guided waves have been identified in crosshole data sets from the field, and interpreted according to their dispersion, amplitude-depth distribution, and polarization patterns. We show that guided waves are very sensitive to crack parameters, direction of propagation, to crack orientation, degree of saturation, and type, position, and frequency of source excitation. We suggest guided waves have potential applications in monitoring enhanced oil recovery (EOR) procedures in thin hydrocarbon reservoirs.

INTRODUCTION

This study suggests that guided waves (channel waves) may be prominent in many crosshole seisograms and could have important applications for monitoring temporal changes in a layer of interest between wells. In recent years, seismic crosshole surveys in production geophysics have been carried out to monitor enhanced oil recovery (EOR) principally by P-wave tomography. It has been recognized that the dominant amplitudes in some crosshole surveys are guided waves (channel waves, or interface waves), propagating parallel to interfaces displaying appropriate impedance contrasts, rather than body waves as are sometimes assumed. Krohn (1990) has observed guided waves in several field and model experiments, and suggested the Crosswell Continuity Logging in an oil or gas reservoir using seisograms.

Any continuous plane interface will support guided waves in crosshole surveys, if a signal of appropriate frequency and radiated signal is excited with an appropriate source at appropriate depths in the reservoir layer. Many sedimentary reservoirs have approximately plane layers with low velocities, and such thin layers in reservoirs may act as seismic waveguides in crosshole surveys (Lou and Crampin, 1991). Determination of the size, position and physical parameters of a buried low-velocity lens or layer is a difficult problem when using seismic reflection or VSP methods (Phadtke and Kanasewic, 1990). Guided waves may provide a new signal for monitoring such thin-layer reservoir characteristics in enhanced oil recovery (EOR) procedures. The unique advantage of guided waves is that most of their energy will be trapped in the zone of interest and, should they display the properties of the zone of interest more strongly and spatially than near-vertically propagating reflection profiles or VSPs.

Guided waves have been widely used in coal-seam tomography (Jackson, 1985), and their propagation in isotropic structures have been extensively studied (Krey, 1963; Buchanan et al., 1983; 1987; Rader et al., 1985). We have now extended the technique to calculate the dispersion three-component amplitude-depth distributions and synthetic seisograms of guided waves in multilayer anisotropic structures. [In anisotropic media, the separate families of Rayleigh and Love modes in plane isotropic layers combine into one family of Generalized modes, with three-dimensional particle motion, Crampin, 1970.] It has been recognized that stress-aligned fluid-filled cracks, microcracks and preferentially oriented pore-space exist in most reservoir rocks, where it is known as extensive-dilatancy anisotropy, or EDA (Crampin, 1987). Based on a gas-sand reservoir (White & Sengubhur, 1987), we calculate a series of dispersion curves, three-component amplitude-depth distributions, and synthetic seisograms of guided waves, and examine the effects on dispersion, amplitude, polarization and seisograms with different EDA crack parameters: crack density, crack aspect ratio (or porosity), crack orientations, crack saturation, and saturation level in the reservoir. The comparison of theoretical results with seisograms could provide a forward modeling technique for inverting the dispersion and polarization of guided waves in anisotropic layers.

Finally, we examine a crosshole field dataset, where guided waves are identified and interpreted according to their dispersion, dominant amplitude distribution, and polarization patterns. We suggest that guided waves may have potential applications in monitoring enhanced oil recovery (EOR) operation by propagating possible guided waves between two wells, since there are changes to saturation or other characteristics of the reservoir.

CALCULATION OF DISPERSION AND AMPLITUDE-DEPTH DISTRIBUTION OF GUIDED WAVES IN MULTILAYERED ANISOTROPIC STRUCTURES

The dispersion and amplitude-depth distribution are important for understanding the propagation of guided waves. Preliminary numerical investigations show that these parameters can assist in choosing the most suitable source and geophone positions, and source characteristics to excite suitable guided waves in given velocity structures. The techniques of Crampin (1970) and Crampin and Taylor (1971) for calculating the dispersion of surface waves in multi-layered anisotropic halfspace have been extended to calculate the dispersion of guided waves. The structure is a multi-layered anisotropic model embedded between two isotropic halfspaces (Lou and Crampin, 1991).

A GAS SAND RESERVOIR WAVEGUIDE

We choose a gas-water sand reservoir encased in shale from the Gulf Coast as a sample waveguide. The P-wave and density log through gas-water sand is shown in Figure 2 (White and Sengubhur, 1987). The Poisson ratios of shale, gas sand and water sand are 0.25, 0.10 and 0.20, respectively. The isotropic matrix parameters are given in Table I. Since we are considering a thin reservoir layer, we scale the thickness of the sandstone to about 5 meters. Note that frequencies and thickness scales interchange, so that thicker layers would correspond to proportionally lower frequencies.

We will use the following EDA crack parameters to model different characteristics of a cracked reservoir:
- Crack density (CD): 0.02, 0.05, and 0.1;
- Crack aspect ratio: 0.01 for Hudson's crack formulation (1981) and 0.05, 0.1, 0.3 for Nishizawa's crack formulation (Nishizawa, 1982);
- Crack orientation: 0°, 22.5°, 45°, 67.5°, and 90° east of north;
- Crack saturation: gas or liquid filled.

DISPERSION AND AMPLITUDE-DEPTH DISTRIBUTION FOR DIFFERENT EDA-CRACK PARAMETERS

Except for propagation in directions of sagittal symmetry, generalized modes of guided waves in anisotropic structures have three-dimensional particle displacements (polarizations) intermediate between Rayleigh and Love motion. In directions where the equivalent Rayleigh and Love modes would cross each other, the phase velocities of generalized modes in off-symmetry directions may pinch together. At such pinches, the guided wave modes effectively exchange properties, in particular, the slopes of the dispersion curve and type of particle displacement will be interchanged. The group velocity curves usually show large changes of slope in the equivalent positions of these pinches in phase velocity.

Figure 3 shows three-component amplitude-depth distributions of the three-component generalized guided wave modes at 300Hz frequency for 2...
CONCLUSIONS

We have developed techniques for the calculation of dispersion, amplitude-depth distribution, and synthetic seismograms of guided waves in cracked layered structures. Based on a gas sand reservoir in shale, our study shows that thin-layers in sedimentary reservoirs may support the propagation of guided waves in seismic cross-hole surveys, and that such guided waves are sensitive to crack parameters, crack orientations, degree of liquid-gas saturation. A crosshole field data set has been examined, and it is found that the dominant signal energy is of guided waves, not body waves. These guided waves may provide a new signal to monitor production geophysics. It suggests that they have a potential application in monitoring Enhanced Oil Recovery (EOR) operations of thin layered reservoirs by seismic crosshole surveys.

ACKNOWLEDGEMENTS

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Guided waves and EOR monitoring

Figure 1. (a) A Conoco three component crosshole field data set; (b) Velocity structure of crosshole site. (after Liu et al., 1991).

Figure 2. A gas sand reservoir example (after White and Sengbush, 1987).

Figure 3. Amplitude-depth variations of first four generalized modes of 300Hz guided waves in a 5m thick channel containing parallel vertical cracks with crack density $CD=0.1$, and crack strike $45^\circ$ from the radial direction, where solid lines are water saturated sand, and dashed lines are gas saturated sand. (a) First generalized mode; (b) Second mode; (c) Third mode and (d) Fourth mode.
Figure 4. Phase (left) and group (right) velocity dispersion curves of first four generalized modes of guided waves in the same anisotropic waveguide model as Figure 3 in a direction 45° to the crack strike, where solid lines are water saturated sand, and dashed lines are gas saturated sand, and dashed-dot lines are 50% water and 50% gas saturated sand, and arrows indicate pinch positions at phase velocity.

Figure 5. Synthetic seismograms for water and gas saturated sand with the same crack parameters as Figure 3. (a) Transverse force source; (b) Vertical force source.

Table 1. The material parameters

<table>
<thead>
<tr>
<th>Material</th>
<th>V_p (m/s)</th>
<th>V_s (m/s)</th>
<th>Density (g/cm³)</th>
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<tbody>
<tr>
<td>Gas sand</td>
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<tr>
<td>Shale</td>
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