FLEXURAL WAVES IN AN ANISOTROPIC HARD FORMATION BOREHOLE MODEL

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ABSTRACT

To investigate the propagation of flexural waves in a borehole surrounded by an azimuthally anisotropic hard formation, we made an ultrasonic borehole model of Delabole slate with very strong anisotropy. The axial and azimuthal acoustic fields generated by a dipole source were measured in the fluid-filled borehole. The results show that there are three dominant wave modes: fast and slow flexural waves and one we call a "flexural Stoneley wave. The phase velocities of the fast and slow flexural waves are lower than and close to those of the fast and slow shear waves of the formation, respectively. The phase velocity of the "flexural Stoneley" wave is higher than that of the borehole fluid. Regardless of the polarization of the dipole source, the particle motions of the fast and slow flexural waves are linear and in the direction of the fast and slow shear waves, respectively. The "flexural Stoneley" wave, similar to the normal Stoneley wave generated by a monopole source, is a tube wave with low frequency and high amplitude. Its main particle motion is in the horizontal plane perpendicular to the borehole axis. If the formation is azimuthally anisotropic, its particle motion is linear only when the source polarization is in the same direction as the fast and slow shear waves, and is elliptic everywhere else. Dipole acoustic well logging could be an effective and potential means for determining the anisotropy of a formation.

INTRODUCTION

Determining a shear wave parameters is one of the most important applications of full waveform acoustic well logging. However, a conventional monopole source cannot generate a direct shear wave in a soft formation where the shear wave velocity is lower than the acoustic velocity of the borehole fluid. Theoretical studies (Kurkjian and

Chang, 1986; Winbow, 1988; Schmitt, 1989) showed that a dipole source can generate a flexural wave in a borehole surrounded by either hard or soft formations. At low frequency its velocity along the borehole axis is equal to that of the shear wave in the formation. Laboratory experiments were carried out with dipole transducers in a borehole model (Chen, 1988), and verified the existence of such a flexural wave.

The shear velocity of an anisotropic material in a certain direction depends on the direction of the particle vibration. In general, the shear wave splits into two waves which propagate at different speeds and with the particle vibrations perpendicular to each other (Alford, 1986; Cheadle *et al.*, 1991). The evaluation of anisotropy by shear wave splitting is its potential application in the detection of fractures, cracks and other inclusions (Crampin, 1985; Lo *et al.*, 1986; Winterstein, 1987). The flexural wave generated by a dipole source in a fluid-filled borehole surrounded by an anisotropic formation also splits into fast and slow waves whose velocities are related to those of the fast and slow shear waves (Zhu *et al.*, 1993; Esmersoy *et al.*, 1994; Sinha *et al.*, 1994), respectively. The borehole wave particle motion in anisotropic formations has been observed in laboratory experiments (Zhu *et al.*, 1995).

To observe fast and slow flexural waves separating completely in time domain, we selected Delabole slate, which is a hard rock with very strong anisotropy, to make an ultrasonic borehole model. The measurements were performed in our laboratory with the mono/dipole transducer (Zhu *et al.*, 1993). Fixing the dipole at different azimuths, we moved the dipole source along the borehole axis or rotated it step-by-step to measure the axial or azimuthal acoustic field. The velocities, polarization and particle motion of these flexural waves were further investigated with the recorded waveforms and compared with those in an isotropic or transverse isotropic borehole model described in this paper.

BOREHOLE MODEL AND MEASUREMENTS

Delabole slate is a TI hard rock with apparent bedding. When a shear wave propagates along a direction perpendicular to the symmetric axis, its velocity depends on the direction of the particle vibration. Usually, the shear wave splits into two waves—the fast and slow shear waves. The "hard implies that both fast and slow shear velocities are greater than that of the borehole fluid. Two cubic rocks of $20 \times 20 \times 20cm^3$ are cut along its principle axes of the slate. We define the direction perpendicular to the horizontal bedding as the Z-direction; the others are the X- and Y- axes. A borehole with 1.27 cm in diameter is drilled along the X- or Z-direction of the cubic rocks. Therefore, the model with a borehole in the X-direction is an azimuthally anisotropic one; the other is a TI borehole model.

Figure 1 shows a schematic diagram of the slate model with an X-direction borehole and the P- and S-velocities. We define the Y-axis, the direction of the fast shear wave vibration, as 0^o or 180^o, and the Z-axis as 90^o or 270^o. The velocities shown in Figure 1 are measured directly on the cubic rock with the standard P- or S-plane transducers.

When a shear wave propagates along the Z-axis, its velocity is the same (2650 m/s) regardless of the polarization of the shear wave. When a shear wave propagates along the X-axis, if its particle vibration is at the Y-direction, its velocity is fast (4150 m/s); if it is at the Z-axis, the velocity slow (2650 m/s); and if the vibration is between the Y-axis and the Z-axis the shear wave splits into two waves, the fast and slow ones.

In our water-tank measurement system we perform two kinds of measurements—array and rotating—with mono/dipole transducers (Zhu *et al.*, 1993), which can be connected as a monopole or a dipole transducer. When a dipole source is fixed at a certain azimuth, a dipole receiver moves along the borehole axis or rotates at the same spacing, and records the waveforms received at each location (Figure 2).

The function generator produces a single sine burst to excite the source transducer. The amplitude of the burst is 5 V and the center frequency is 150 kHz. The frequency variation of the electric signal affects the amplitude ratio of these waves due to their different excitations. To record the flexural waves with various modes clearly, we select the center frequency of 150 kHz.

Figure 3 shows two plots of the waveforms recorded in the array measurement when both the dipole source and receiver are fixed at 0^o (a) or 90^o (b) and the receiver moves along the borehole axis in 0.25 cm/trace. The phase velocity can be calculated from the arrival time of the waveforms with the same phase (slope). It is clear in Figure 3b that there are three kinds of waves with different velocities (slopes) that are 3950 m/s, 2100 m/s, and 1580 m/s, respectively. We define them as a fast flexural wave, a slow flexural wave, and a "flexural Stoneley" wave. Only the fast flexural wave and the "flexural Stoneley" wave are observed in Figure 3a when the polarization of both the source and receiver are in the direction of the fast shear wave (0^o). The frequency response of the waves is different from each other. The center frequencies of the fast and slow flexural waves are between 220 kHz and 250 kHz, about 150 kHz for the "flexural Stoneley" wave.

Figure 4 shows the waveforms recorded by a rotating dipole receiver starting from 0^o with an increment of 9.72^o/trace when the dipole source is fixed at 0^o (a), 30^o (b), 60^o (c), and 90^o (d), respectively. From these waveforms we observe their variations in amplitude and phase with the azimuths. The particle motion can be drawn by extracting two wavelets from the waveforms with the same mode and at azimuths perpendicular to each other.

Our measurements record the waveforms linearly. Because the amplitude of the "flexural Stoneley" wave is usually greater than that of the fast and slow flexural waves by more than ten times, the biggest amplitude is saturated and clipped in the plot showing the fast and slow waves. We performed similar experiments with the Z-direction slate and aluminum borehole models and compared their results. In this paper, we investigate the main properties of these waves in an azimuthally anisotropic borehole.

FAST FLEXURAL WAVE

We measure the phase velocity of the fast flexural wave by its slope (Figure 3). It is about 3950 m/s which is lower than but close to the fast shear wave velocity (4150 m/s). A theoretical study by Sinha *et al.* (1994) shows that the velocity of the flexural wave is lower than the real shear velocity due to its frequency dispersion. Figure 5 shows the particle motion of the fast flexural wave when the polarization of the dipole source is at 0° (a), 30° (b), 60° (c), and 90° (d), respectively. The main motion is at the direction of the fast shear wave regardless of the source polarization and its amplitude varies with the source polarization. On the other hand, if the formation is isotropic, the linear particle motion of the flexural wave should be in the same direction as the dipole source and will have the same amplitude.

In real dipole logging the fast flexural wave, as the first arrival of the recorded waveforms, can be used to determine its particle motion. In an azimuthally anisotropic borehole the direction of the particle motion coincides with that of the fast shear wave and is perpendicular to that of the slow one.

SLOW FLEXURAL WAVE

When the spacing between the source and receiver is large enough, the fast and slow flexural waves separate completely from each other in time the domain due to the strong anisotropy of the slate (Figure 3b). Therefore we can determine the phase velocity of the slow flexural wave by its slope. Because of the frequency dispersion character of the flexural wave (Sinha *et al.*, 1994) the phase velocity of 2100 m/s determined from Figure 3b is lower than the slow shear velocity. The slow flexural wave depends on the polarization of the source and the receiver. For example, when the dipole source is at 0^o (the direction of the fast shear wave), it is hard to find the wave component which propagates with the velocity of the slow flexural wave (Figure 3a).

To eliminate the influence of the fast flexural wave on the slow one, all the traces in Figure 3 are added together according to the slope of the fast flexural wave in order to get an average wavelet. Subtracting the average wavelet from the original trace obtains a clearer slow flexural wave. Then we can draw its particle motion when the dipole source is at a different azimuth. Figure 6 shows the particle motion of the slow flexural wave when the polarization of the dipole source is at 0^o (a), 30^o (b), 60^o (c), and 90^o (d), respectively. The particle motion is similar to the fast flexural wave. It is linear motion and always at the direction of the slow shear wave regardless of the source polarization.

Our experiments demonstrate that a flexural wave splits into two—fast and slow flexural waves—in an azimuthally anisotropic borehole. Their particle motions of them are linear and in the directions of the fast and slow shear waves, respectively. Their phase velocities are close to those of the fast and slow shear waves, respectively.

FLEXURAL STONELEY WAVE

Comparing the Stoneley wave generated by a monopole source in a fluid-filled borehole, the "flexural Stoneley" wave is generated by a dipole source. Both of them are at lower frequency range and with higher amplitude than other wavelets received in the borehole. Their velocities and particle motion, however, are not the same. This paper investigates the main properties of the "flexural Stoneley" wave.

The "flexural Stoneley" wave's phase velocity, V_{fst}, is about 1580 m/s, determined by the waveforms in Figure 3. This velocity is higher than the velocity V_f of the borehole fluid (1480 m/s). The Stoneley velocity V_{st} is about 1450 m/s measured by the monopole transducers in the same borehole model. Although these velocities (V_{fst}, V_f, and V_{st}) are close to each other, they are not the same waves within the experiment error. This means that the monopole and dipole sources generate the tube waves with different modes.

Figure 6 shows the waveforms received by a rotating monopole receiver when a monopole source is fixed in the X-direction slate borehole model with constant spacing. From the plot we see that the phase and the amplitude of a normal Stoneley wave do not vary with the azimuth.

Compared to the waveforms in Figure 6, the phase and the amplitude of the "flexural Stoneley" wave (Figure 4) vary with the azimuth and the dipole source polarization. When the dipole source is fixed at the direction of the principle axes, 0^o or 90^o (Figures 4a or 4d), the maximum or minimum (small) amplitudes are recorded at the azimuth parallel or perpendicular to the source polarization. It is clear that the phase of the "flexural Stoneley" wave changes 180^o at the principal axes.

When the source is not located on the direction of the principal axis, [e.g., it is at 30^o or 60^o (Figures 4b or 4c)], there is no minimum amplitude at the same scale as that in Figures 4a and 4b. The phase of the "flexural Stoneley" wave varies with the azimuth gradually. When the dipole source is at 30^o, its phase increases with the azimuth. If the source is at -30^o (330^o) the phase will decrease with the azimuth. This implies that the dipole source that is not at the principal axis will generate the particle motion in both principal axis directions at the same time. The particle motion becomes an elliptic motion in the horizontal plane. The direction of the elliptic motion, clockwise or counterclockwise, depends on the source polarization.

Figure 7 shows the particle motion of the "flexural Stoneley" wave when the dipole source is at 0^o (a), 30^o (b), 60^o (c), and 90^o (d), respectively. When the source is at the principal axes, Y-axis or Z-axis, the particle motion is linear and is in the same direction of the source. When the source deviates from the principal axes (Figures 7b or 7c), the motion is elliptic. This is the most important property in an azimuthally anisotropic borehole, which is different from that in an isotropic or TI borehole.

In similar experiments performed in the Z-direction Delabole slate borehole model (TI model) and in an aluminum borehole model (isotropic hard formation model), the "flexural Stoneley" wave with high amplitude and low frequency was also observed. The particle motion is always linear and in the same direction as the dipole source regardless of the source direction.

We know that the main particle motion of the normal Stoneley wave generated by a monopole source is an elliptic motion in the vertical plane parallel to the borehole axis (Toksöz and Stewart, 1984) and it is a linear motion in the horizontal plane. In general, the particle motion of the "flexural Stoneley" wave is elliptic in the horizontal plane perpendicular to the borehole axis, and is linear in the vertical plane. When the polarization of the dipole source coincides with the principal axes it will become linear motion in both planes. Figures 8 and 9 demonstrate the particle motions of the normal Stoneley wave (in isotropic borehole) and the "flexural Stoneley" wave in the vertical and the horizontal planes by means of the schematic diagram, respectively.

CONCLUSIONS

Ultrasonic experiments have measured the axial and azimuthal acoustic fields generated by a dipole source in the Delabole slate borehole model with very strong azimuthal anisotropy. The experiment results show that there are three kinds of flexural waves: fast and slow flexural waves and a "flexural Stoneley" wave. The phase velocities of the fast and slow flexural waves propagating along the borehole are lower than and close to those of the fast and slow shear waves in the slate, respectively. Their particle motions are linear and in the directions of the fast and slow shear waves, respectively. The "flexural Stoneley" wave is similar to the tube wave (Stoneley wave) generated by a monopole in a fluid-filled borehole. Its phase velocity is a little higher than the fluid velocity. Its particle motion generally is elliptic in the plane perpendicular to the borehole axis. The direction of the particle motion is related to the source polarization. When the source polarization coincides with the rock principal axes (fast or slow axis), the elliptic motion becomes linear. The particle motion of the "flexural Stoneley" wave generated in an isotropic borehole is different from that in an azimuthally anisotropic borehole and is always linear and in the same direction as the dipole source.

Our investigation demonstrates that dipole well logging is a useful and potential means to explore the anisotropy of a formation. Anisotropy can be qualitatively evaluated by the particle motion of the "flexural Stoneley" wave with high amplitude and low frequency, and quantitatively determined by the velocities of the split fast and slow flexural waves.

The "flexural Stoneley" wave is easily recorded in field well logging due to its high amplitude. Therefore, it is important to further investigate its properties, such as frequency dispersion and the relationship with the porosity or permeability of the formation.

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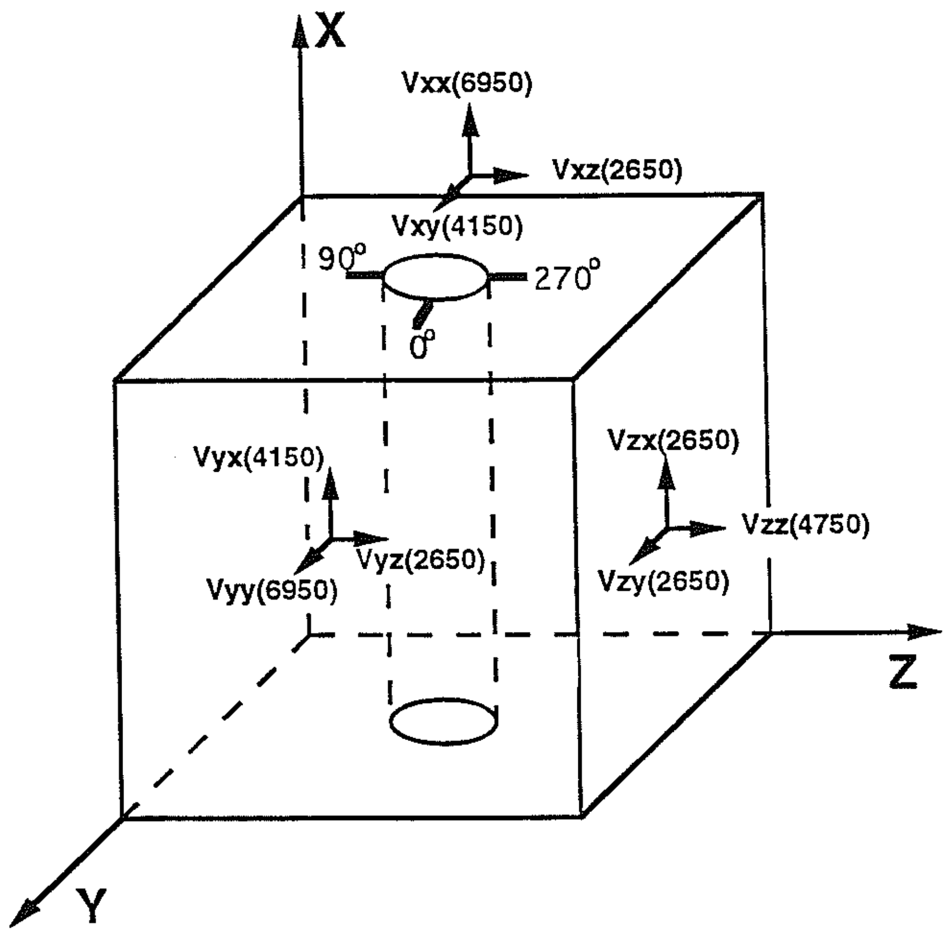


Figure 1: Schematic diagram of the Delabole slate mode with the X-direction borehole and its compressional and shear velocities (m/s). The diameter of the borehole is 1.27 cm.

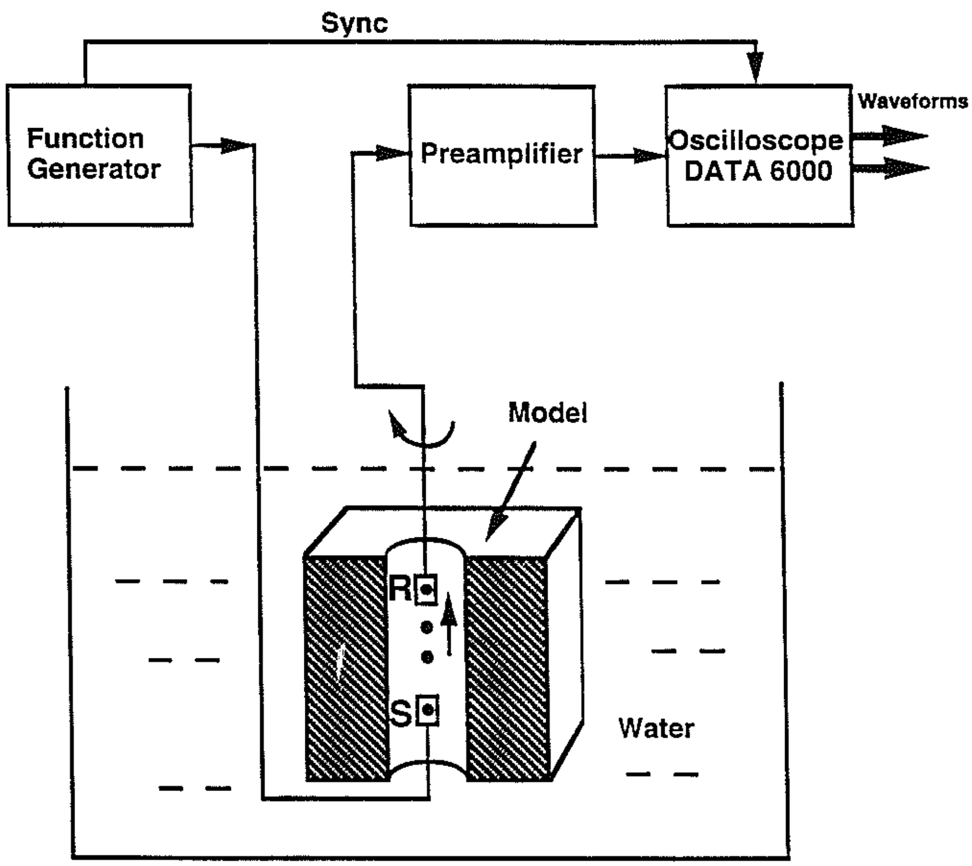


Figure 2: Schematic diagram of the measurement system. The source and receiver can be fixed, moved or rotated in the water-filled borehole.

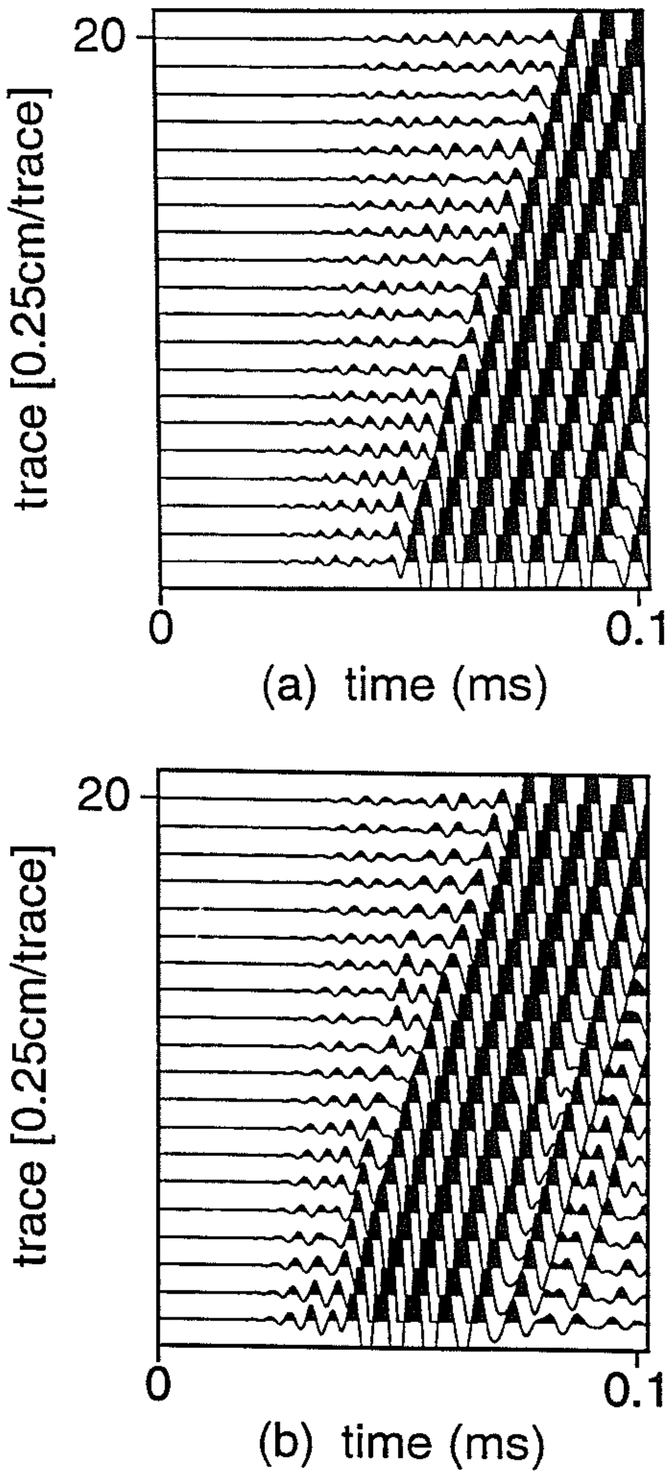


Figure 3: Waveforms recorded by fixing the dipole source and receiver at 0^o (a) and 90^o and moving the receiver with 0.25 cm/trace in the array measurement.

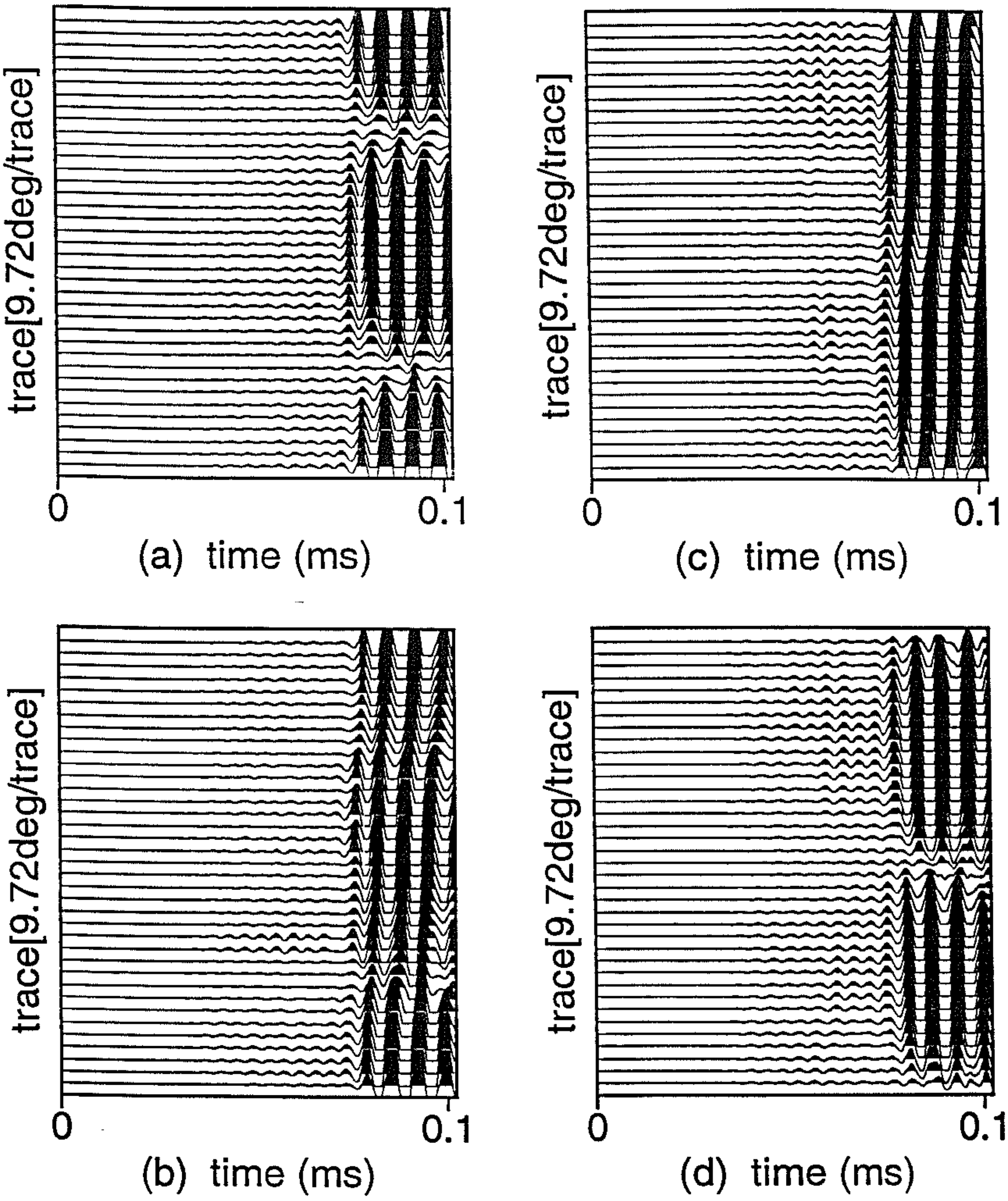


Figure 4: Waveforms recorded by fixing the dipole source at 0^o (a), 30^o (b), 60^o (c), and 90^o (d), and rotating the dipole receiver with 9.72^o/trace starting from 0^o.

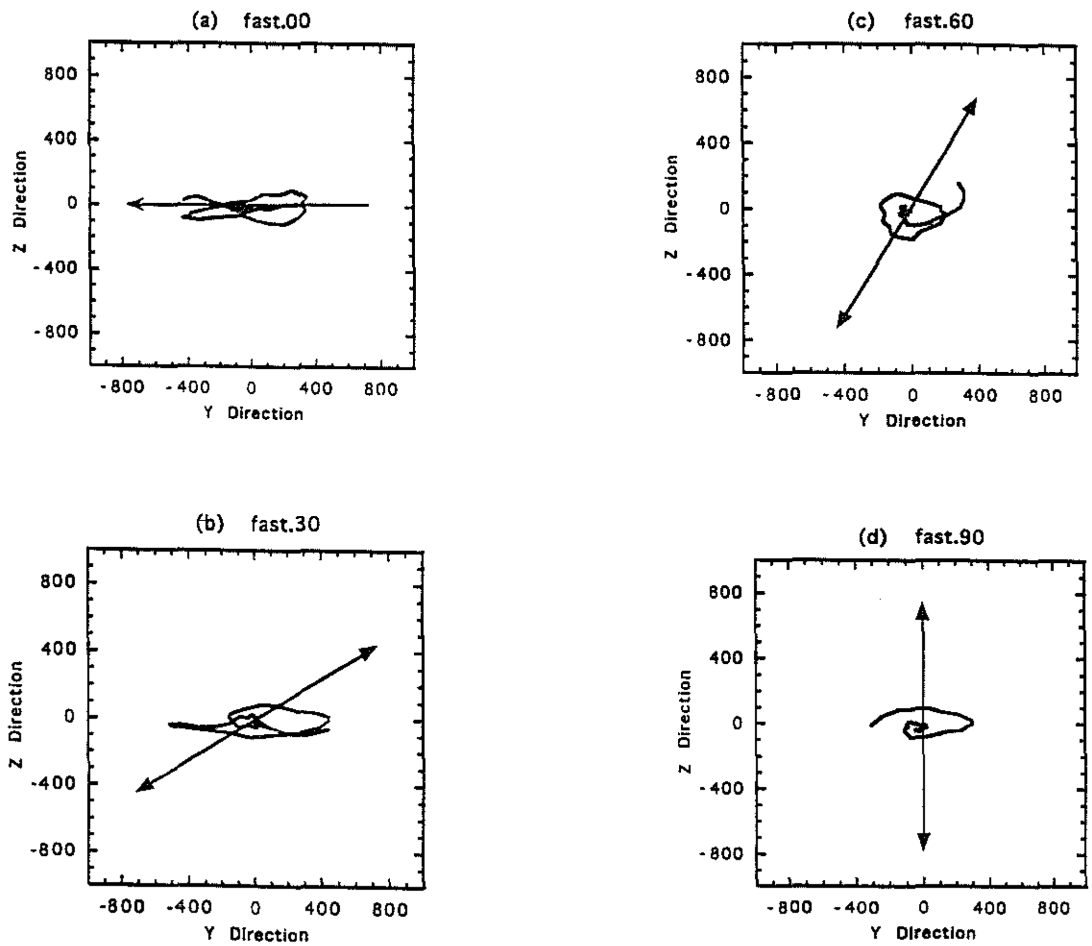


Figure 5: Particle motion of the fast flexural wave in the Delabole slate borehole. The arrow indicates the direction of the dipole source located at 0^o (a),30^o (b), 60^o (c), and 90^o (d).

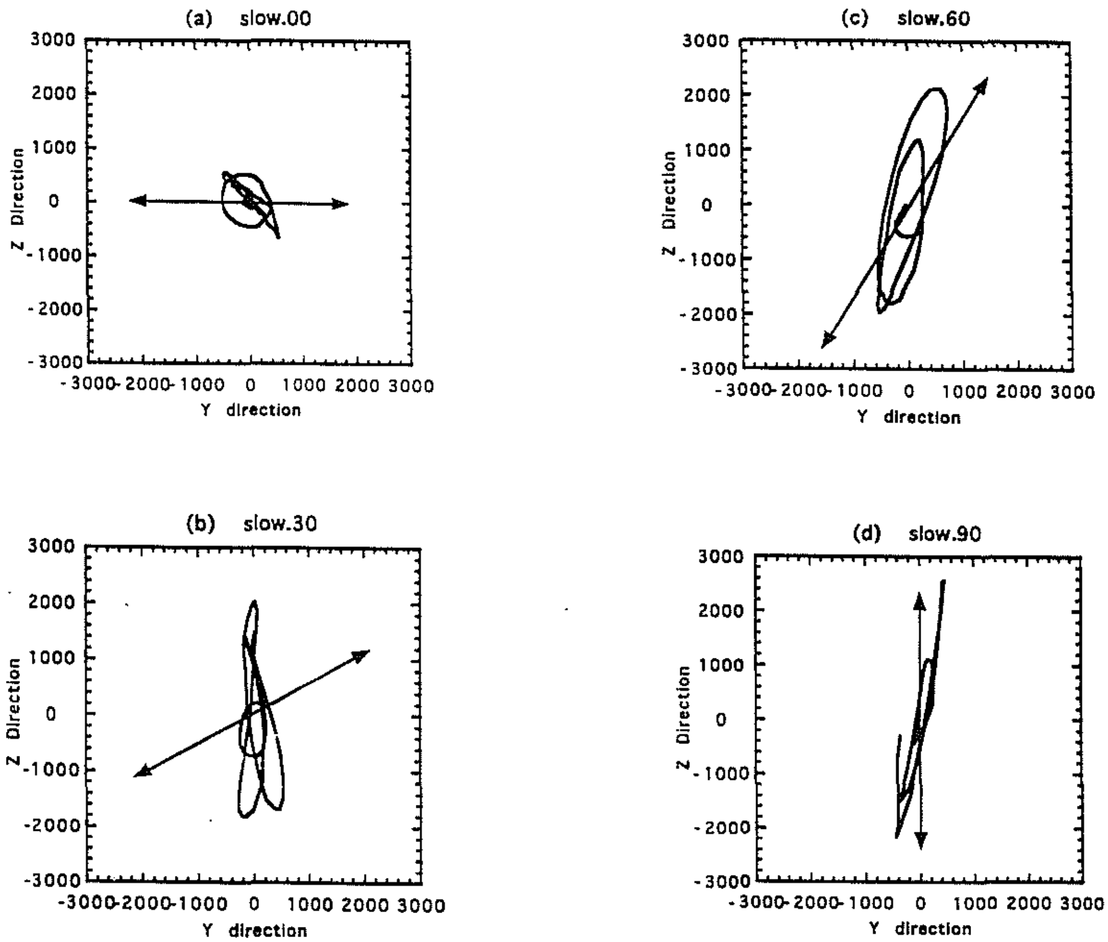


Figure 6: Particle motion of the slow flexural wave in the Delabole slate borehole. The arrow indicates the direction of the dipole source located at 0^o (a), 30^o (b), 60^o (c), and 90^o (d).

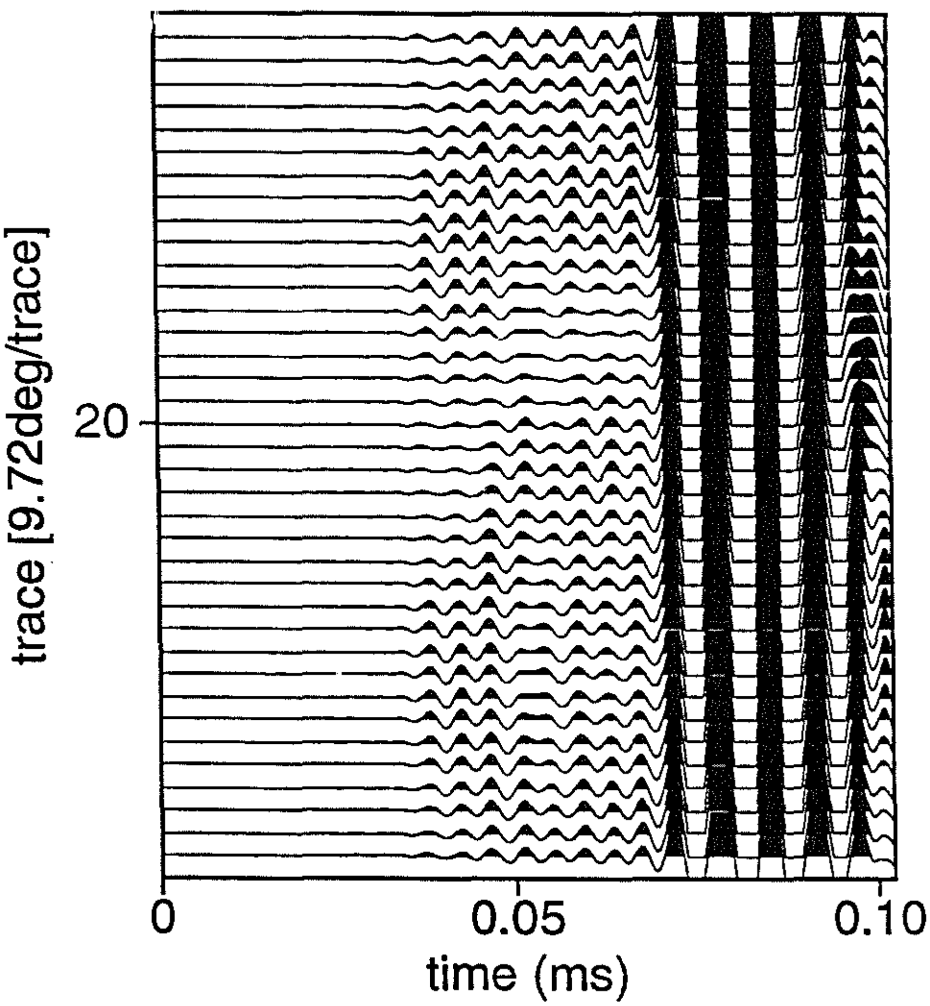


Figure 7: Waveforms recorded by fixing the monopole source and rotating the monopole receiver with 9.72°/trace in the borehole shown in Figure 1.

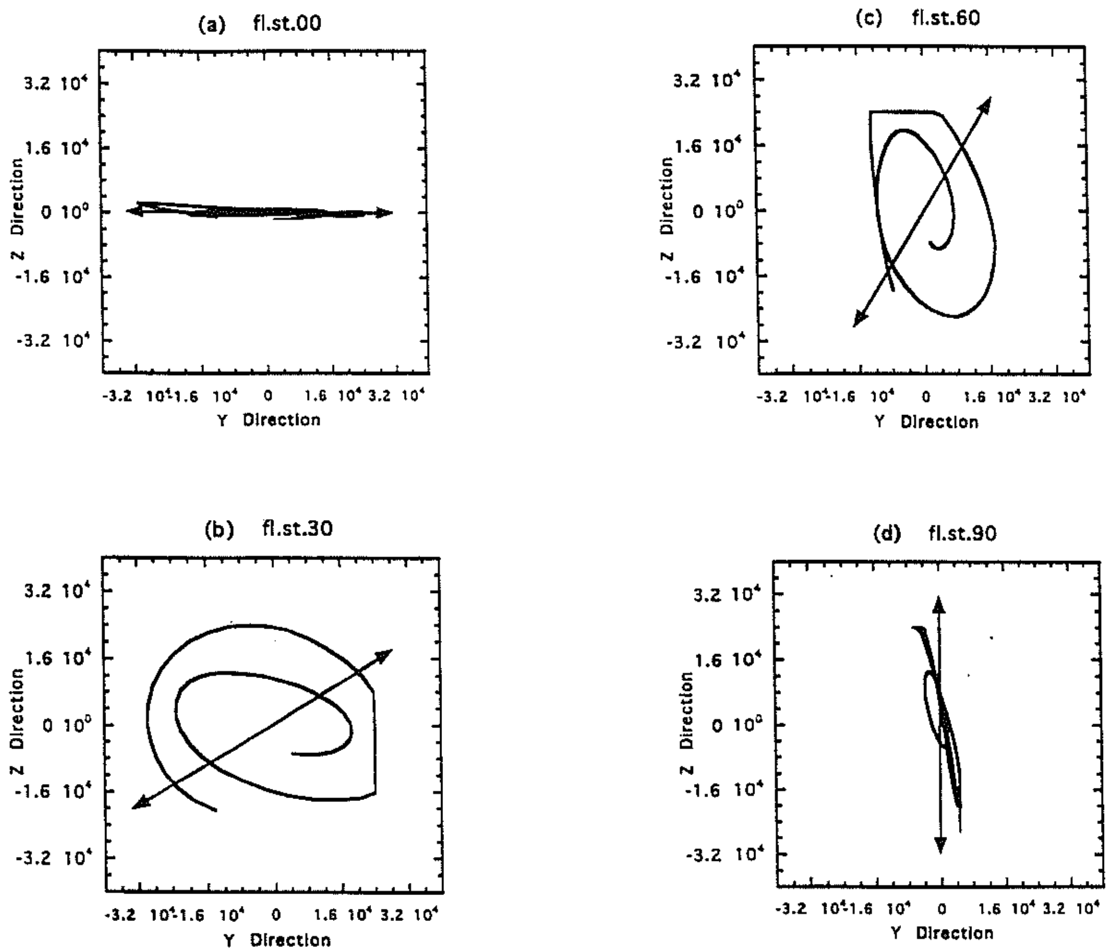


Figure 8: Particle motion of the flexural Stoneley wave in the Delabole slate borehole. The arrow indicates the direction of the dipole source located at 0^o (a), 30^o (b), 60^o (c), and 90^o (d).

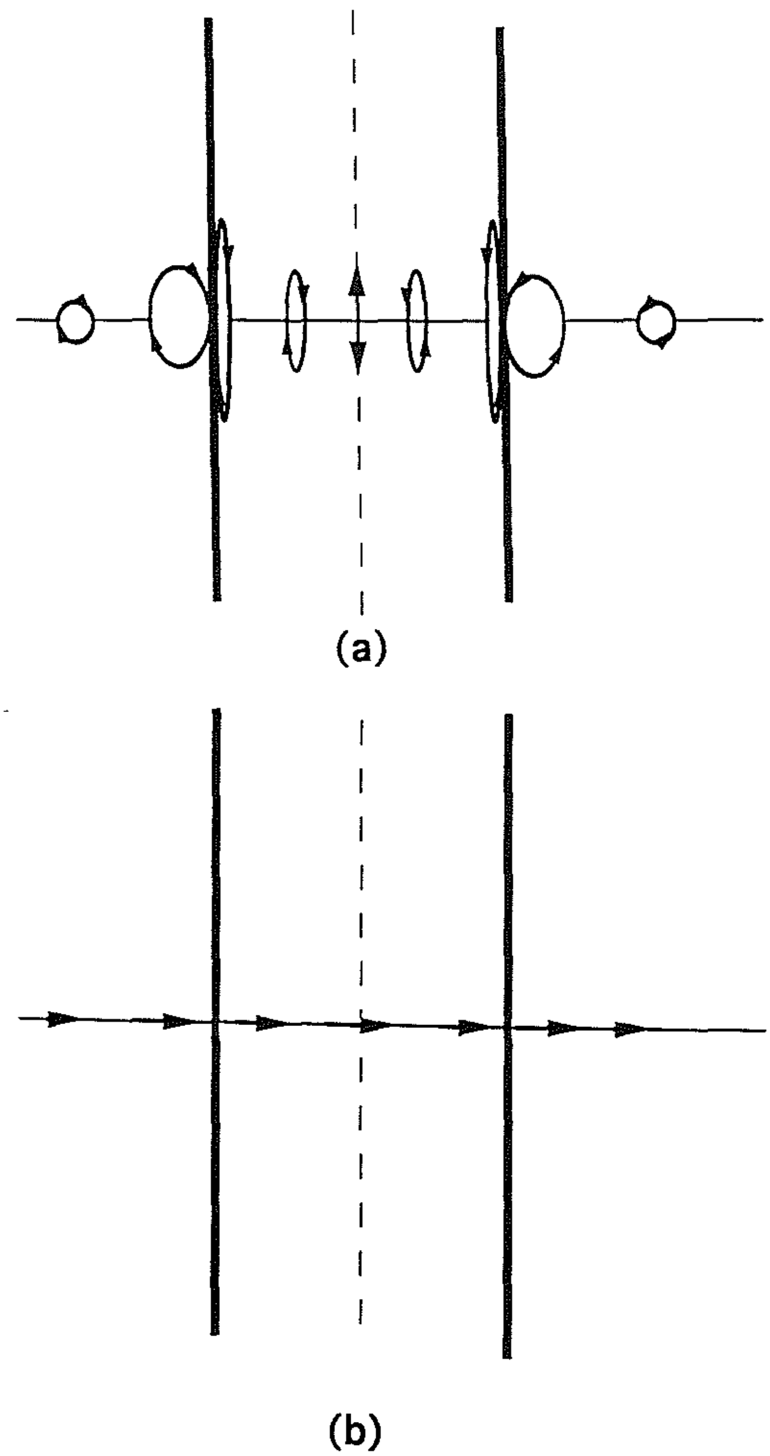
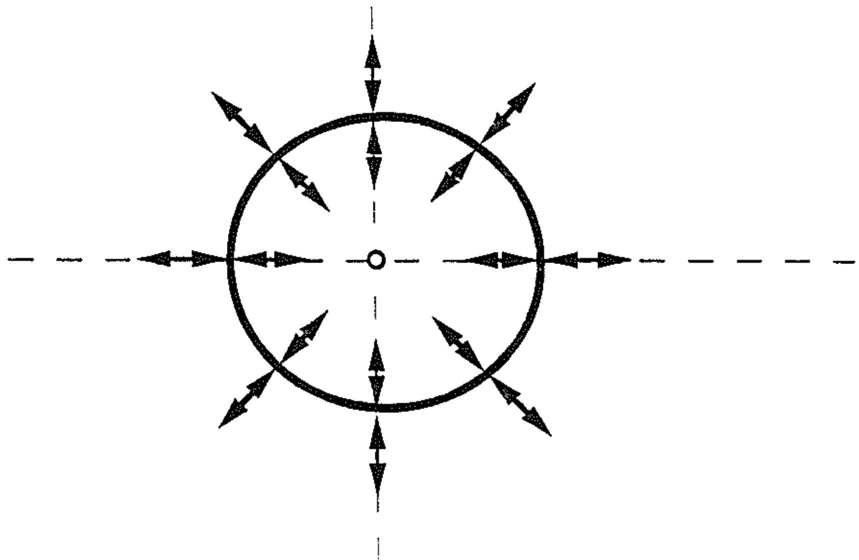


Figure 9: Schematic diagram of the particle motions of the normal Stoneley wave (a) and the flexural Stoneley wave (b) in the vertical plane.



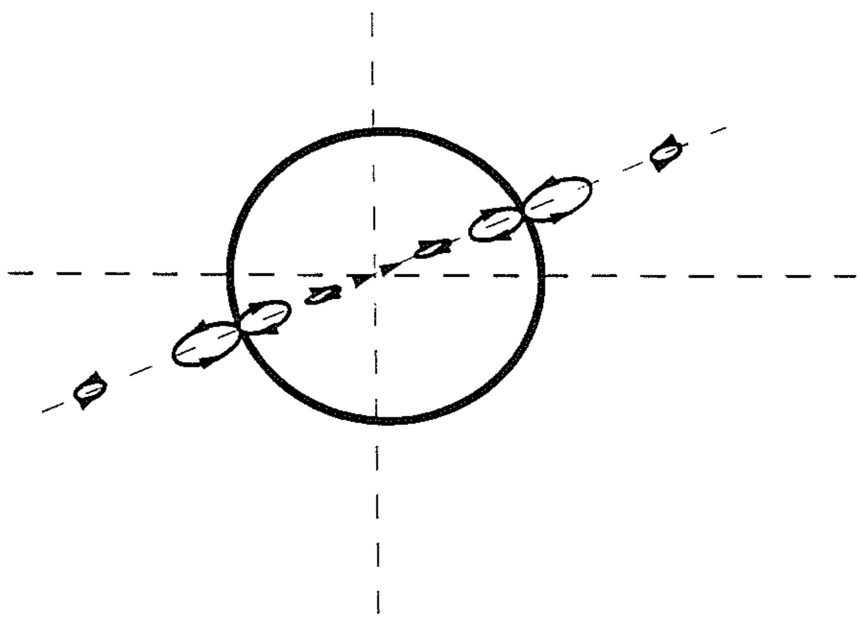


Figure 10: Schematic diagram of the particle motions of the normal Stoneley wave (a) and the flexural Stoneley wave (b) in the horizontal plane.