Experimental studies of the acoustic wave field near a borehole

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Summary

A monopole or a dipole source in a fluid borehole generates acoustic waves, part of which propagate along the borehole and the other part enter the formation propagating as P- or S-waves. The refracted waves propagating along the borehole wall are used to determine P- and S-wave velocities. However, a significant fraction of the seismic energy radiates into the formation. In this laboratory study, we measure the acoustic waves in the borehole and the seismic waves in the formation at different distances from the borehole.

We use scaled borehole models made of Lucite and of concrete to simulate a soft and a hard formation, respectively. The waveforms are measured in the boreholes as well as in the formations with different radial distances from the axis of the borehole. The results show that the investigation depth of the wave measured in the borehole is less than one half of the wavelength. The seismic energy radiating into the formation and scattered from interfaces and heterogeneities can be used for imaging the formation.

Introduction

The acoustic fields generated by a monopole or a dipole source in a fluid-filled borehole and in the surrounding formation were theoretically studied in early of eighties (Tsang and Rader, 1979; Cheng and Toksöz, 1981; Toksöz and Willis, 1983). The P-, S-, Pseudo-Rayleigh, and Stoneley waves can be generated by a monopole source. A flexural wave can be generated by a dipole source in a borehole. The acoustic well logging in oil fields confirms the theoretical results to extract the p-, S-, and Stoneley wave velocities (Cheng and Toksöz, 1983; Kimball and Marzetia, 1984).

When a source generates an acoustic wave in a borehole, part of the acoustic energy propagates along the borehole and part of the energy enters into the formation. Only part of the energy propagates into the formation area near the borehole wall and returns back to the borehole fluid. The formation area is called a radial investigation area, or radial invasive area. In this area the acoustic waves propagating in the borehole and in the formation are affected by each other. Usually the radial area is estimated as one wavelength in depth. We cannot investigate the area in the oil fields. Theoretical studies usually ignore the real sizes of acoustic source and receivers. Therefore it is important to investigate the acoustic fields in the invasive area experimentally. No laboratory experiments investigate the distribution of the acoustic waves in this area.

Because the formation surrounding a borehole in an oil field is unlimited, we do not consider the effects of the formation thickness. If we build a test borehole model for calibrating an acoustic well logging tool, the radial investigation depth is an important parameter for designing the model. The reflection from the outside surface of the borehole model and the effects of limited borehole wall on the acoustic mode in the borehole are very important. We need to know more about the acoustic fields in the near formation.

In this paper, we build a scaled borehole model and measure the acoustic waves generated by a monopole or a dipole source in the borehole or in the surrounding formation. Laboratory experiments investigate the acoustic wave fields in a borehole and in the surrounding formation. The experimental results provide the parameters for building a real borehole model in order to calibrate a real well logging tool.

### Scaled borehole models and acoustic measurements

To investigate the acoustic wave field in a borehole and in the formation experimentally, we build a scaled borehole model. Figure 1 a) shows a photo of the concrete borehole models and b) schematic diagram of the model structure and the measurement methods.

In order to measure the acoustic waves in the formation, we make several columns of probe holes, 0.32 cm in diameter, and with different depths in the radial direction.
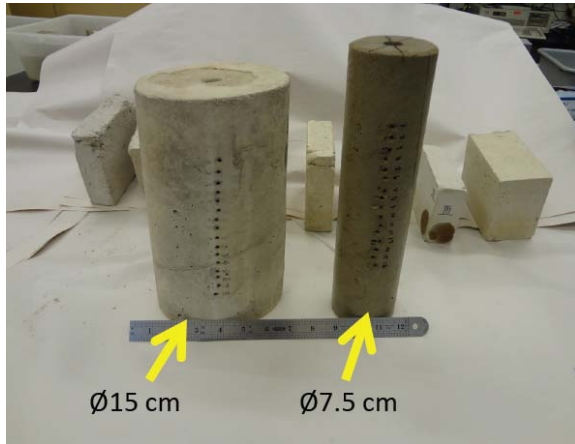
(a)
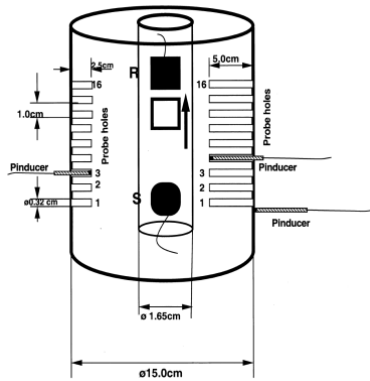
(b)

Figure 1: a) Photo of the scaled concrete borehole models with different outside diameters and b) the schematic diagram of the model structure and the measurement methods. The P- and S-wave velocities of concrete with 15 cm diameter are 3700 m/s and 2160 m/s, and those with 7.5 cm diameter are 3950 m/s and 2350 m/s, respectively. The borehole diameter is 1.65 cm.

A piezoelectric PZT tube is cut into two pieces along its axis. Then the pieces are gathered and insulated from each other by sealing them with rubber resin. Four electrodes from the two PZT pieces are connected with a switch. The transducer can work as a monopole or a dipole source, by changing the polarizations with the switch (Zhu et al, 1993). The diameter of this mono/dipole transducer is 1.2 cm. The mono/dipole transducer can be used for monopole and dipole borehole measurements.

When a source generates an acoustic wave in a borehole, we use a pinducer (P-wave receiver), 0.237 cm in diameter,

to record the acoustic waves in the bottom of the probe holes (Figure 1b).

When we build the concrete borehole model, we also make several concrete block samples with the same material. The P-wave and S-wave velocities are measured with plan transducers (Panametrics, V101 and V152). They are 3950 m/s and 2160 m/s, respectively.

Acoustic measurements in the boreholes

We measure the borehole acoustic waveforms when both source and receiver are the monopole transducers and when both source and receiver are dipole transducers, respectively. The electric source exciting the source is a sine burst with the center frequency of 100 kHz. From the recorded waveforms we calculate their time-domain semblance to analyze their phase velocities.

Figure 2 shows the monopole waveforms and the time-domain semblance recorded in the big concrete borehole model. The monopole source generates P-, S-, pseudo-Rayleigh, and Stoneley waves. The P- and S- wave velocities are the same as those measured with the concrete block samples. The Stoneley wave velocity is slower than, but close to, the water velocity (1,500 m/s).
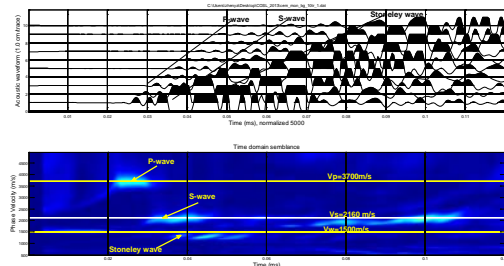

Figure 2: Acoustic waveforms generated by a monopole source and the time-domain semblance.

Figure 3 shows the dipole acoustic waveforms recorded in the big borehole model and the time-domain semblance. The flexural waves are generated by the dipole source in the borehole and their velocity is close to the shear wave velocity. The dipole source also generates a strong guide wave, whose velocity is higher, but close to, the water velocity.
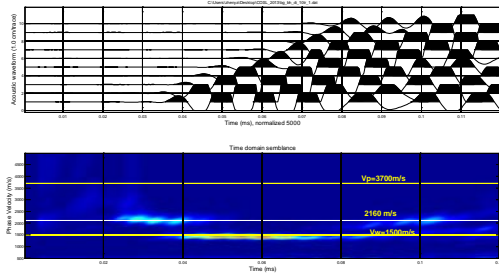
Acoustic wave field near a borehole

Figure 3: Acoustic waveforms generated by a dipole source and the time-domain semblance.

The center frequency of the P-wave in the borehole is about 140 kHz, and the S-wave frequency is about 100 kHz. The wavelength in the concrete is about 2.5 cm. This means the formation thickness of the 15-cm model is about three wavelengths.

In order to investigate the influence of formation thickness on acoustic waves, we also build a small borehole model, 7.5 cm in diameter. The borehole diameter is still 1.65 cm. In this model the formation thickness is about one wavelength. We conduct the monopole and dipole borehole measurements similar to those conducted in the big borehole model. The results are similar to those shown in Figure 2 and Figure 3. We do not record the other acoustic modes in the small borehole model. This means that when the formation thickness is about one wavelength, the thickness does not affect the measurements in the borehole.

 Because the thickness of the formation is finite, the acoustic wave in the formation would be reflected at the outer surface of the borehole model and the reflected wave can enter into the borehole and, be received by the acoustic receiver. The main acoustic waves recorded in the experiments are the waves propagating along the borehole, not the reflected wave. Because the amplitudes of the waves are reflected and refracted at the wall and outer surfaces, the energy is weak compared with the borehole waves. On the other hand, the apparent velocity of the reflected wave is much higher than the P-wave velocity. Therefore, the velocity of the reflected wave can be separated by the semblance method.

The cylinder model is an axis-symmetric model, with borehole in the center. The waves reflected from the out wall of the model arrive at the borehole at the same and induce large oscillation. If the model were not symmetric, these effects would be less.

Acoustic measurements in the formation

An acoustic wave generated by a source in a borehole generates guided waves inside the borehole and refracted P- and S-waves propagating in the surrounding formation along the borehole. Theoretic simulation indicates that the arrival times of the acoustic waves recorded in the probe holes (Figure 1b) are on a hyperbolic curve. The apparent velocities of the acoustic waves recorded far from the source are close to the P- or S- wave velocity of the formation.

For the guided waves in the borehole and for the refracted P- and S-waves along the borehole, the velocity calculation were done by the semblance method is based on the acoustic waves propagating along a straight line. When the acoustic arrivals are along a hyperbolic curve, the semblance method cannot be used to determine the velocity.

Because the diameter (0.32 cm) of the probe holes is much less than the wavelength (2.5 cm), it does not affect the propagation of the first acoustic wave, but the following waves become very complex due to scattering, reflection, and overlap.

The acoustic waves are measured in the probe holes, where the distances from the borehole wall are about three wavelengths (6.7 cm), two wavelengths (4.2 cm), and one wavelength (1.7 cm) using the borehole model shown in Figure 1b. When the distance between the borehole wall and the bottom of the probe holes is about two wavelengths
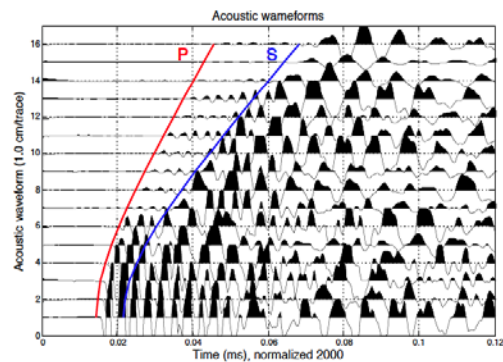
(4.2 cm), we record the waveforms (Figure 4).

Figure 4: Acoustic waveforms recorded in the probe hole at the 2.5cm probe holes. The red and blue lines denote the hyperbolic curves of the P and S wave arrivals.

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From the recorded waveforms, we see the first arrivals of P- and S-waves are along a hyperbolic curve, which is close to a simulated hyperbolic curve in Figure 4. We cannot see any group energy with the P- or S-wave velocity. The following waveforms are more complex than those recorded in a borehole due to reflection, scattering, and overlap of the acoustic waves in the formation. The acoustic waves in the formation are different from those propagating in the borehole.

In order to investigate the acoustic waves in the formation, we build a small concrete borehole model with 7.5 cm in outer diameter and 1.65 cm in borehole diameter (Figure 5).

The distances between the borehole wall and the bottoms of the probe holes are about 23 mm, 17 mm, 11 mm, and 5mm, which are close to 1.0, 0.75, 0.5, and 0.25 wavelengths. Figure 6 shows the acoustic waveforms recorded in the hole D4 (about 0.25 wavelengths) and their semblance. The first arrivals are along a straight line and the wave propagates with the S-wave velocity on the semblance plot. In the formation, the experiments record a shear wave similar to the shear wave in the borehole. I other words, the acoustic wave in a borehole invades to the formation in the invasive area. The experimental measurements show that the acoustic waves propagating in less than 0.5 wavelengths radial formation area are identical with the acoustic waves propagating in the borehole. This means that the invasive radial depth of the borehole acoustic wave is less than 0.5 wavelengths.
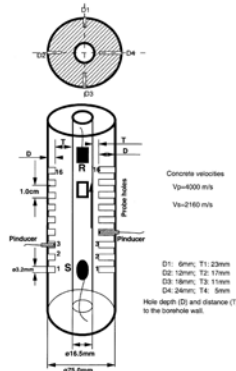

Figure 5: Schematic diagram of the concrete borehole model with 7.5 cm in outer diameters and four columns of the probe holes.
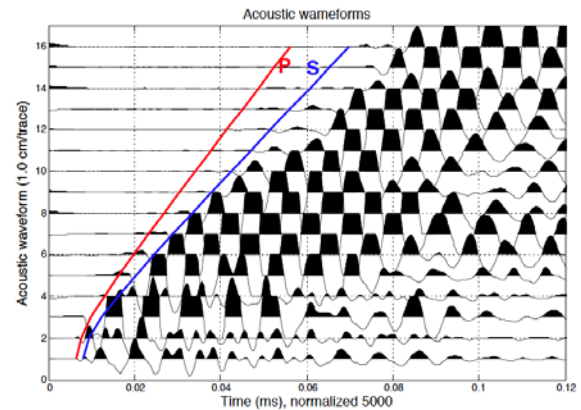

Figure 6: Acoustic waveforms generated by a monopole source and recorded in the probe holes with distance of 5 mm. The red and blue lines denote the hyperbolic curves of the P and S wave arrivals.

Conclusions

Concrete borehole models with small probe holes are built. When a monopole or a dipole source generates acoustic waves in the borehole, we measure the acoustic field in the borehole or in the probe holes of the model formation and analyze the waveforms with the time-domain semblance. When the wall thickness is about one wavelength, borehole measurements record typical full waveforms generated by the monopole source and typical flexural waves generated by a dipole source. The P- and S-velocities measured in the borehole are identical with the velocities of the concrete. The flexural velocity is also very close to the S-velocity. The measurements in the formation show that only the P- and S-waves propagating in about 0.5 wavelengths formation area are in agreement with the wave propagating in the borehole. This means that the borehole acoustic waves are only related to the formation within 0.5 wavelengths radial area. These experimental studies of the acoustic wave fields inside the borehole and in the surrounding formation help to design a real borehole model for testing the field logging tools.