Experimental Studies of Reflections from Single and Multiple-Fractures Using Lucite Models

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Summary

Laboratory acoustic measurements are performed with Lucite fracture models to understand the reflection characteristics of a seismic wave in a fracture zone. The fracture models include single fracture, dual fracture, and fracture zones having different fracture geometries. First we check the acoustic measurement system without fractures so we can identify the surface waves and the characteristics of the acoustic source and receiver. We then measure P-waves reflected and scattered by the different fracture models using a suite of illumination directions and receiver positions. The acoustic waves are reflected from the top of the fractures and their arrival times, frequencies and amplitudes are related to the depth and width of the fracture. We compare the acoustic waves reflected from dual fracture with those reflected from the single fracture and observe the effects of multiple scattering between the two fractures. In the fracture zone model, the scattered waveforms vary in different acquisition directions, which can help determine the fracture orientation. Variations in the scattering characteristics from the top and base of the fractures may provide information on fracture geometry, spacing, and orientation.

Introduction

Fractures are common features in the subsurface and often have a first order effect on the mechanical and transport properties of rocks, particularly in carbonate formations. Fractures affect the velocity and attenuation of the seismic waves in rocks (Kuster and Toksöz, 1974; Hudson, 1981; Spencer, 1981), and their orientations induce anisotropy of fluid-saturated rocks (Thomsen, 1995). The effects of fractures on the rock mechanical properties have been well studied (Hudson, et al, 1996; Tod, 2001). Laboratory measurements with fracture samples under pressures show velocity and attenuation variations (Winkler and Nur, 1982; Medlin and Marsi, 1984; Pyrak-Nolte, et al, 1990). Fractures have also been shown to scatter seismic energy on the field scale (Willis et al., 2006)

In this paper, we perform laboratory acoustic measurements with Lucite fracture models to understand the reflection characteristics of seismic waves in a fracture zone. The fracture models include a single fracture, two parallel fractures (referred to as the dual fracture model), and a fracture zone containing a series of parallel fractures. In these models the effect of fracture width (aperture) and height was also considered. A model containing no fractures was also used to help identify the surface waves and edge reflections as well as the characteristics of the source and receiver transducers. We measure the P-wave reflected and scattered by the different fracture models using different source-receiver offsets and orientations relative to the fracture strike direction. We compare the acoustic waves reflected from the dual fracture model with those reflected from the single fracture model and observe the scattering between two fractures.

Lucite fracture models

To simulate a fracture or fracture zone in a formation, we build three kinds of Lucite models; single fracture, dual fracture, and fracture zone models. Fractures are represented by channels cut by a table saw. Using a variety of saw blades we can create cuts that are 0.5 mm, 0.6 mm, 0.8 mm, and 1.1 mm, respectively. The P-wave and S-wave velocities of Lucite are 2,700 m/s and 1,300 m/s, respectively. The density of Lucite block is 1.18 g/cm^3 .

We investigate eight different single fracture models by varying the fracture width and height. The length of each fracture is 150 mm. The widths of the single fractures are 0.5 mm, 0.6 mm, 0.8 mm, and 1.1 mm; the heights (h_1/h_2) of the fractures are 5 mm and 7.5 mm.

We also create four different dual fracture models. For these models two fractures are cut with a 5 mm spacing between the fractures. The widths of the fractures are 0.5 mm, 0.6 mm, 0.8 mm, and 1.1 mm, respectively. The height of the fractures in each model is 7.5 mm.

Figure 1 shows a Lucite fracture zone model. Twenty-five fractures are made on the bottom side of a Lucite block. The width of each fracture is 0.5 mm, the height is 5 mm, and the space between the fractures is 6.5 mm.

Figure 1: Lucite fracture zone model (a) and the construction of the fractures (b). The 25 fractures extend through the Lucite block.

Acoustic source and receiver system

We put each fracture model on top of a second Lucite block (Figure 2) to simulate fractures in the earth. We use pump oil, as a coupler, on the interface between the two Lucite blocks to eliminate the reflection from the interface. Only when the reflection from the interface is small, can the effects of the fracture on the acoustic field be measured.

We apply two P-wave plane transducers (Panametrics, V103, 1.27 cm in diameter) to the top surface of the fracture model (Figure 2a) with a coupler of petroleum jelly. One transducer is used as a source excited by a single sine wave pulse, whose center frequency is 400 kHz and amplitude is $\pm 10 \text{ V}$. The wavelengths of a P-wave and the S-wave are 6.75 mm and 3.25 mm, respectively. The wavelengths are larger than the widths of the fractures, and similar to the spacing between fractures for the dual fracture and fracture zone models. The main acoustic energy propagates down to the fracture, the interface, and the bottom of the model (Figure 2a). The other transducer receives the acoustic waves reflected from the fracture and interfaces as the vertical components of the surface waves.

Experimental studies of fracture reflections

b) Top view

Center frequency: 400 kHz
Lucite: $V_p=2700$ m/s, $\lambda_p=6.75$ mm
 $V_s=1300$ m/s, $\lambda_s=3.25$ mm

Figure 2: Lucite fracture model (a) with single fractures. The measurements at the different directions on the top surface are shown in (b). The center frequency of the source is 400 kHz.

Before showing the waveforms from the fracture models, it is helpful to look at the results when no fractures are present. To accomplish this, a Lucite block without fractures replaces the fracture block in Figure 2a. We fix a source on the surface of the Lucite block and move the receiver in increments of 2.0 cm. We record acoustic waveforms when the space between the source and receiver changes from 4 cm to 14 cm. From the arrival times and the slopes of the waveforms, we mainly record the surface P-wave, the surface S-wave; waves reflected from the interface and the bottom. Because the two Lucite blocks are stacked together with the oil, the amplitudes of the waves reflected from the interface are smaller than those reflected from the bottom.

When the distance between the source and receiver is fixed at 8.0 cm, we record the acoustic waveforms (Figure 3) propagating along different directions (as shown in Figure 2b). Because Lucite is a homogeneous material, the waveforms at the different directions are similar to each other. The surface P-wave and S-wave as well as the waves reflected from the bottom are clearly separated in the time domain (Figure 3). The consistent surface waves in each trace also means that consistent coupling was achieved between the transducer and the surface for each experiment. In the fracture experiments we will focus on the waveforms reflected from the fractures and the interface at the base of the fractures.

Figure 3: Acoustic waveforms recorded in different directions when a Lucite block with no fractures replaces the Lucite block with the fractures in Figure 2. The source and receiver spacing is 8.0 cm.

Measurements with the single fracture model

To understand the effects of fractures on the acoustic field we apply the single fracture model shown in Figure 2a and measure the reflected acoustic waves. The widths of the single fractures are 0.5 mm, 0.6 mm, 0.8 mm, and 1.1 mm; their height is 5 mm. We measure the reflected waveforms according to the setup shown in Figure 2b. The space between the source and receiver is fixed at 8.0 cm. The center point of 8.0 cm is directly above the fracture. We define the direction perpendicular to the fracture as 0 degree and the direction parallel to the fracture as 90 degree.

Figure 4: Acoustic waveforms recorded in different directions for a Lucite block with a single fracture with a width of 1.1mm (Figure 2). The source and receiver spacing is 8.0 cm.

Figure 4 shows the waveforms for the model with a single fracture with a width of 1.1mm. The last trace (at top of the panel) is recorded at the area without any fracture in order to compare the effects of the fracture on the acoustic field. Comparing this with the waveforms shown in Figure 3, we see the waveforms around 0.1 ms, which are reflected from the fracture and the interface at the base of the fracture. Note the small event that arrives before the wave reflected from the interface. Based on arrival times, this event is reflected from the top of the fractures.

Figure 5 compares the traces for all four fracture widths for the arrival from the fracture for the source-receiver orientation at 0 degrees (normal to the fracture). Figure 5a shows the waveforms reflected from the interface and the fracture. From the waveforms before the interface reflection, we see that the frequency and

Experimental studies of fracture reflections

amplitude of the reflected wave from the top of the fractures are related to the width of the fractures. Figures 5b and 5c show the relationship between the frequency and amplitude and the fracture width, respectively. When the fracture width increases, more acoustic energy is reflected, and the response frequency decreases. In this fracture model the height of the fracture is 5 mm, the top reflection is not completely separated in time from the interface reflection. If the height of the fracture increases, the two waves separate clearly in the time domain.

Figure 5: Acoustic waveforms (a) recorded in a direction normal to the fracture strike (0 degree) when the widths of the fracture are 0.5 mm, 0.6 mm, 0.8 mm, and 1.1 mm, respectively. The trace at the top of the plot is recorded in the area without any fracture. The center frequency (b) and normalized amplitude (c) of reflected waves from the fracture top are related to the fracture widths.

Measurements with the dual fracture model

In order to study the scattering from multi-fractures, we first test a dual fracture model with the same fracture widths. The fracture cuts are separated by approximately one wavelength. The source-receiver spacing is 8.0 cm centered at the midpoint between the two fractures. The fracture height for these experiments is 7.5mm compared to 5mm for the single fracture models.

We record waveforms in different directions just as we did for the single fracture model.

Figure 6 shows a comparison between the single and dual fracture waveforms recorded normal to the fracture strike (0 degree azimuth) for the arrivals from the fracture zone itself. From this figure we make several observations:

- (1) The amplitudes of the wave reflected from the tops of the dual fractures are larger than those in the single fracture models while the center frequency of those reflections are the same.
- (2) Multiply scattered waves between the two fractures arrive after the interface reflection.
- (3) The waves converted from P-wave to S-wave at the top of the fractures are recorded around 0.155 ms before the P to S

converted wave from the interface (0.16 ms). The amplitude of this event increases when the fracture width increases.

Measurements outside of the fractures

All of the above measurements are conducted directly above the single fracture or dual fractures. We also made out-of-place measurements observing the changes in the waveforms and the effects of the fractures on the acoustic field.

Figure 6: Comparison of the waveforms recorded with the single fracture (top panel) and the dual fracture (bottom panel) models at the direction of 0 degree when the widths of the fracture are 0.5 mm, 0.6 mm, 0.8 mm, and 1.1 mm, respectively. The waveforms in the square box are reflected from the fracture tops and scattered between the dual fractures (dot-dash line).

Figure 7 shows the acquisition method for out-of-plane measurements for four directions relative to the fracture strike along the lines of x0, x30, x60, and x90. The source-receiver spacing is fixed at 8.0 cm and they move along the lines at steps of 2.0cm/trace.

Waveforms are shown for both the single fracture model and the dual fracture model for the line direction x60 and fracture width of 1.1mm in Figure 8. Trace 4 (blue trace) shows the waveforms when the measurements are directly above the fracture. The arrival times of the waveforms reflected from the interface do not change, but the reflection from fracture tops as well as the multiple scattering energy (arriving after the interface reflection) in the dual fracture model can be seen to vary as the source-receiver positions change.

Experimental studies of fracture reflections

Figure 7: The out-of-plane scattering acquisition method. Measurements are made along the lines of x0, x30, x60, and x90. The space between the source and receiver is fixed at 8.0 cm and they move along the lines with 2.0 cm/trace.

Figure 8: Waveforms measured with the single fracture model (top panel) and the dual fracture model (bottom panel) with a fracture width 1.1 mm along the line x60 (figure 7). Trace 4 (blue line) is located directly above the fracture.

Measurements with the fracture zone model

Finally we show measurements for the fracture zone model shown in Figure 1.

Figure 9 shows the waveforms (trace 1-10) recorded on the surface of the model along the different azimuthal directions (0 degree to 90 degree, where 0 degrees is normal to the fractures and 90

degrees is parallel to the fractures) with 10 degree/trace increments. The waveform in trace 11 is measured in the area without any fracture. The wave reflected from the interface between the two Lucite blocks is recorded at 0.087 ms. The arrival preceding the interface (in the blue ellipse) is from the tops of the fractures. This event is quite stable in amplitude behaving almost as an interface reflection. The amplitude of the base of fracture interface reflection increases when the measurement direction is close to 90 degrees (direction parallel to the fractures). When the measurement direction is closer to the direction perpendicular to the fractures, more acoustic energy is scattered by the fractures. Therefore, more energy is received after the interface reflection (in blue square box).

Figure 9: Waveforms recorded with the fracture zone model at the different directions. Trace 11 shows the waveform recorded in the area without any fracture. The waveforms in the blue ellipse box are reflected from the fracture tops. The waveforms in the blue square box are scattered among the fractures.

Conclusions and discussions

In this paper, we experimentally study the seismic scattering from a single fracture model, dual fracture model, and a fracture zone model. The incident P-waves are reflected from the top of the fractures and the interface at the base of the fractures. We also record the vertical components of converted S-waves from the fracture zones. The frequency and amplitude of the waves reflected from the top of the fracture are related to the width of the fracture. Its arrival time is related to the height of the fracture. When there are two parallel fractures, the incident waves are scattered between the fractures. In the fracture zone model, the scattered waveforms vary in different acquisition directions, which can help determine the fracture orientation. Variations in the scattering characteristics from the top and base of the fractures may provide information on fracture geometry, spacing, and orientation.

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