Effects of fracture scale length and aperture on seismic properties: An experimental study

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Summary

In this paper, we investigate the effects of fracture scale length and aperture on seismic wave propagation through seismic physical modeling. The physical models are constructed from a solid background of epoxy resin with inclusions of silicon rubber chips of different diameter and thickness to simulate fractures with different scale length and aperture. The chips embedded in each model are of the same diameter and thickness, and the fracture density is kept constant for all models. P and S waves that propagate parallel and perpendicular to the fractures are then recorded using a pulse transmission method. The experimental results show that given the same fracture density the changing of diameter has only a minor effect on the P-wave velocity and amplitude, and there are also little effects on the shear-wave amplitudes. The main observable effect is an increase of the slow shear-wave velocity with diameter, leading to a decrease in shear-wave splitting with diameter. The changing of fracture thickness (aperture) also has only a small effect on the shear-wave except an obvious decrease in the slow shear-wave velocity, leading to an increase of shear-wave splitting with thickness. However, the increasing in fracture thickness induces a strong attenuation in the P-wave, in particularly for the P-wave propagating perpendicular to the fracture.

Introduction

Equivalent medium theories, such as Hudson (1980), are often used to model seismic wave propagation in fractured media. These theories can effectively describe the effects of fracture density and orientation, as well as multiple fracture sets, but they cannot account for the effects of fracture scale length and aperture, which become increasingly important for fractured reservoir characterization. Chapman (2003) extended the existing equivalent medium theories to account for the effects of fracture scale length. However, there is still a lack of understanding on the effects of fracture aperture. Here, through experiment studies in the laboratory with controlled fracture models and seismic physical modeling, we aim to investigate the effect of different fracture scale length and aperture on seismic properties, such as velocity and amplitude.

Several approaches have been reported in the literature to study the effects of fracture parameters on seismic waves through seismic physical modeling in laboratories (e.g. Tatham et al., 1992; Rathore et al., 1995; Wei, 2004). However, these studies were designed only to study the effects of fracture density. In this paper, the embedding method with round chips, as in Wei (2004), is adopted. Fracture models with different fracture radius, or diameter (scale length) and thicknesses (aperture) but with the same fracture density are constructed and the pulse transmission method is used to study the effects on seismic wave propagation.

Fracture model construction

The construction is based on Hudson's (1980) assumption of thin penny-shaped fractures. The models consist of a solid base with inclusions of low velocity thin penny-shaped materials (Figure 1). For each model, the fracture density (ε) is given by $\varepsilon = Nr^3/V$, where V denotes the volume of the base material, r denotes the radius of the round chips and N is the total number of chips in the base material. The fracture density changes when we alter N or r.

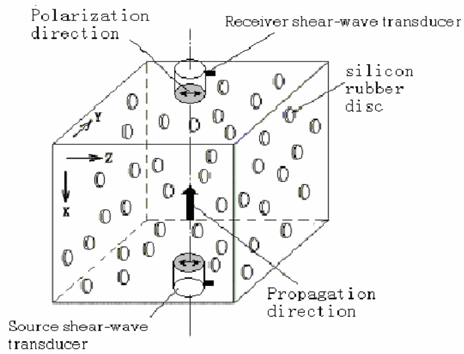


Figure 1. The controlled fracture model using epoxy resin and round chips of silicon rubber.

Two sets of fractured models are constructed and there are six models for each set. One set has different fracture diameter; the fracture density is about 0.074 and the average fracture thickness is 0.14mm. The other set has different thickness, and the fracture diameter is fixed at 4.2mm. All models are constructed from a solid base of epoxy resin. The density of the base material is 1.18g/cm^3; the P-wave velocity is 2630m/s and the S-wave velocity is 1200m/s. The round chip simulating a fracture is made from a mixture of silicon rubber; the density is 1.09 g/cm^3; the P-wave velocity is 1360m/s; the S-wave velocity is very small and there is no S-wave signal received from this rubber mixture. Each fractured model is made of 35 layers of epoxy resin with equal weight to ensure that the separation between two neighboring layers is kept the same. The thickness of each layer is 1.72mm. Once a layer is laid, silicon rubber chips with random distribution are embedded into the layer, and another layer of epoxy resin is then added on the top.

Experimental setup

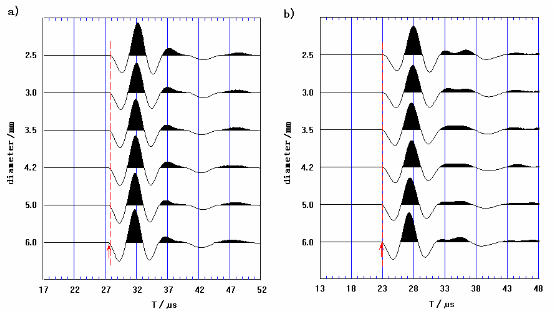
The pulse transmission method is used to measure P and S wave velocities for all the models for the direction parallel (X-axis) and perpendicular (Z-axis) to the fracture chips. The transducer in the experiment has the characteristics of broad bandwidth and short pulse. The S-wave transducer has good polarization direction. The centre frequency of P-wave transducer is 200kHz and the bandwidth is 100kHz to 300kHz. The centre frequency of S-wave transducer is 100kHz and the bandwidth is 60kHz to 250kHz. The wavelength of the P- and S-waves generated in the experiment is 20 to 30mm, which is much larger than the fracture diameter, and approximately satisfies the long wavelength assumptions of the equivalent medium theories.

Experimental results: P-wave

Figures 2 and 3 show the P-wave records for the two sets of fracture models at the propagation direction of X-axis (parallel to the fractures) and Z-axis (perpendicular to the fractures), and the corresponding P-wave velocities are listed in Tables 1 and 2.

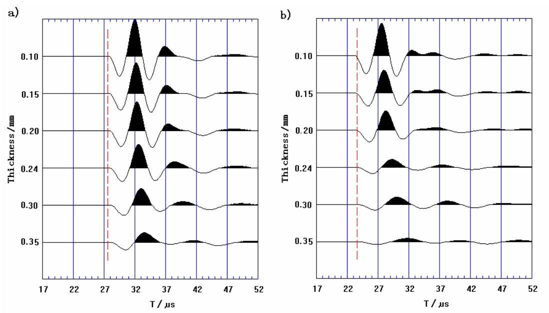
In Figure 2a, the fracture diameter (scale length) increases from 2.5mm to 6mm, and the P-wave travel time decreases from 27.3μs to 26.9μs. The variation in 0.4μs(about 1.5%), and this is larger than the measurement error of ±0.1μs. This indicates that the P-wave velocity parallel to the fracture strike increases with increasing diameter. Furthermore, there is little variation in the waveforms in Figure 2a, suggesting that the change of diameter within the long wavelength assumption for non-saturated cracks has negligible effects on the P-wave amplitude. There is a 14% reduction in magnitude in Figure 2a for a 2.4 times increasing in fracture diameter. For P-wave traveling perpendicularly to the fractures (Z-axis), there is a 1.5% reduction in P-wave velocity (Table 1), and a slight decrease in the P-wave amplitude (Figure 2b), compared with the P-waves parallel to the fractures in Figure 2a. Furthermore, the change in fracture diameter has little effects on the P-wave velocity, and its effect on the amplitude is also small (Figure 2b).

In contrast, changes of thickness (aperture) have a stronger effect on the P-wave, as shown in Figure 3. At the direction parallel to the fracture, there is a small variation of 1.1% in the P-wave velocity for a 3.4 times changes in fracture aperture. However, there are very significant changes in the P-wave amplitude and waveforms. As the fracture aperture increases, the P-wave is substantially attenuated, as shown in Figure 3a. For a 3.4 times change in fracture aperture, there is a 3.8 times reduction in P-wave amplitude, and the higher frequencies are also attenuated (Figure 3a). These effects are even more significant for the P-waves propagating at the perpendicular direction, as shown in Figure 3b. The P-wave velocities have changes up to 3% (Table 2), and the effects on the amplitude are also more than doubled (Figure 3b). This shows a clear link between P-wave attenuation and variations of fracture aperture.



(a) Parallel (b) Perpendicular

Figure 2. Comparison of P-waves recorded for the fracture models with different diameter, propagating (a) parallel and (b) perpendicular to the fractures.



(a) Parallel (b) Perpendicular

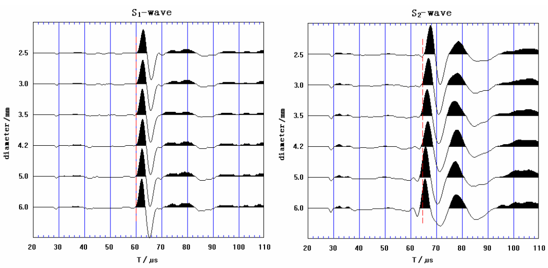
Figure 3. Comparison of P-waves recorded for the fracture models with different thickness, propagating (a) parallel and (b) perpendicular to the fractures.

Experimental results: S-wave

For propagating at the X-direction, we have recorded both the fast shear-wave (S1) and the slow shear-wave (S2). For propagating at the Z-direction, we have also recorded both the wave polarized along the X-axis (Sx) and the one along the Y-axis (Sy).

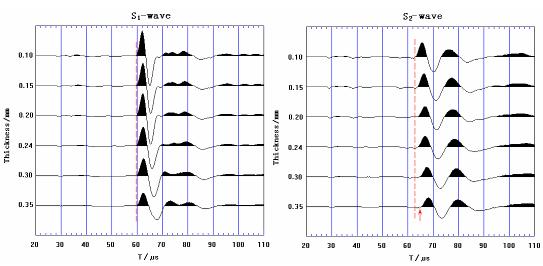
Figure 4 shows the fast S1 and slow S2 waves for the fractures models with varying fracture diameter. Similar to the P-waves, the changes in fracture diameter have almost no effects on the velocity of the fast waves (Figure 4a and Table 1); the effects on the amplitude are also small; there is about 16% reduction in amplitude and the waveforms remain similar. The influence of fracture diameter to the slow S-wave velocity is evident and the velocity is increased by 2.6% as the fracture diameter increases (Table 1), whilst the amplitude is decreased by 20%. There are some visible distortions to the S2 waveforms. When the diameter is 6mm, noise signal can be observed before the onset of the slow waves due to scattering effects (Figure 4b).

Figure 5 shows the fast S1 and slow S2 waves for the fractures models with varying thickness. Contrary to the P-waves, changes in fracture thickness have a smaller influence on the shear-waves. S1 velocity shows almost no changes, and there is a 34% decrease in S1 amplitude (Table 2, Figure 5a). The S1 waveforms also show little changes except for very large thickness. Some distortion and attenuation of higher frequency about 30% can be observed when the thickness is 0.35mm. The only obvious change is in the S2 velocity that is decreased by 2.6%; surprisingly the S2 amplitudes also show little changes (Figure 5b).



(a) Fast S1 (b) Slow S2

Figure 4. Comparison of (a) the fast S1 and the slow S2 waves recorded for the fracture models with different diameter, propagating parallel to the fractures along the X-axis.



(a) Fast S1 (b) Slow S2

Fig. 5. Comparison of (a) the fast S1 and the slow S2 waves recorded for the fracture models with different thickness, propagating parallel to the fractures along the X-axis.

The two shear-waves (Sx and Sy) recorded propagating perpendicularly to the fractures are very stable. Their velocities are very much the same and the differences between them are very small. The effects of changes in fracture diameter or thickness on these two waves are very similar to those on the S2, The trend of the variations is the same but with a smaller magnitude. This confirms that the fracture models possess transverse isotropy.

Discussion

As shown in Tables 1 and 2, the effects of changing fracture diameter on P- and S-wave amplitude and waveforms are small. Some scattering effects can be observed only when the fracture diameter reaches 6mm. This may be due to fact that the fracture scale length is much smaller compared with the wavelength and is still within the limits of the long wavelength assumption. The main effects of changing fracture diameter are on the P and S-wave velocities. As the fracture diameter increases, the P-wave velocity parallel to the fractures increases, but the P-wave velocity perpendicular to the fractures remains almost constant (Table 1). Therefore, there is an increase in the P-wave velocity anisotropy. There are possible two reasons for this. One is due to the changes of aspect ratio. As the fracture diameter increases, the aspect ratio increases since the thickness remains constant at 0.14mm. This will increase the P-wave anisotropy as predicted by the equivalent medium theory such as Hudson (1980). The other reason may be due to scattering. As the fracture diameter increases, the number of fractures decreases substantially in order to keep the fracture density constant. Therefore the total fracture area decreases. For example, the fracture area for the fracture model with a diameter of 2.5mm is 2.36 times larger than the fracture area in the fracture model with a diameter of 6mm due to a substantial reduction in the number of fractures. As a result, the fracture spacing will also increase. This will certainly reduce the scattering effects and increases the velocity.

The amount of shear-wave splitting as defined by the Thomsen (1986) parameter γ decreases as the fracture diameter increases. Again this can be explained by the reduction in the number of fractures as fracture diameter increases since the fracture density is kept constant, as in the P-wave case.

The P-waves suffer serious attenuation as the fracture aperture increases, and the P-wave attenuates more when propagates along the fracture normal then along the fracture strike. This is consistent with expectation. However, the S-wave shows little attenuation with increasing fracture thickness. This is likely induced by the material properties of the round chip that is not a real fracture but a solid inclusion. This indicates that the use of a round chip of silicon rubber to simulate a fracture is probably more appropriate for P-wave propagation than for S-wave. Despite this, there is significant decreasing in S2 velocity, hence, an increasing in shear-wave splitting, as the fracture aperture increases.

Conclusions

It is common to simulate a fractured medium through embedding round chips with a low density and velocity into a solid background. Using this technique, we have constructed two sets of fracture models with fixed fracture density but with different fracture diameter and aperture to study their effects on seismic wave propagation. The main findings of these experiments can be summarized as follows:

1). As the fracture diameter varies from 2.5mm to 6mm, for a given fracture density and fracture thickness, the P-wave anisotropy increases from 1% to 2%, whilst the amount of shear-wave splitting decreases from 7.4% to 5.6%. In contrast, the changes in fracture diameter have little effects on the P- and S-wave amplitude and waveforms.

2) As the fracture thickness (aperture) varies from 0.1mm to 0.35mm, for a given fracture density and given fracture diameter the P-wave anisotropy increases from 1.2% to 2.5%, and amount shear-wave splitting increases from 5.0% to 7.6%.

3) The changes in the fracture aperture show a significant effect on the P-wave amplitude and waveform. The P-wave decreases by 3.8 times when the fracture aperture increases by 3.4 times. However, the effect on the S-wave amplitude is small.

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Table 1. Measured seismic velocities and Thomsen (1986) parameter γ for the models with different fracture diameter. The fracture thickness is kept at 0.14mm.

Model No.	Fracture diameter (mm)	Vp-X (m/s)	Vp-Z (m/s)	Vs – X (m/s)		Vs -Z (m/s)		γ -X (%)	γ -Z (%)
				S1	S2	Sx	Sy		
1	2.5	2577	2559	1181	1094	1137	1133	7.37	0.3
2	3.0	2586	2560	1183	1108	1141	1137	6.34	0.4
3	3.5	2588	2562	1187	1115	1142	1142	6.07	0
4	4.2	2596	2572	1187	1106	1141	1141	6.83	0
5	5.0	2607	2575	1189	1123	1146	1151	5.55	0.4
6	6.0	2614	2580	1190	1123	1151	1146	5.63	0.4

Table 2. Measured seismic velocities and Thomsen (1986) parameter γ for the models with different fracture thickness. The fracture diameter is kept at 4.2mm.

Model No.	Thick-ness (mm)	Vp-X (m/s)	Vp-Z (m/s)	Vs-X (m/s)		Vs-Z (m/s)		γ -X (%)	γ -Z (%)
				S1	S2	Sx	Sy		
1	0.1	2620	2589	1198	1136	1156	1156	5.04	0
2	0.15	2610	2576	1198	1129	1151	1146	5.62	0.43
3	0.2	2605	2565	1197	1124	1146	1142	5.9	0.35
4	0.25	2601	2548	1199	1119	1137	1142	6.46	0.44
5	0.3	2594	2534	1201	1106	1141	1137	7.58	0.43
6	0.35	2590	2525	1201	1106	1141	1137	7.58	0.43

Experimental study of the effects of fracture length and aperture

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