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Physical modelling studies of the effect of fracture thickness on P-wave attenuation

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Summary

The seismic physical approach was used to investigate the effect of fracture thickness on P-wave attenuation, using a laboratory-scale model of two horizontal layers. The first layer is isotropic while the second layer has six fractured blocks, each consisting of thin penny-shaped chips of 3mm fixed diameter and same thickness to simulate a suite of aligned vertical fractures. The chips' thicknesses vary according to the blocks while the fracture density remains the same in each block. 2D data were acquired with the physical model submerged in a water tank in a direction normal to the fracture strikes using the pulse-transmission method. The seismic quality factor, Q was estimated from the pre-processed CMP gathers using the QVO method, which is an extension of the spectral ratio method of measuring attenuation. The results of our measurements show a direct relationship between attenuation and fracture thickness. The induced attenuation was observed to increase systematically with fracture thickness, implying more scattering of the wave energy in the direction of increasing thickness. This information may be useful to differentiate the effect caused by thin micro cracks from that of large open fractures.

Introduction

There exist a number of equivalent medium theories for seismic wave propagation in fractured media. One of such theories is the Hudson's (1980, 1981) theory which proposes that fractures could be modelled as thin-penny shaped crack inclusions in an isotropic background with as aspect ratio much less than unity. The fracture density from this model is defined mathematically as:

$$\chi = nr^3 v^{-1} \tag{1}$$

Where n is the number of cracks in the base material, v is the volume of the base material and r is the radius of each crack. From equation (1), it becomes obvious that many small cracks or a few large cracks within the same volume of material can result in the same fracture density. Furthermore, equal number of cracks with the same radius but with varying thicknesses within the same volume of material can also give rise to the same fracture density. Thus, the investigation of the effects of the fracture scale lengths and thicknesses on seismic wave response may be of great interest in fractured reservoir characterization.

In this paper, we used the seismic physical modelling approach to investigate the effect of fracture thickness on the induced attenuation for the same fracture density. The physical model consists of two horizontal layers, the second of which is made anisotropic by the inclusion of thin penny-shaped chips of fixed diameter and varying thicknesses as in Wei *et al*. 2007 and Ekanem *et al.* 2009 to simulate fractures with different fracture thicknesses. 2D data were acquired in a direction normal to the fracture strikes using the pulse-transmission method in a water tank. The seismic quality factor, Q was estimated from the pre-processed CMP gathers using the QVO method introduced by Dasgupta and Clark (1998). The results of our measurements show a direct relationship of attenuation and fracture thickness, indicating the potential of using P-wave attenuation to distinguish the effect caused by thin micro cracks from that caused by large open fractures.

The physical model

The physical model consists of two horizontal layers (Figure 1). The first layer is made from a mixture of epoxy resin and silicon rubber and has a thickness of 38mm, P-wave velocity of 2150m/s, S-wave velocity of 1100m/s and density of 1.15g/cm^3. The second layer is made from epoxy resin with a thickness of 75.5mm, P-wave velocity of 2573m/s, S-wave velocity of 1200m/s and density of 1.18g/cm^3. To simulate fractures with varying thicknesses, thin penny-shaped chips made from a mixture of epoxy resin and silicon rubber with a fixed diameter of 3mm and P - wave velocity of 1300m/s are randomly embedded in the isotropic background of the second layer in accordance with Hudson's (1980, 1981) equivalent medium theory (Figure 1). The chips are arranged to form six fractured blocks with their thicknesses as 0.10, 0.15, 0.20, 0.25, 0.30 and 0.35mm respectively in each block. Each block is made up of 30 layers of epoxy resin. Once a layer is laid, 60 thin chips are randomly embedded into the layer and another layer is added on the top. The whole process is repeated until a total of 30 layers were achieved. All the six fracture blocks have the same fracture density. The model is constructed with a scale of 1:10,000 and is a simplified analogous representation of a fractured reservoir with varying fracture thicknesses.

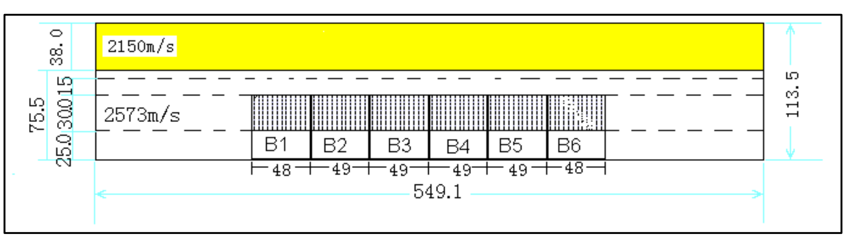

Figure 1: Base model made up of two layers. Numbers shown indicate model dimensions scaled up by 1:10,000. Second layer has six fractured blocks, B1 to B2 in order of increasing chips' thicknesses.

Experiment set up and data acquisition

The pulse-transmission method was used to record the seismic response from the physical model in a direction perpendicular to the fracture strikes. 2D data were acquired in a water tank where the base model was submerged (Figure 2). The water depth to the top of the model is 100mm. The net thickness of the overburden above the anisotropic layer is 138mm. The modelling system comprises an ultrasonic pulse source and a receiver system, an analogue/digital converter and a motor driven positioning system with a precision of 0.1mm. The ultrasonic pulse source has a centre frequency of 230KHz and a bandwith of 130 – 330KHz. The dominant wavelength of the P-wave generated in the experiment is 11.2mm which is greater than the fracture diameter, thus, almost satisfying the long wavelength approximation of the equivalent medium theories of wave propagation in fractured media.

The source and receiver were located on the water surface. Each time, a single shot was fired into a single receiver at a minimum offset of 16mm, the receiver was then moved a distance of 2mm away and another shot fired until a total of 120 receiver positions was occupied for a single shot position. The shot was then moved a distance of 2mm in the direction of the receiver and the procedure repeated. A total of 230 shots was made and the distance between each shot was 2mm. The model acquisition parameters are scaled up by 1:10,000 while frequencies are scaled down by 10,000:1.

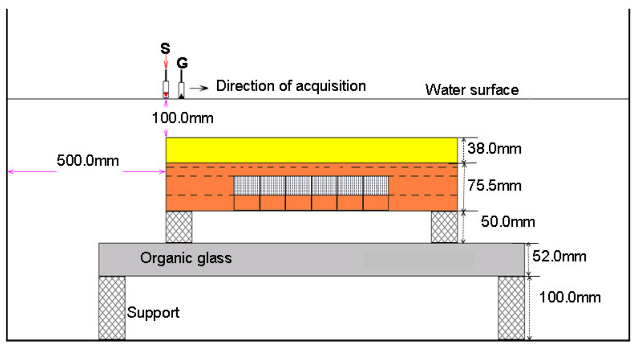

Figure 2: Experimental set up. Base model submerged in a water tank. S and G are the shot and receiver positions respectively.

Data Processing and Q estimation

Prior to Q estimation, the following processing sequences were applied to the data: geometry configuration, common mid-point (CMP) sorting, traces muting, velocity analysis and NMO correction. Stacking was also included in the processing sequence for event identification of and picking of the traveltimes to the target layers, even though the Q values were estimated from the pre-stack CMP gathers.

Methods of estimating Q from seismic data include the spectral ratio, the amplitude decay, the rise-time, the centroid frequency-shift, the wavelet modelling, the Pulse broadening and the Inversion methods (Tonn, 1991), of which the most common one is the spectral ratio method. In this study, the QVO method, an extension of the classical spectral ratio method introduced by Dasgupta and Clark (1998) was used to estimate the seismic quality factor from the NMO corrected CMP gathers. In each gather, the first trace from the top model reflection was selected as the reference trace for comparison of the spectral ratios. The spectral power (instead of the spectral amplitude as in the original QVO method) of the top and bottom fractured-layer reflections were computed on a trace-by-trace basis and divided by that of the reference trace. Next, a simple linear regression of the power ratios against frequency was carried out according to the equation:

$$\ln\left(\frac{P_2(f)}{P_1(f)}\right) = 2\ln(\mathrm{RG}) - 2\pi f\left(t_o - t_{ref}\right)/Q \qquad (2)$$

where $P_2(f)$ and $P_1(f)$ are the spectral powers of the top or bottom fractured-layer reflections and the reference trace respectively, f is the frequency, R is the reflectivity term, G is the geometrical spreading term, t_o is the travel-time of target reflection, t_{ref} is travel-time of reference event and Q is the quality factor down to the reflector. Sample plots of the Log Spectral Power Ratio (LSPR) against frequency are shown in Figure 3. The spectral ratio slopes were computed from the regression as;

$$p = 2\pi\left(t_{ref} - t_o\right)/Q \tag{3}$$

Since the travel-times are hyperbolic, a second simple linear regression of the ratio slopes against the square of the offsets gives the zero-offset slope from where the interval Q value down to the reflector is computed using the equation (Dasgupta and Clark, 1998):

$$Q_i = \frac{[t_n - t_{n-1}]}{t_n / Q_n - t_{n-1} / Q_{n-1}} \tag{4}$$

where Q_n and Q_{n-1} are the quality factors for the reflectors at the two-way traveltimes of t_n and t_{n-1} respectively.

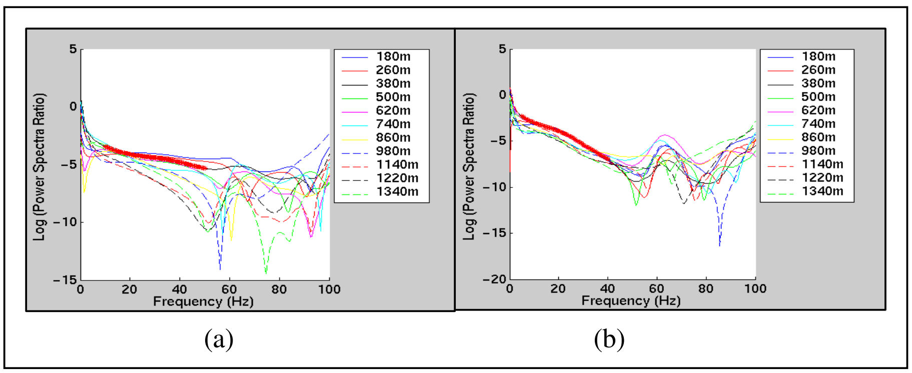

Figure 3: Samples of Log Spectral Power Ratio (LSPR) against frequency plots. (a) Top fracture layer reflection (b) Bottom fractured layer reflection. Regression bandwidths highlighted in red. Inserted legend indicates the respective offsets.

Results

The results of our analysis show direct correlation of the Q values with fracture thickness. High Q values are obtained at the two ends of the survey line where there are no fractures (Figure 4). Q values decreases systematically in the direction of increasing fracture thickness implying more induced attenuation.

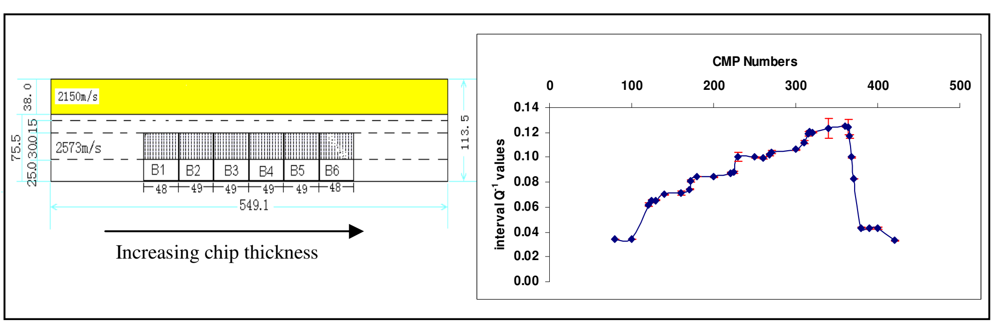

Figure 4: 1/Q results for the fracture blocks. Higher Q values at the ends of the line. Q decreases with increasing fracture thickness implying more attenuation.

Conclusions

We have carried out a seismic physical modelling study of the effect of fracture thickness on P-wave attenuation. The results of the study reveal that given different fracture sets of fixed radius and fracture density but with varying thicknesses, P-wave attenuation has a direct relationship with the fracture thickness. Attenuation increases with the fracture thickness, implying more scattering of the wave energy as the wave propagates in the direction of increasing thickness. This information may be used to distinguish the effects caused by thin micro cracks and large open fractures.

Acknowledgements

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