Water saturation effects on shear wave splitting in synthetic rock with fractures aligned at oblique angles

Kelvin Amalokwu, Angus I. Best  
Mark Chapman, Giorgos Papageorgiou  
National Oceanography Centre, School of Geosciences,  
University of Southampton Waterfront Campus, University of Edinburgh,  
European Way, Southampton, SO14 3ZH, UK EH9 3JW, UK  
Contact email: kelvin.amalokwu@noc.soton.ac.uk

Summary

We present novel laboratory measurements of ultrasonic velocity as a function of water/air saturation in synthetic sandstones both with and without aligned penny-shaped fractured. Interesting fluid effects on shear wave splitting (SWS) were seen for the sample containing fractures aligned at oblique angles. The results suggest the possible use of SWS from multi-component seismic datasets for discriminating between full liquid saturation and partial liquid/gas saturation in reservoir sandstones. Combining an isotropic partial saturation model and a fractured rock model, we were able to obtain qualitative agreement with our experimental observations. In modelling the fractured rock response, we conclude that a better model is needed to describe the isotropic (non-fractured) case, which would yield better results for the fractured case.

Introduction

Shear wave splitting is a commonly used method for fractured rock characterisation. For isotropic rocks, Gassmann’s formula predicts that the shear modulus of the rock is insensitive to saturation. However, in the anisotropic case fluid compressibility can affect shear wave propagation (Brown and Korringa, 1975), causing fluid-dependent shear wave splitting (SWS). The compressibility of fluid-saturated rocks is frequency dependent as a result of wave-induced fluid flow (WIFF) (see Müller et al., 2010) and could in turn lead to frequency dependent SWS. This fluid-dependent shear wave splitting could be used as a diagnostic tool to infer the saturation properties of fractured reservoirs (Qian et al., 2007).

The presence of partial gas saturation is also known to affect compressibility of rocks, also causing velocity dispersion and attenuation (Murphy, 1982, Gist, 1994). However, the seismic response to partial gas saturation in fractured rocks is still poorly understood at present, even though such conditions are commonly encountered in the Earth’s crust.

Theoretical and experimental fractured rock studies have shown that SWS for wave propagation at 90° to the fracture normal is independent of the saturating fluid (Hudson, 1981, Tillotson et al., 2012, Rathore et al., 1995). Theoretical predictions of fluid sensitivity of the slow shear-wave propagating at
oblique angles to the fracture normal was observed in laboratory experiments by Tillotson et al. (2011) using a synthetic fractured sample cored at 45° to the fracture normal and saturated with liquids of different viscosities. Fractured rock studies have so far focused on single fluid saturation while partial saturation studies have focused on approximately isotropic rocks.

Here, we present laboratory measurements of velocities as a function of water/air saturation ($S_w$) in synthetic, silica-cemented sandstones: one sample containing fractures aligned at 45° to the fracture normal; and the other sample is blank (no fractures). The results show interesting saturation effects which we found could be explained by combining partial saturation models for isotropic rocks with the fractured rock model of Chapman (2003).

**Results and discussion**

For details on sample description and preparation, see Tillotson et al. (2012) and Amalokwu et al. (2015) respectively. We measured ultrasonic wave velocity to an accuracy of ± 0.3% using the pulse-echo (reflection) method (see McCann and Sothcott, 1992 for detailed equipment description). Shear-wave splitting was measured by rotating the piezoelectric shear-wave transducer (while the sample was under elevated pressure) and observing the maximum and minimum signal amplitudes corresponding to S1 and S2 waves, respectively. We present all results at an effective pressure of 40 MPa and a single frequency of 650 kHz obtained from Fourier analysis of broadband signals.

![Figure 1. SWS versus $S_w$ for a) the blank sample, and b) the fractured sample.](image)

Figure 1a shows a small amount of shear wave splitting of about 0.5% for the non-fractured (blank) sample as a result of grain layering (a function of the sample manufacturing process), relatively constant over the entire saturation range. In the fractured sample (Figure 1b) there is significant shear wave splitting as expected, beginning at ~ 2% at $S_w = 0$ (dry), remaining fairly constant until $S_w \approx 0.7$, followed by a steady decrease between $S_w \approx 0.8 – 1.0$. SWS being lowest at full water saturation. The fluid effect on SWS in the fractured rock is evident with SWS reducing as $S_w$ approaches 1.0.

There is a lack of frequency-dependent theoretical models for partially saturated fractured rocks, so we combined two models to explain our observations (see Amalokwu et al., 2015). The modelling was done using White’s model for partial saturation modelling (Figure 2a) and then a fracture correction was applied using the model of Chapman (2003) (Figure 2b). However we found that the modelling under-predicts the amount of dispersion in the partially saturated case because White’s model only considers one mechanism (mesoscopic fluid flow). We then attempted to model the data for the non-
fractured rock and found that White’s model unsurprisingly under-predicts the amount of velocity dispersion (Figures 3a and 3b). Local (or “squirt”) flow is another mechanism believed to be responsible for velocity dispersion and attenuation in these rocks, but this is not considered in White’s model.

Many attempts have been made to develop mathematical theories which model the effects of partial gas saturation on seismic waves and this is still an actively developing field (see Müller et al., 2010). However, there is still a lack of mathematical theories that can satisfactorily model the velocity dispersion and attenuation as a result of partial gas saturation as the underlying mechanisms are still poorly understood. It then follows that in order to better model the fractured rock case, we need an improved model for the non-fractured case.

Conclusions

We investigated the effect of partial liquid/gas saturation on SWS using novel synthetic fractured and non-fractured sandstones. The results shows a saturation dependence of SWS in the rock containing fractures aligned at 45° to the fracture normal. This is as a result of the sensitivity of the quasi-shear
wave to the effective bulk modulus of the rock-fluid mixture which is frequency dependent as a result of wave induced fluid flow (WIFF).

By applying a fracture correction to a partial saturation model, we were able to explain our observations qualitatively. A better agreement with our modelling results would be possible if a more suitable model were used for the isotropic case. The results show that shear wave splitting observations from multi-component seismic surveys for rocks with fractures aligned at oblique angles to wave propagation could potentially be used to distinguish between partial gas saturation and full liquid saturation.

Further experimental and theoretical studies are needed to better understand the underlying wave propagation mechanisms and we hope this work would serve as a catalyst.

Acknowledgements

The authors wish to thank the United Kingdom Natural Environment Research Council and the sponsors of the Edinburgh Anisotropy Project for supporting this work which forms part of the PhD studies of Kelvin Amalokwu under a NERC-BGS PhD studentship.

References


MÜLLER, T., GUREVICH, B. & LEBEDEV, M. 2010. Seismic wave attenuation and dispersion resulting from wave-induced flow in porous rocks — A review. GEOPHYSICS, 75, 75A147-75A164.


