The role of fluid on wave propagation across a non-perfect interface

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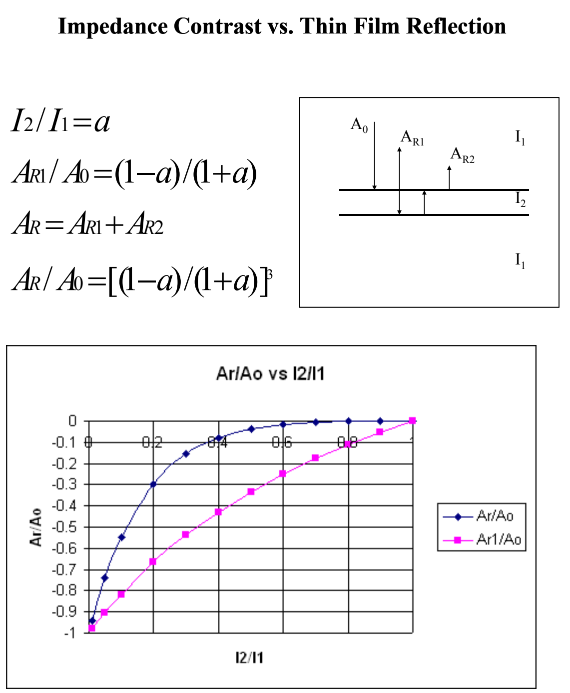
Summary

On a non-perfect coupling interface, the reflection coefficient doesn't obey the Snell's Law and Zoeppritz's equation, which is based on the impedance contrast and displacement continuity. The fluid saturation status in the interface plays an essential role in P-wave propagation across the interface. Two laboratory experiments were carried out to study the effect of interface fluid saturation rate on P-wave transmission and reflection. The results show that a partial saturated interface may cause drastic energy loss for P-wave transmission, along with frequency shift to low end.

Introduction

Current industry seismic interpretations are all based on the reflection coefficient analysis, which is associated with the impedance contrast between different layers. However, the real interfaces between geological layers may be far away from ideal contacts. We can simulate the non-ideal interface by a thin layer model as shown in Figure 1. A thin bed is placed in between two layers with same impedance. We calculated amplitude ratio A_r/A_0 (reflection coefficient) with elastic theory based on impedance ratio between cap and thin layer (I_2/I_1). If the impedance ratio is less than 0.6, the reflection coefficient can be significantly high affected by the thin layer. However this model doesn't account for any energy loss in the interface. The non-ideal interface has been theoretically modeled by applying particle displacement /velocity discontinuity boundary conditions to wave equation, and an energy loss and frequency shift had been predicted for dry and fluid saturated interface. [Pyrak-Nolte, 1990]. However, the partial saturated interface, which may be more common in situ, hasn't been well studied yet. The energy loss in the interface can impose significant change to wave amplitude and may cause impedance based interpretation fail. Our laboratory study is a continuous attempt trying to associate the fluid saturation status to the energy loss in the interface, especially for the partial saturation.



$$I_2/I_1 = a$$
$$A_{R1}/A_0 = (1-a)/(1+a)$$
$$A_R = A_{R1} + A_{R2}$$
$$A_R/A_0 = [(1-a)/(1+a)]^3$$

Figure 1: Reflection coefficient affected by the presence of a thin layer simulating the non-ideal interface.

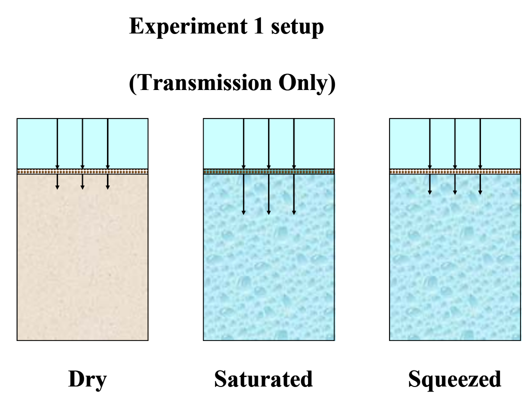


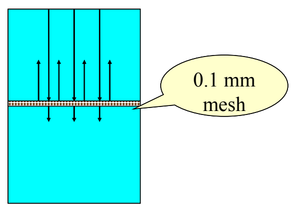
Figure 2: Different saturation status in the interface between a sand sample and plastic buffer were obtained and corresponding P and S waveforms were recorded.

Experiments

In first experiment, only transmission wave was investigated. Figure 2 is the experiment setup. A loose sand sample was jacketed and sandwiched between two plastic buffers. A confining pressure (500 Psi) was applied. The transmission P and S waveforms were recorded under initial dry condition. Then the sample was fully saturated with water under 1000 Psi confining and 500 Psi pore pressures. Again, P and S waveforms were recorded. After that, we opened the pore fluid line, and increased the confining pressure to 2000 psi. A very small amount of water was expelled out of the pore fluid line. Then we released the confining pressure back to 500 psi. During this process, there was no fluid supply connected so that the water squeezed out was not refilled. In other word, we managed to de-saturated the interface between the buffer and sample itself. Again, the P and S waveforms were recorded.

Experiment 2 Setup

(Transmission & Reflection)



Dry --- Fully Saturation --- Partial Saturation --- Almost Dry

Figure 3: Four different saturation statuses were obtained in an interface between two identical buffers.

In experiment 2, we used a pair of two identical plastic buffers, with a 0.1 mm thick metal mesh in between them to mimic a non-perfect interface (Figure 3). A pair of high damping commercial P transducers were attached to both buffers, so that we could record both transmission and reflection waveforms. Initially the interface was in the room dry condition. Then a fully saturation status was obtain by typical vacuum-injection method. Next, we used a well controlled digital pump to suck a certain amount of water out of the pore fluid system, and obtained a partial saturation status in the interface. Finally, we applied a compressed air to blow out most of the water out, and brought the interface back to an "almost dry" status. Under all four statuses, the transmission and reflection P waveforms were recorded.

Observations and Discussion

The P transmission waveforms under all three statuses in experiment 1 are plotted together in Figure 4, along with their corresponding frequency spectrums. When the system changed from status 1 dry to status 2 saturation, not only the interface properties, but also the bulk sample properties had changed. In this case, both the density and velocity of the rock sample increased. This reduced the impedance contrast between the sample and buffer. The large increase of P transmission wave amplitude is partially attributed to the increase of transmission coefficient, and partially attributed to the decrease of energy loss in the interface. We can also see the waveform shifted to left due to the increased velocity.

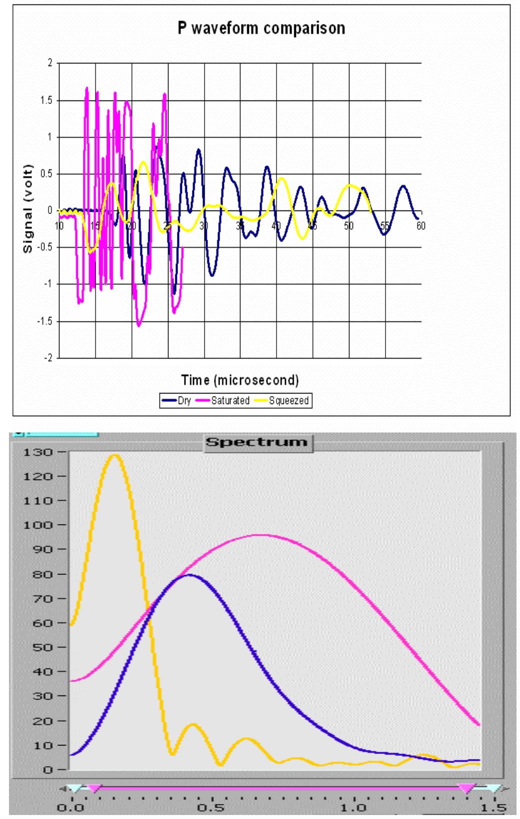


Figure 4: P waveforms and Frequency spectra for dry, saturated, and squeezed cases. The same color legend applied to waveform and spectra.

When the system changed from status 2 (saturated) to status 3 (squeezed), the bulk properties of the sample remained unchanged. So did the impedance contrast between the sample and buffer. Only the interface, maybe including a thin transition layer immediately besides interface, was de-saturated. However, from the waveforms recorded, we can clearly see the transmission P wave amplitude dropped drastically while the interface is de-saturated. Since the impedance contrast in this process remained the same, we can conclude that the energy change in transmission wave could only be contributed by the interface property change. More specifically, the saturation status change in an interface will significantly change the transmitted and reflected energy for the compressional wave propagating across the interface.

In Figure 4, we also show the frequency spectra for the P transmission waveforms recorded under three statuses. Here we ignore the spectrum for dry, since it represents totally different bulk properties. We only compared the "Saturated" and "Squeezed" spectrum, which had the same bulk properties but different interface properties. We observed an obvious frequency shift to low end when the water leaves the interface. In our experiment, the center frequency dropped from 700 kHz at Saturated condition to 170 kHz at De-saturated condition.

In order to better evaluate the energy conservation and dissipation, we designed second experiment, in which both transmission and reflection waveforms could be obtained. Further more it can isolate the interface effect from bulk media effect for two reasons. First, the material is identical at the two side of the interface. Second, when changing the fluid saturation status inside the interface, the properties of the bulk material remain unchanged.

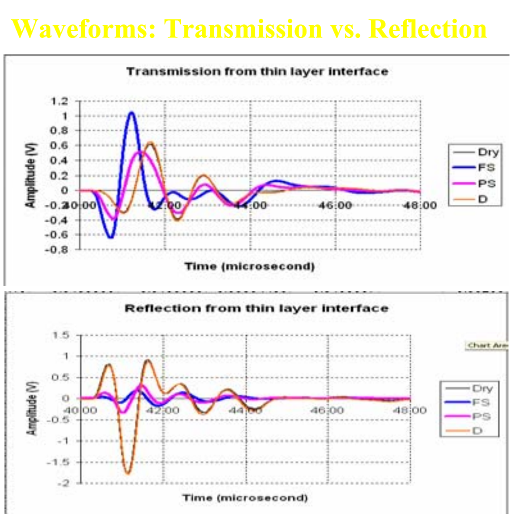


Figure 5: Transmission and reflection P waveforms on simulated non-ideal interface.

In figure 5, we plot both the transmission and reflection P waveforms for all the 4 saturation status. Since the plastic buffer was not water satiable under our experiment conditions, the only change was in the interface between the 2 buffers. Initially the interface was at room dry condition. Although there was no impedance contrast between the 2 buffers, because of the presence of interface, there was a clear reflection signal as well as the transmission signal.

After it was fully saturated, there were 3 noticeable changes. First, the transmission wave shifted to left which represented a velocity increase, while the reflection wave didn't have shift. We calculated the velocity across the interface increasing from 233m/s at dry to 250m/s at saturated condition.

Second, the amplitude of transmission wave increased while the reflection amplitude decreased to a very low level. However, when we plot the summation of transmitted and reflected energy (Figure 6), the total energy observed in saturated condition was almost double the dry condition. This means the saturation reduces the energy loss in the interface. Since the energy loss is associated with the velocity discontinuity, it is suggested that the change of fluid saturation may change the velocity discontinuity across interface.

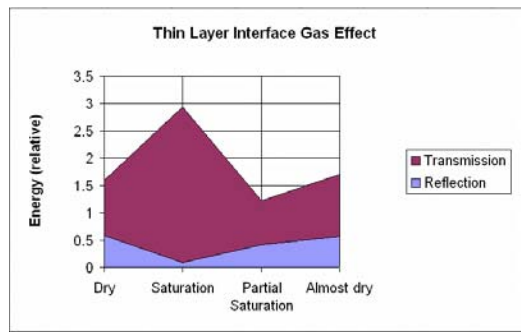


Figure 6: Reflection, transmission and total energy for a P wave across non-perfect interface for different saturation statuses.

Carcione presented a formula to associate the energy loss to 2 parameters characterizing the interface: specific stiffness and specific viscosity [Carcione, 1996]. Further study to associate the fluid saturation to these two parameters might open a door to better understand the energy loss mechanism in non-perfect interface.

Finally, we also notice a frequency shift to the high end. In Figure 7, we plot the Fourier Transform Spectra for both transmission and reflection wave. Since the frequency dependency is associated with the displacement discontinuity, it is suggested that the change of fluid saturation may change the displacement discontinuity across interface.

Next, we obtained the partial saturation in the interface as described in Experiment section. This time there was no obvious velocity change observed. The reflection amplitude increased and transmission amplitude decreased as expected.

However, when we plot the total energy of reflected and transmitted wave again in Figure 6, it appeared to be even lower than the level of dry. In velocity discontinuity model, apparently the dry interface should have the largest discontinuity and therefore causes largest energy loss. This suggests that in a partial saturated interface there may be extra energy absorption mechanisms, compared with dry and fully saturated cases. It can be caused by bubble resonances which absorb the wave energy and finally convert it to heat; Or it can be caused by some local fluid flow. It can also be slow P wave generated by Biot fluid-solid coupling. (Pyrak-Nolte, 1992).

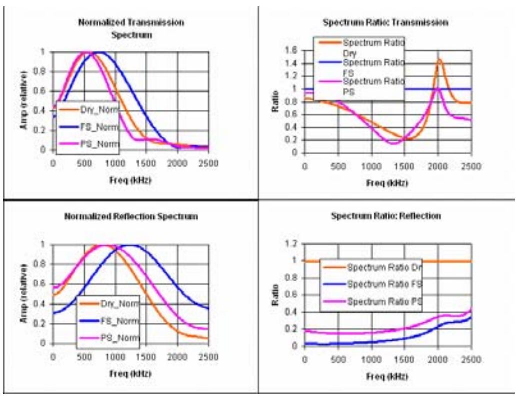


Figure 7: Normalized spectra for transmission and reflection P wave across non-perfect interface for different saturation statuses.

Similarly, the spectrum in Figure 7 shows that the transmission wave frequency was even lower than the dry case. It suggests that partially saturation has higher attenuation at high frequency waves.

In the last step, we recovered the system back to dry condition. Both transmission and reflection waveforms came back to match very well with the dry waveforms. This means the experiment is well repeatable without significant un-reversible variations.

Conclusion

Large energy loss along with frequency shift was observed for a compressional wave propagating across a partially saturated interface between two identical materials. Several possible causes, other than particle velocity discontinuity model, for this energy loss were suggested. Further investigations are needed to fully understand the mechanism for this phenomenon. The possible application for this phenomenon might include fracture detection from seismic data, and correction on AVO.

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EDITED REFERENCES

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