Measurement of Elastic Frame Properties on Weakly Consolidated Sandstone in Support of Fluid Substitution Studies

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Introduction

Fluid substitutions are an important concept in seismic attribute studies because they provide the interpreter with a valuable tool for modeling various scenarios that might explain an observed amplitude variation with offset (AVO) anomaly at seismic frequencies or can assist in interpreting time lapse seismic responses. The most commonly used approach is to employ Gassmann's (1951) formula relating the bulk modulus (K_{eff}) of a rock to its porosity, frame, and fluid properties:

$$K_{eff} = K_d + \frac{(1 - K_d / K_s)^2}{\frac{1 - K_d / K_d - \phi}{K_s} + \frac{\phi}{K_f}} \qquad (1)$$

where K_f is the bulk modulus of the saturating pore fluid; K_s is the bulk modulus of the solid mineral material; K_d is the bulk modulus of the rock's frame, and ϕ is the porosity. Gassmann further assumed μ_{eff} to be unchanged by fluid saturation and hence equal to the frame shear modulus μ_d. Unfortunately, there are few relevant studies on weakly consolidated materials.

The intrinsic values of K_s and K_f are usually relatively easy to find (e.g., Batzle and Wang, 1992; Bass, 1995; Theune and Schmitt, 2004). The greatest uncertainty limiting the successful application of Gassmann's equation is lack of knowledge of K_d and μ_d. Some consensus has arisen that these values can be estimated from P- and S-wave velocities measured on the "dry" (i.e., unsaturated) sample. If the dry density ρ_{frame}, P- and S-wave velocities are available we can determine the frame elastic properties of the sandstone according to

$$K_d = \rho_{frame}(V_p^2 - \frac{4}{3}V_s^2); \quad \mu_d = \rho_{frame}(V_s^2); \quad \lambda_d = K_d + \frac{2}{3}\mu_d \qquad (2)$$

Prior to applying Gassmann's equation, it is necessary to determine the bulk modulus of the porous rock frame. This is the low frequency, drained bulk modulus of the rock.

In this paper, we measured the P-wave and S-wave velocities on weakly consolidated sandstone under confining pressures up to 100 MPa. This sample is representative of many Cretaceous sands in Alberta; the sample was extracted from an outcrop on the bank of North Saskatchewan River in Edmonton. The results show a strong variation of the velocities with confining pressure complicated by a time-dependency. Here, we describe the experimental procedure, show a portion of our raw waveform acquired, and the values of the dry frame moduli determined.

Experimental results and procedure

P-wave and S-wave measurements were made on a machined cylinder of weakly consolidated sandstone (2.54 cm diameter X 3.00 cm length). This sample was dried in the vacuum oven for 24 hours at temperature of about 80°C then exposed to the room conditions for 2 days for the component quartz grains to absorb a small mount of moisture from the air (overly dry samples are not appropriately representative of the frame moduli). Ultrasonic transducers were mounted on each end of the cylinder. The current experiment unfortunately required that it be carried out separately for the P- and S-wave measurement. The sample was then hermetically sealed. The experimental setup is shown in Figure 1. The pressure was varied in four full cycles to see the effect of pressure on the seismic properties of the sandstone.

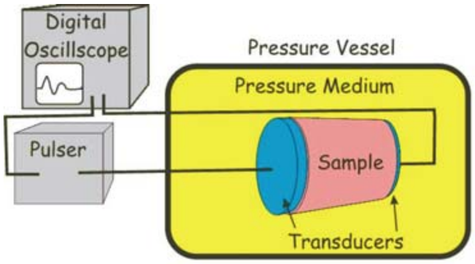


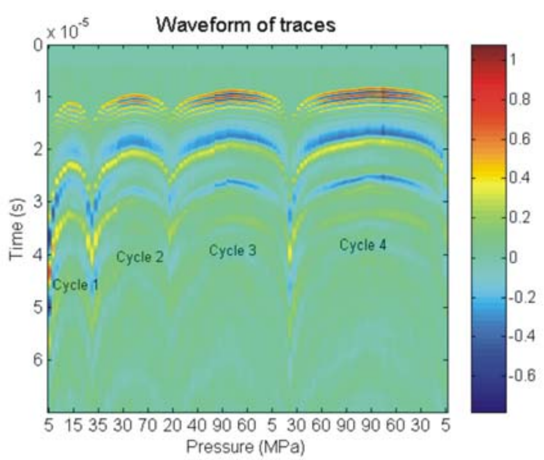
Figure 1: Cartoon of the experimental setup of the velocity measurement.

The full set of waveforms obtained is given in Figure 2. The frequencies used in this experiment are centered near 1MHz. Both sets of waveforms display a marked reduction of travel time with confining pressure, this is not unexpected as the velocities, and hence elastic moduli, of such material are known to be highly dependent on the effective stress. The velocity results (Figure 2 and 4) suggest that the sandstone structure is damaged during each cycle, because the velocity increases for each up-pressure cycle (hysterics). The P-wave velocity increases from 1600m/s to 3600m/s with confining pressure from atmospheric to 100 MPa. This is due to the high porosity of the weakly consolidated sandstone.

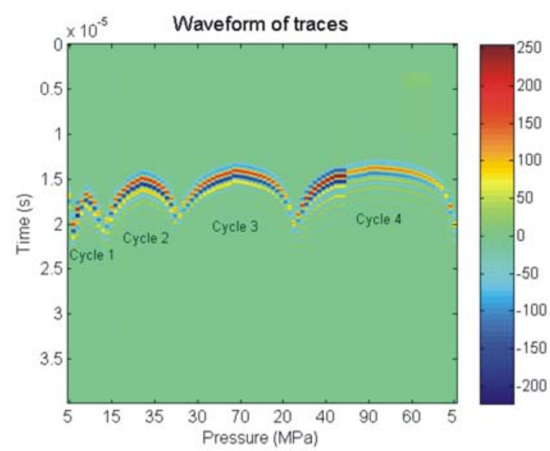
The S-wave transit measurement was taken after the P-wave measurement was finished. Therefore, the pore structure was already damaged before the S-wave measurement, this is possibly confirmed by the fact that the V_S at the same pressure for the four cycles are almost the same. However, the first few velocities after the pressure is released are not the same as that in the last cycle.

An added complication to these experiments is the significant time dependence to the velocity. This is highlighted in Figure 3 that shows how the observed velocity increases by 2.6% while the sample is subject to a constant confining pressure. Several hours may be required for the velocity to stabilize after the pressure is increased. The time for velocity stabilization is mainly affected by the pore structure, the clay content and the mineral contact. This effect cannot be ignored and it calls into question what value of the velocity (and consequently elastic moduli) is most representative of the in situ value. Most likely, this value should be taken after the velocity show little further change.

The drained frame moduli, as calculated from the observed velocities, are shown in figure 5. These also highlight the strong confining pressure dependence of the elastic moduli in such high porosity materials. It is interesting to note that these samples indicate that the ratio of K_d and μ_d range from 0.4 to 1.2. This contrasts with the oft-employed rule of thumb that $K_d / \mu_d = 1$ or the result of Murphy et al, (1993) on unconsolidated mineral grains that $K_d / \mu_d = 0.9$. In this particular sample this ratio depends strongly on confining pressure and even on the pressurization history.



(a)



(b)

Figure 2: Images of the (a) P-wave traces and (b) S-wave traces under cyclical loading at different confining pressures. The confining pressure is cycled four times from atmospheric to a peak pressure that progressively increases with each cycle

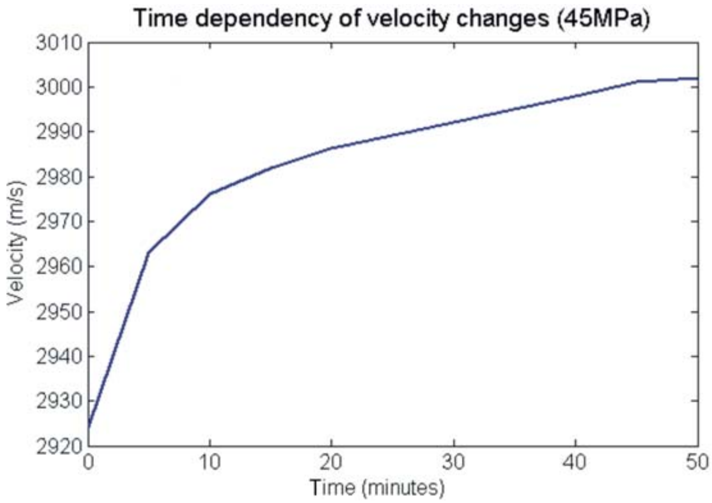


Figure 3: Change in observed V_P with time at constant confining pressure of 45 MPa

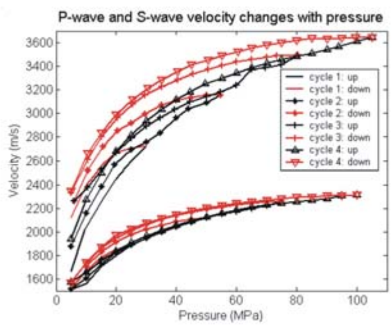


Figure 4: The P- and S-wave velocity changes with confining pressure. The P-wave is measured first, so the sandstone was compacted when the S-wave measurement is taken.

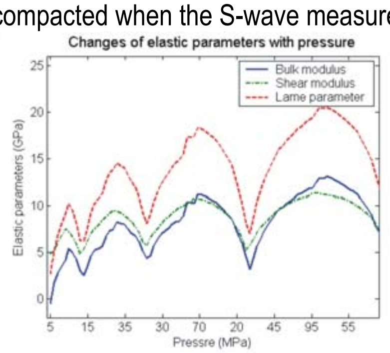


Figure 5: Changes of elastic parameters (K_d, μ_d and / λ_d) with confining pressure.

Discussion

Due to the poor coupling of the weakly consolidated rocks and the transducer, the experimental measurements are challenging. The elastic properties change considerably after the high pressure is released due to the high porosity, clay content, and weak structure of the sandstone sample. The experimental results show that the velocity is quite time-dependent. In order to get more precise results of frame moduli, the P-wave and S-wave measurement would be taken at the same time. Currently, both the P-wave and S-wave transducers are put on a cubic sample and then simultaneously measured under confining pressure. Future experiments will also include saturated samples.

Experimental results and procedure

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