Investigation of Frequency Dependent Velocities in Fluid-filled Porous Media

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1 Introduction

Permeability k is a very important parameter to investigate subsurface formations in groundwater and hydrocarbon exploration. Accurate k measurements give engineers, geologists and geophysicists a better understanding of the structure of the geological formations and its producibility. Currently there exist only a limited number of methods in determining k of formations. It has long been under research to obtain k measurements using seismic method, a cost-effective technique to study in-situ subsurface conditions without causing damage to the formation. Pride (2005) formulated the relationship between P-wave velocity (v_p) dispersion (or seismic attenuation, Q^{-1}) and k (or porosity, Φ) in poroelastic media with predicted dispersion and attenuation models as a function of frequency as shown in Figure 1.

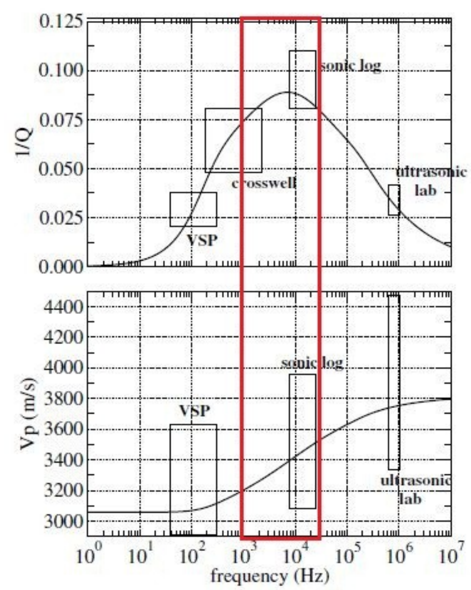


Figure 1: P-wave velocity dispersion model predicted (Pride, 2005). Red rectangular box indicates the frequency range, 1kHz – 30kHz, covered by this research project. Black rectangular boxes define the regions where measurements from Sams et al., 1997 are covered.

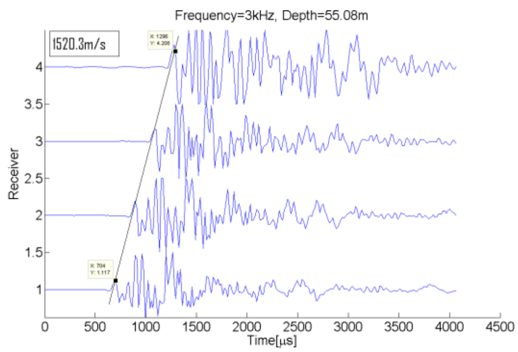
Pride (2005) showed that there is a potential to obtain k measurements from the slope of the attenuation model, which is linked to the dispersion model by the complex slowness. He stated that in the approach to peak attenuation, the slope of Q^{-1} as a function of frequency is inversely proportional to k. So far there exists no experimental data with a continuous frequency band large enough to evaluate his predicted dispersion and attenuation models. In this paper, an automatic, robust method to analyzing multichannel seismic data over the wide range of 1kHz and 30kHz is presented to show that v_p is dependent on frequency in porous media.

2 Methodology

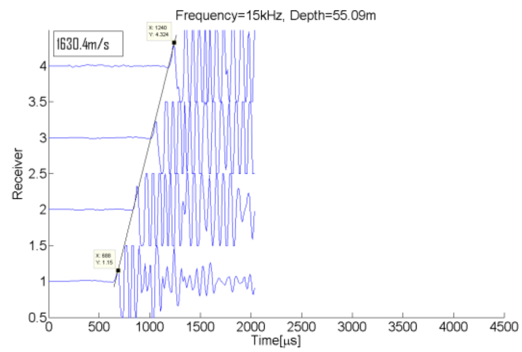
In this research, two sets of seismic data are available for analysis. The first set contains rerun sonic logs obtained from a piezo seismic source with different frequencies covering a range from 1kHz to 30kHz. The sonic probe used for this experiment contains 4 receivers. The source and first receiver spacing is 3 feet and receiver spacing is 1 foot. The second set contains logs taken with a broadband experimental borehole seismic source having the same bandwidth as the first data set. The sonic probe contains 8 receivers. The source and first receiver spacing is 9 feet and receiver spacing is 0.5 foot.

2.1 Manual Velocity Analysis

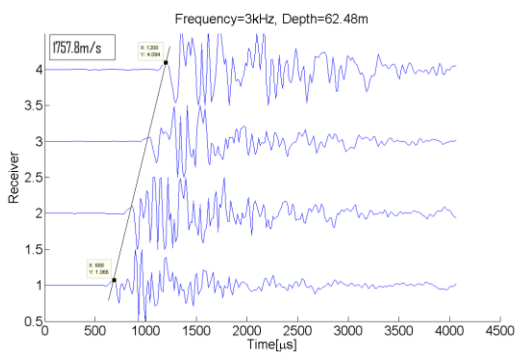
Preliminary analysis has been performed on the first data set with rerun logs. The logs with dominant frequencies of 3kHz and 15kHz are presented in this abstract. Figure 2 shows the waveforms recorded by the 4 channels at a depth of about 55.1m and 62.5m. The first breaks were picked manually to approximate v_p. From Figure 2a and 2b, it is shown that there is a variation in v_p of the two frequencies at the same depth.



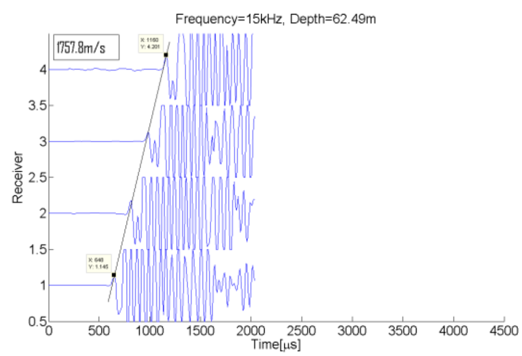
(a) 3kHz, 55.1m depth, 1520.3m/s



(b) 15kHz, 55.1m depth, 1630.4m/s



(c) 3kHz, 62.5m depth, 1757.8m/s



(d) 15kHz, 62.5m depth, 1757.8m/s

Figure 2: Approximated v_p from manual first-break picks for logs 3kHz and 15kHz at depths of 55.1m and 62.5m. At 55.1m depth, v_p are different for the two frequencies, whereas at 62.5m depth the two velocities match.

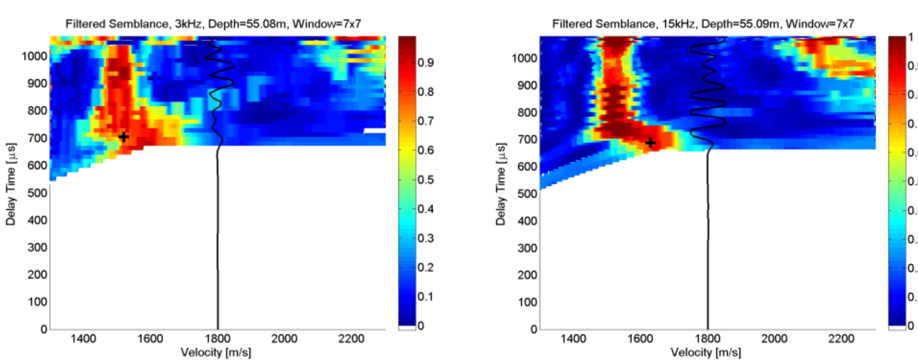
2.2 Semblance Analysis

Since the variation in v_p shown above is determined manually, not every user would agree on the velocity picks. Semblance, an unbiased, automatic and robust method to perform velocity analysis is computed with MATLAB. This technique is based on slant stacking of the multichannel data. It transforms the data from time-space domain (*t*–*x*) to delay time-slowness (or reciprocal velocity v^{-1}) plane (τ–p). τ is taken with respect to channel 1 for this analysis. The shift-and-stack (beamforming) process of semblance analysis increases the signal-to-noise ratio of the data and enables the coherent arrivals to be observed at different τ and *v* (Milkereit, 1987). Coherency values in semblance analysis $s(v,\tau)$ are computed from a non-linear weighting function (Taner et al., 1969) as shown below, where *i* is the channel number, *N* is the total number of channels, $f(v_i, t_i)$ is the value of the trace at time t_i with a given velocity v_i, and τ is the delay time with respect to the first channel. Values of $s(v,\tau)$ lie between 0 to 1, with a value of 0 indicating complete incoherency and a value of unity indicating identical amplitudes for all the traces with the specified *v* and τ (Milkereit, 1987).

$$s(v,\tau)=\frac{\left[\sum_{i=1}^{N} f(v_i,t_i)\right]^2}{N\sum_{i=1}^{N} f(v_i,t_i)^2}$$

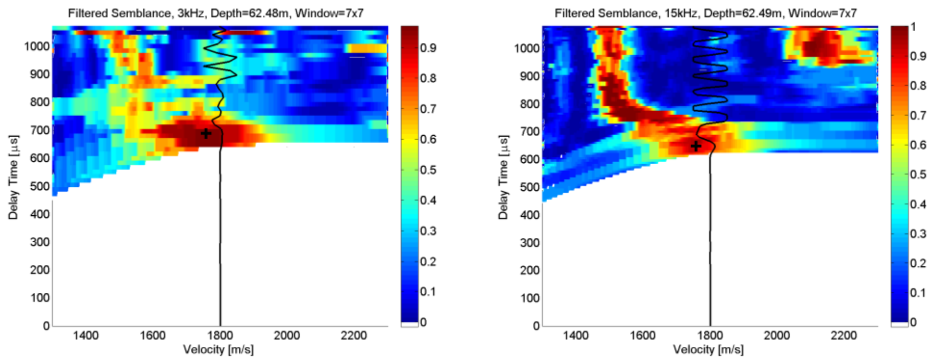
Semblance plots in Figure 3 show the coherency values corresponding to the traces in Figure 2. The values that result from weak signals are filtered out by setting a threshold to the denominator of the weighting function. When the denominator is -30dB of its maximum possible magnitude, the corresponding coherency values are set to be below zero. These values are displayed in Figure 3 in white. This procedure is performed to avoid misleading coherency to show in the plots due to noise. The plots are also smoothed out with a median filter of window size 7 grids by 7 grids to reject extreme noise and produce more focused features. From the semblance analysis, it can be seen that there is a difference in v_p between the two frequencies at 55.1m, whereas v_p at 62.5m are about the same. These agree with the observations from the manual velocity picks. Note that there is no velocity variation in S-wave and tube waves.

P-wave velocity dispersion between 3kHz and 15kHz is investigated by computing the cross correlation of the coherency values at 55.1m depth. Figure 4a shows that maximum correlation occurs at a lag of about 40m/s (15kHz with respect to 3kHz), which is about 2.7% of the reference velocity, taken to be the velocity of water of 1500m/s. This gradient is of the same range as that proposed by Pride (2005). Figure 4b displays the preliminary dispersion graph obtained from the semblance and cross correlation analyses with the two points defined at 3kHz and 15kHz.



(a) 3kHz, 55.1m depth

(b) 15kHz, 55.1m depth



(c) 3kHz, 62.5m depth (d) 15kHz, 62.5m depth

Figure 3: Semblance analysis. The plus sign “+” shows the manual velocity pick corresponding to the waveforms in Figure 2. Red and blue denote strong and weak coherency respectively. White regions contain coherency values of very weak signals. Black wiggle plot superimposed in each subfigure depicts the waveform recorded in channel 1.

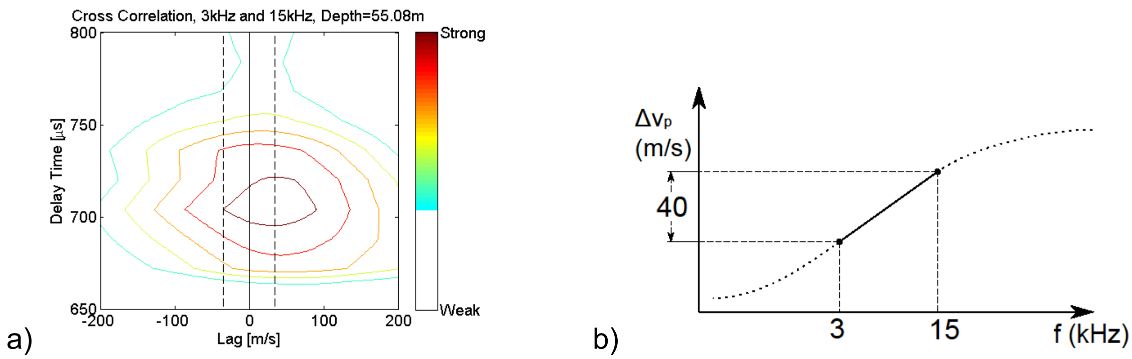


Figure 4: (a) Cross correlation of semblance plots in Figure 3a and 3b. Velocity lag of about 40m/s is observed. Weak correlations are shown in white. (b) P-wave velocity dispersion graph obtained from (a). Dotted line shows predicted trend by Pride (2005).

3 Conclusion and Outlook

A robust, automatic and unbiased processing sequence is developed to analyze weak P-wave velocities. P-wave velocity dispersion is observed in a data set with rerun logs from both manual velocity picks and automatic semblance and cross correlation analyses. However, since only 4 channels are available, signal quality is not greatly improved despite stacking. 8-channel data with broadband source ensures a continuous frequency band of the data. Velocity dispersion results from full logs will be correlated with porosity and permeability logs.

Acknowledgement

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