Direct measurement of frequency-dependent phase velocities from snowflake data

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Abstract

Carbon Capture and Storage (CCS) stands out as an effective technique for mitigating the CO2 footprint in the atmosphere. Ensuring the containment of sequestrated CO2 within geological storage is crucial, necessitating continuous monitoring. The research presented here leverages data from the Newell County facility, a shallow CO2 injection project actively promoting advancements in measurement, monitoring, and verification technologies related to CCS. The seismic method proves valuable for estimating frequency-dependent phase velocities of seismic waves. The concept of dispersion reveals that seismic waves of varying frequencies travel with distinct velocities, primarily due to non-uniform elastic properties in the subsurface, leading to frequency-dependent attenuation. As a preliminary step in estimating frequency-dependent seismic attenuation, this study aims to estimate the frequency-dependent phase velocities of the seismic waves as they propagate through the earth. The chosen method involves the analysis of uncorrelated vibroseis data, with a specific emphasis on the frequency dependence of seismic velocities.

Theory

In vibroseis seismic surveys, the lower frequencies as against the higher frequencies are sent first into the earth. However, Aki and Richards (2002) dispersion models of body waves predict that higher seismic frequencies propagate more quickly than lower seismic frequencies. In a dispersive medium, these high frequencies propagate with a higher phase velocity than the low frequencies in a bid to catch up with the lower frequencies (Innanen et al. 2014). Innanen et al. 2014 describe in detail the analysis and mathematical explanation of estimating dispersion from uncorrelated VSP data.

METHODS

Data set

A walkaway VSP is the seismic technique employed in the acquisition of the data used in this study. Hall et al. 2018 explicitly describe the acquisition geometry.

The departure time of seismic wave with frequency from the sweep

At the time, t=0 marks the beginning of the vibroseis sweep program. A typical mathematical representation of the sweep program is expressed as:

$$S(t) = \mathrm{Im}[\mathrm{a(t)e}^{i\emptyset(t)}] \tag{1}$$

The amplitude function, $\mathrm{a}(t)$ decreases as time moves away from the center of the function (exhibits a tapering effect during the early and late times) while the phase is defined as:

$$\emptyset(\mathrm{t}) = 2\pi \mathrm{f(t)t} \tag{2}$$

The equation shows that frequency is time-dependent, and that phase is a function of time-dependent frequency. The linear sweep can be mathematically represented as:

$$f(t) = fmin + \frac{(fmax - fmin)t}{T} \tag{4}$$

where $fmin$ and $fmax$ are the low and high-frequency limits respectively while T is the sweep length. The time, $T_s(f)$ at which the frequency f departs the vibroseis sweep is the inverse of $f(t)$.

$$T_s(f) = \frac{f - fmin}{fmax - fmin} T \tag{5}$$

The propagation time of a seismic wave of frequency f within the medium.

The time, $\Delta T(f)$ it takes the seismic signal at frequency f to travel from the source to the geophone depends on the path taken within the subsurface medium and the propagation velocity of the wave. We assume that the seismic waves travel in a straight line between the source and the receiver (straight ray path) in this study:

$$\Delta T(f)^2 = \frac{x_s^2 + z_g^2}{C(f)^2} \tag{6}$$

Time, $T_M(f)$ at which the seismic wave with frequency f arrives at the accelerometer after travelling through an assumed straight ray path of distance $L = (x_s^2 + z_g^2)^{1/2}$ is:

$$T_M(f) = T_s(f) + \frac{L}{C(f)} \tag{7}$$

The dispersive phase velocity, $C(f)$ of the seismic wave can thus be calculated by the relationship:

$$C(f) = \frac{L}{T_M(f) - T_s(f)} \tag{8}$$

where L is estimated from the assumption of a straight ray path between source location, x_s^2 and geophone depth, z_g^2.

Time-frequency decomposition of the vibroseis response

Gabor transform is a mathematical function transformation that yields a combined time-frequency representation of a given signal and a method to extract the signal from this time-frequency representation. The Gabor transform $G\,f(t,w)$ of a given signal $f(t)$ identifies the spectral strength energy present in the signal close to time t at frequency, w as a function of two variables.

$$G\,f(t,w) = \int_{-\infty}^{\infty} f(s)g(s-t)e^{-2\pi i s w}\,ds \qquad (9)$$

Calibration of phase velocity

The arrival and departure time picks were picked with high accuracy but were exposed to a constant error. To account for this error, calibration time, Tcal is introduced from the group velocity of the direct P wave from the near offset shot record.

$$C(f) = \frac{L}{T_M(f) - T_s(f) - \mathrm{T(cal)}} \qquad (10)$$

Results

The arrival and departure times were picked on the Gabor transformed uncorrelated seismic traces using the modified energy ratio (MER) code, an automatic picking approach for first arrivals written by Joe Wong. Wong et al. 2023 describe the MER code in detail. The arrival and departure times were picked with relatively high accuracy, but they were exposed to constant error. This error was accounted for by calibrating the estimated phase velocities in figure 1 with calibration time, Tcal. Tcal, was estimated from the group velocity of the direct P wave arrival.

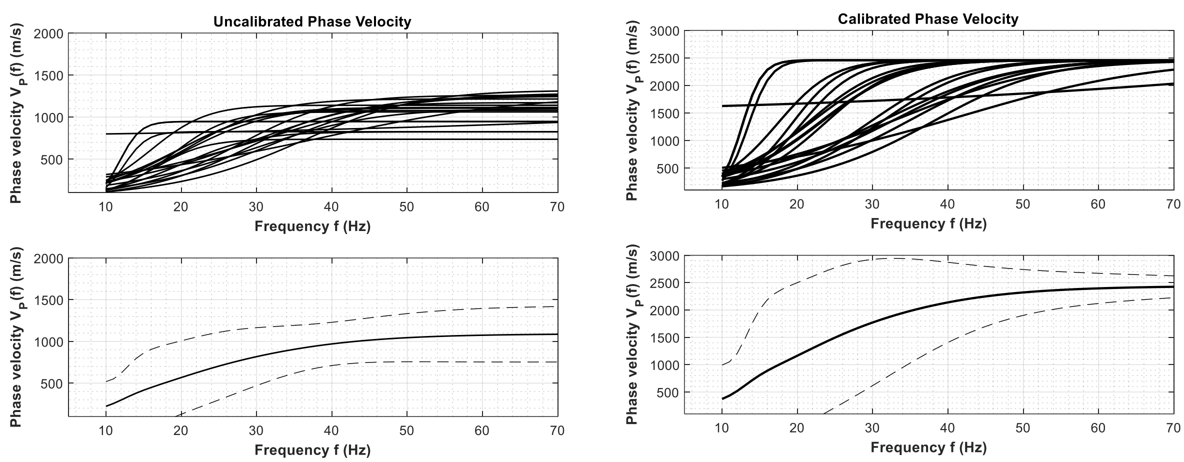

Figure 1: Calibration of the raw phase velocity to give the calibrated phase velocities.

This analysis was repeated for all the 12 shot lines at all the offsets and results of the study shows the variation of phase velocities with frequency and along VSP line azimuth.

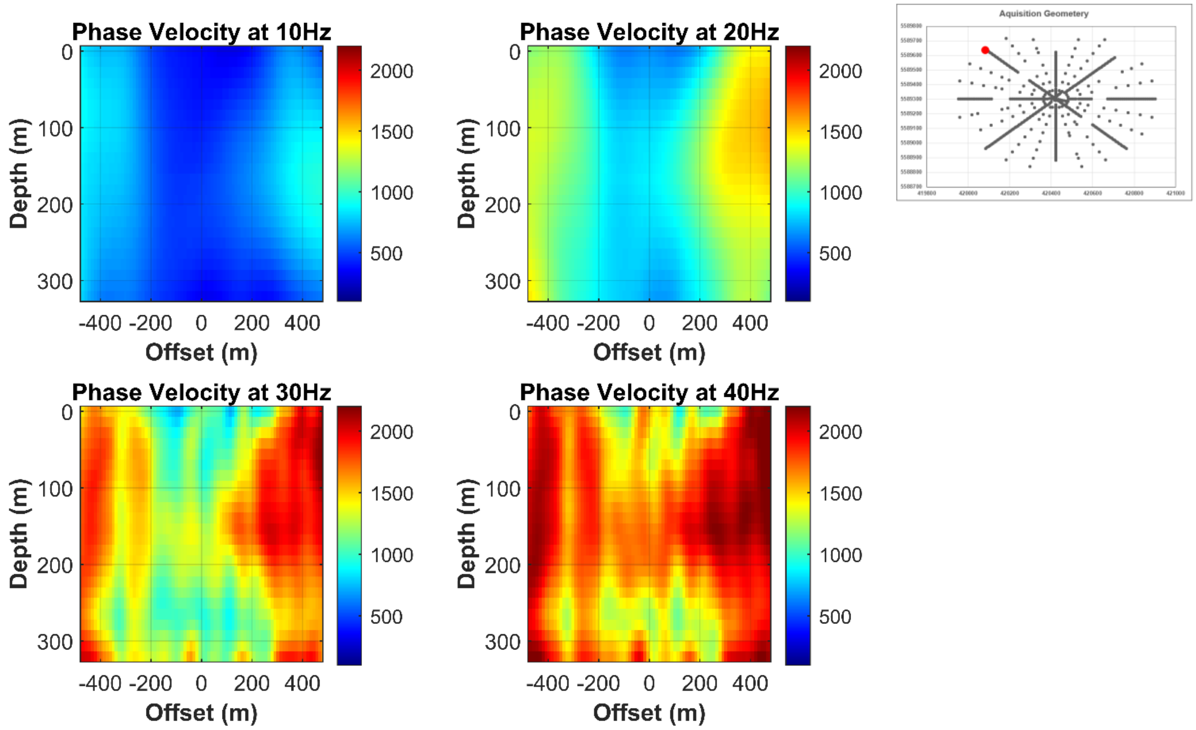

Figure 2: Frequency-dependent phase velocity along line 10

Analyzing the uncorrelated VSP dataset from the Newell County facility indeed improves the understanding of the complicated near surface. The fluctuations in the phase velocity along VSP line azimuth suggest a potential connection to spatial heterogeneity in attenuation/dispersion while the variations in phase velocity at different frequencies affirm its frequency dependence. Estimating the frequency-dependent phase velocities in the near-surface is the first step toward understanding the Q, and it could also serve as a starting model for FWI.

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