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Using Well Operation Noise To Estimate Shear Modulus Changes From Measured Tube Waves – A Feasibility Study

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Summary

Geophysical monitoring techniques are commonly used to image the subsurface and potential changes. These monitoring techniques are important for CO2 storage projects to ensure a safe operation. A detailed image of the subsurface can be achieved from borehole seismic where mostly transmitted and reflected waves are investigated. However, these measurements are time consuming and costly as receivers and sources need to be moved within the well during the acquisition. We investigate the monitoring potential of tube waves, which propagate along the interface between the well and geological formation. An experiment is conducted where the signal from a rotating metal pipe in a borehole is recorded in a nearby observation well. The tube wave velocity can be measured with a high precision, around ± 1.2 m/s, during the experiment, which is an important measure to evaluate the potential of the method. Therefore, it might be possible to use noise sources like CO2 injection phases to monitor changes of the formation surrounding the well. This would reduce the time and cost needed for borehole seismic as only receivers at a constant position are required. Further field test are needed to investigate the feasibility at larger scales and for real injection cases.

Introduction

Monitoring injection and storage of CO_2 in the subsurface is important to keep track of the migration path and ensure a safe operation. This surveillance is commonly performed with geophysical methods and satellite measurements (Korre et al., 2011) - in particular, borehole seismic can construct a detailed image of the changes in the subsurface, as the acquisition system is close to the reservoir. For CO_2 injection, measured changes for P- and S-wave velocities are presented by several authors for both cross well and single well measurements, e.g. Gritto et al. (2004).

In active seismic borehole measurements, P- and S-wave velocities are often determined by the travel time between source and receiver. In addition, tube waves are generated at interfaces striking the well, e.g. the well head, fractures or geometry changes within the borehole (Peng et al., 1996), and propagate along the interface between borehole and formation. The high-amplitude tube waves are mostly considered as noise as they can mask later arrivals from reflections. However, the tube wave velocity is related to the shear modulus of the formation surrounding the well (White, 1965).

The calculation of the shear modulus from the tube wave is a demanding task, as the tube wave velocity V_t also depends on several other parameters like borehole geometry, casing properties and borehole fluid. Nevertheless, for specific settings it could be possible to monitor changes in the geological formation from active or passive tube wave measurements as discussed by Borges et al. (2018). If we can make use of the tube wave, the cost and time for borehole measurements is reduced: no source is needed, only hydrophones or fiber cables to record data.

We conduct an experiment to further investigate the potential of passive recordings. While an experiment with an up- and downward rotating metal pipe is performed in a 95 m deep well, we record the signals in a nearby, 30 m deep, observation well with a hydrophone array. As the rotating metal pipe is no controlled source the seismic recordings are considered as passive. Similar sources at CO_2 storage sites could be the injection phase or micro seismic events.

Experiments

Several authors discuss the theory of the coupling between the tube wave and the shear modulus of the surrounding formation (Schoenberg et al., 1981; Norris, 1990). For a more detailed description of how the shear modulus and S-wave velocity could be estimated from the measured tube wave velocity the reader is referred to Norris (1990).

The experimental set up is illustrated in Figure 1. A 24-channel hydrophone array records signals with time sampling of 0.25 ms for 320 s, and the drill string is active for 76 s during the measurements. The drill string rotates in vertical direction with approximately 300 rpm and a displacement of a few millimeters at the top. During the operation it is expected that the drill string hits the casing at different depth locations. The average spectrogram for all hydrophones (with a 4 s window) is shown in Figure 1, together with mean f-k plots for the noise and active string recordings.

Results

We notice that amplitudes above 65 Hz are increased by 10 - 25 dB when the drill string is active (Figure 1, Top Right). Noise recordings have a strong event at 50 Hz, a weak V-shape event below 200 Hz and a vertical event at zero wavenumbers (Figure 1, Bottom Right). The vertical event corresponds to waves arriving at all receivers at the same time, probably due to noise sources from far distances. The V-shape event is the tube wave, the focus of this study. The f-k plot while the drill string is active indicates a tube wave that is much stronger than in the noise measurements. In addition, the upgoing tube wave (negative wavenumbers) is stronger than the downgoing wave.

The tube wave velocity is estimated by two methods: by fitting a line in the f-k domain and by applying a Radon transform in the f-k domain. The Radon transform $R(x', \theta)$ of a two-dimensional function $F(x, y)$

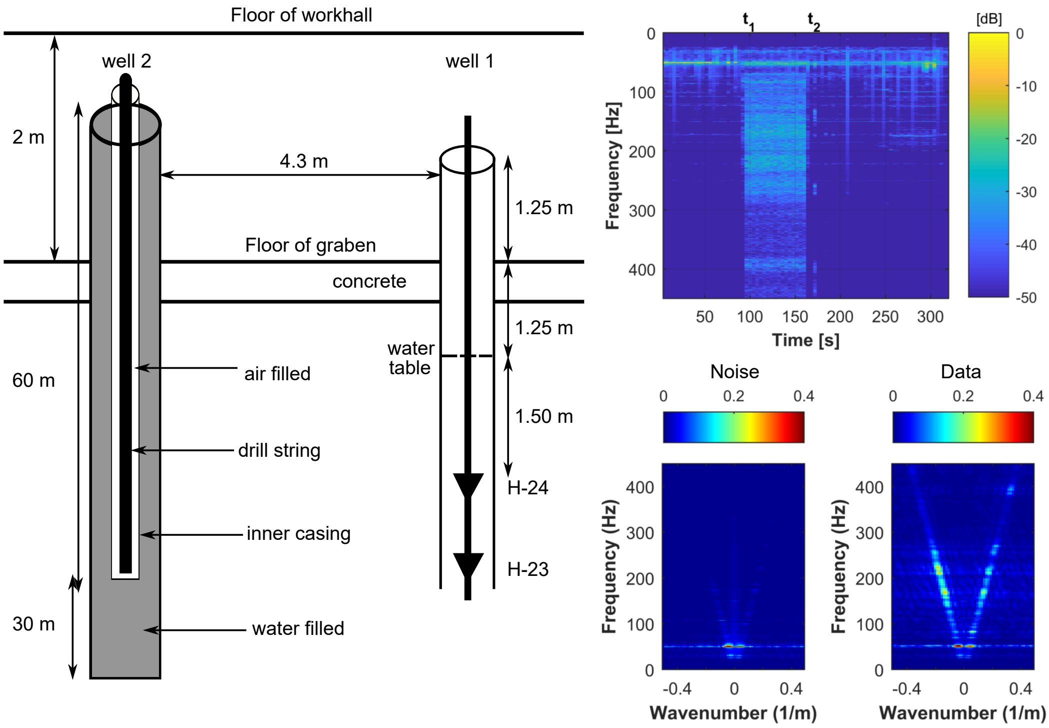


Figure 1 ***Left*** *Experimental setup with the observation well 1 (30 m deep) and well 2 (95 m deep), where the drill string is operating. Dimensions are not in scale.* ***Top Right*** *Mean spectrogram of all hydrophones in the observation well. The times t_1 and t_2 indicate the interval when the drill string is active.* ***Bottom Right*** *Frequency-wavenumber (f-k) plot of noise recordings, outside t_1 and t_2, and when drill string is active. A 40 Hz high-pass filter is applied to all the data.*

is the projection of F on an axis x', which is rotated in an angle θ around the x axis. In the f-k domain, the Radon transform highlights the angle that gives the maximum projection when going through the origin. As in the line fit method, the tangent of the angle gives the velocity of a linear event. To avoid noise and aliasing, we first bandpass the data (50 - 450 Hz) and apply a fan-filter to remove velocities below 300 m/s and above 6000 m/s. Figure 2 shows a f-k transform panel, before and after pre-processing, and the resulting line fit and Radon transform.

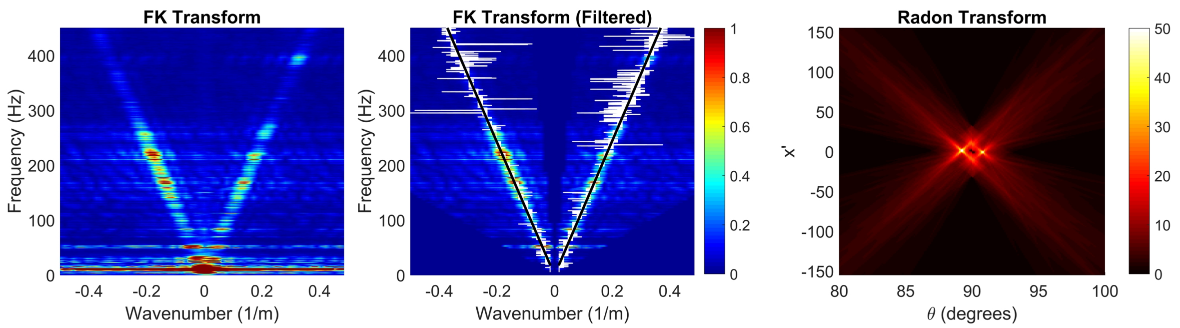
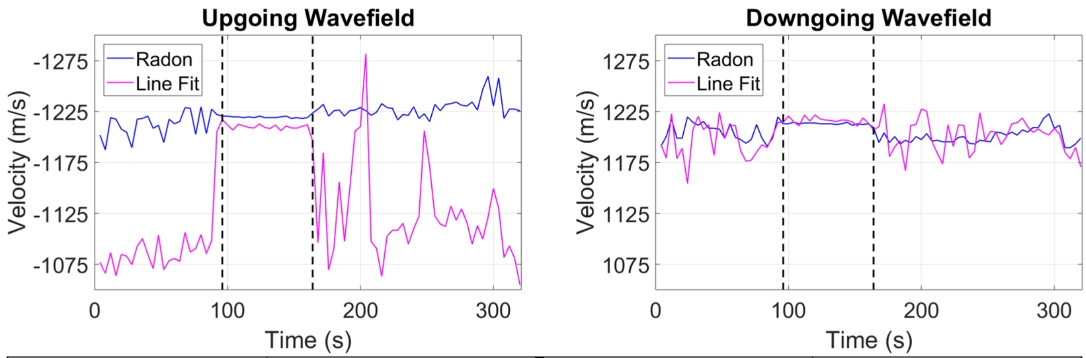


Figure 2 ***Left*** *Frequency-wavenumber plot of a 4 s recording.* ***Center*** *Same plot as left, but bandpass-filtered (50-450 Hz) and fan-filtered. Black lines are the least-square fits of amplitude maxima (in white).* ***Right*** *Radon transform, showing two bright spots. Each spot is a linear event in the f-k plot.*

The velocity estimation is then performed for the up- and downgoing waves (Figure 3). The results for both modes show consistency, with more precise results (up to 1.2 m/s) being achieved using the Radon transform. The accuracy of the results could potentially be improved with longer recording intervals.

The different results from line fit and Radon transform can be explained by the criteria used to calculate the velocity: while the Radon aims at picking the value of maximum amplitude of a line integral, the line fit is a least-square optimization. Sharp peaks in the f-k domain can influence the line fit, making the result oscillate more, especially for low signal-to-noise ratios, as seen in Figure 2 (center, white line).



Noise (Up)	Drill (Up)	Noise (Down)	Drill (Down)
1222 ± 13 m/s	1219 ± 1.3 m/s	1203 ± 8.3 m/s	1213 ± 1.2 m/s
1110 ± 43 m/s	1209 ± 4.2 m/s	1200 ± 17 m/s	1216 ± 3.8 m/s

Figure 3 Top *Estimated tube wave velocity V_t for the upgoing (left) and downgoing (right) tube waves. Blue line is the Radon result, and magenta line is the least-square fit.* ***Bottom*** *Table with averages and standard deviations for each method and wave mode.*

Discussion

In previous experiments, both with and without an active source on the surface, the downgoing tube wave was always stronger than the upgoing wave. In this experiment the upgoing wavefield is stronger, as can be seen in Figures 1 and 2. One might intuitively expect this because of the source (drill string) in the bottom of the deep well. However, the acquisition is conducted in a situation of a "slow" formation (Schoenberg et al., 1981), in which the formation shear velocity is lower than the fluid velocity inside the deep well 2. This causes most of the energy to be trapped inside the borehole, and the only energy that propagates outward will be confined in a Mach cone (Meredith et al., 1993).

Previous estimations of shear wave velocities β in this area are 450 - 500 m/s, and the measured tube wave velocity V_t in well 2 from earlier tests is about 1145 m/s. It should be noted that the tube wave velocity in this well has probably changed compared to earlier measurements as different equipment is deployed inside the well. As an example, these values gives a Mach number of $M = V_t/\beta = 2.41$ and a Mach angle $\varphi = \sin^{-1}(1/M) \approx 22.5°$. As shown in Figure 4 (left), this angle makes the energy of the deep source reach the shallow well at its bottom, before the tube wave reaches the surface.

If the energy source of the upgoing wave is the Mach cone, it should appear as a linear moveout event in the data, with the tube wave velocity of well 2. Since the tube wave velocities of both wells are within a close range, the difference would not be detected in our test. Direct modelling of data including tube waves and Mach waves with velocities of 1220 m/s and 1145 m/s respectively and SNR compatible with our experiments show that our method would identify an intermediate velocity (Figure 4, right). Hence, the existence of the Mach wave could explain the small deviation in the estimated velocity between the up- and downgoing wave (Figure 3). For settings where the tube wave velocity in two neighbouring wells has a larger difference, modelling shows that both waves types could be investigated separately.

Therefore, the tube wave monitoring might be used in different ways to estimate changes caused by injected CO_2. The receivers can be installed directly in the injection well, and noise from operations could be used to monitor changes of the formation shear modulus. Furthermore, monitoring wells can be equipped with receivers and the emitted Mach wave from the injection well might be recorded at these wells. Hence, the monitoring wells would track changes in their own vicinity and around the injection well when the conditions to generate Mach waves are given (formation S-wave slower than tube wave).

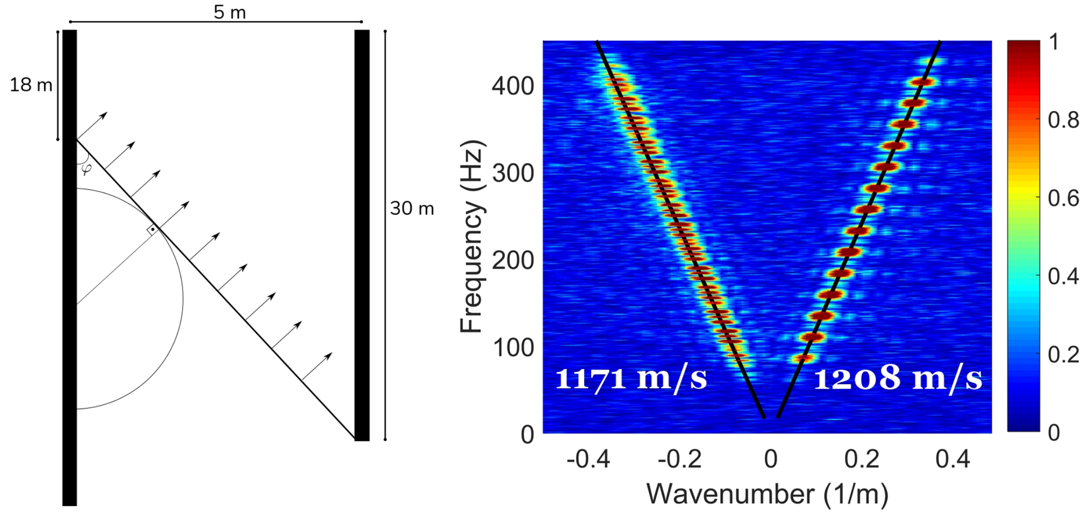


Figure 4 Left *Sketch showing the Mach cone from the deeper well ($\varphi \approx 22.5°$). Adapted from Meredith et al. (1993). Distances are not in scale.* ***Right*** *FK transform of modelled data, with best line fits in black. Estimated velocities (white) are intermediate values between Mach wave and tube wave velocities.*

Conclusions

The tube wave velocity is estimated with a high accuracy in the performed experiment and hence the tube wave monitoring technique might be used as a low-cost, simple to install technique where only receivers are needed, and the background noise, e.g. injection processes, could be used as sources. For CO_2 injection the method could be applicable for specific geological settings and field sites, especially where the initial shear modulus of the formation is low. The feasibility needs to be further investigated for larger field examples. For a characterization of the shear modulus of the reservoir the tube wave is not suitable as it depends on several other parameters, as borehole geometry and casing.

Acknowledgements

We acknowledge the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 641943 for funding Daniel Wehner's PhD project within WAVES, and Petrobras for funding Filipe Borges's PhD. Martin Landrø acknowledges financial support from the Norwegian Research Council.

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