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On the potential of multi-component vertical seismic profiling to monitor CO₂ storage

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Summary

We simulate wavefield within a VSP survey geometry for a simple geological model containing a fluid-filled cased or uncased borehole, subjected to a vertical incident P wave of two different central frequencies. We interpret the hydrophone, radial displacement and vertical strain along the borehole. We demonstrate that multicomponent measurements can detect and differentiate small changes (e.g. CO₂ saturation) and defects (cement degradation) along wells by jointly interpreting acoustic waves within the borehole (i.e., tube waves) together with elastic waves along cased wells. Therefore, we recommend using geophone or DOFS data together with hydrophone data to interrogate well integrity.

On the potential of multi-component vertical seismic profiling to monitor CO₂ storage

Introduction

Seismic data are essential for the safe development and operation of CO₂ storage projects, particularly when it comes to baseline characterization and injection monitoring. In the offshore environment, most seismic data are acquired via a surface-to-surface configuration, e.g., towed sources and streamers (Furre et al., 2017), where sensing occurs far from the target of interest (e.g., a CO₂ plume or an injection well). On the other hand, downhole sensors can be placed physically closer to these targets to provide a more direct measurement. A limited amount of data is often the shortcoming of downhole sensing, because it is costly to install many densely-spaced sensors in a well. Recently, distributed optical fibre sensing (DOFS) has become an attractive technique for downhole measurements, especially for onshore CO₂ storage projects (Hopkins et al., 2021), because it overcomes these shortcomings. The biggest advantage of DOFS is the ability to measure data almost continuously in time and space, as long as the fibre optic cables are installed in the right location. We expect that soon these same advantages will manifest in the offshore environment as well.

Minato et al. (2021) studied the physical mechanisms of the so-called tube wave generated along a fluid-filled borehole, and they developed a new finite-difference modelling approach to efficiently synthesize vertical seismic profile (VSP) data, exploring mostly the acoustic waves within a borehole (hydrophone response). In this study, we use a more general numerical approach, i.e. finite element modelling (FEM) via *COMSOL Multiphysics*TM, to investigate the potential use of VSP data to CO₂ storage monitoring. We explore not only the acoustic response but also the elastic response in terms of displacement and strain (i.e., mechanical deformation) which can be acquired via DOFS methods such as distributed acoustic sensing (DAS) and distributed strain sensing (DSS). We consider the consequences of CO₂ saturation changes and cased-well integrity (e.g., cement degradation) in the CO₂ reservoir layer onto different components of VSP data. Namely, we extend the simple geological model (consisting of two infinite half spaces) in Minato et al. (2021) to include a cased-well (1-cm steel casing and 2-cm cement) and a 5-m thick CO₂ plume layer (**Figure 1**). We simulate the acoustic and elastic responses within the borehole and behind the steel casing, respectively, to a vertically incident *P*-wave. The geometry and wave propagation in the current study are fully axisymmetric, and the synthetic data represent all components of such a wavefield. In addition, we discuss the sensitivity of each wavefield component in the context of the target of interest, i.e., CO₂ saturation changes and cased-well integrity. We note that this modelling approach is similar to Minato et al. (2021); however, more general incident waves (e.g., inclined *P*-waves or *S*-waves, etc.) are possible within the FEM framework developed in this study. These additional incident wave scenarios will be investigated in the near future in a reservoir scenario similar to that presented here.

Numerical simulation results

Using the simple three-layer geological model shown in **Figure 1** and inspired in the configuration presented by Minato et al. (2021), we simulate both the acoustic and elastic wave response due to a vertically incident wave propagating parallel to the borehole axis. The *P*-wave source is a Ricker wavelet with either 200 or 600 Hz central frequency. 200 Hz is typical for hammer source, and 600 Hz is used just to show a higher frequency example. Both transmitted and reflected *P*- and tube waves are further analysed. The optical fibre is modelled behind the casing and the hydrophone responses are modelled in the cased-well. We consider four different simulation scenarios:

- Model 1: "not-cased, without CO₂"
- Model 2: "cased, without CO₂"
- Model 3: "cased, with CO₂"
- Model 4: "case-degraded, with CO₂"

The cement in Model 4 is degraded only in the interval of the 5-m thick CO₂ plume layer and represents a 50% reduction in both *P*- and *S*-wave velocities, without change in density.

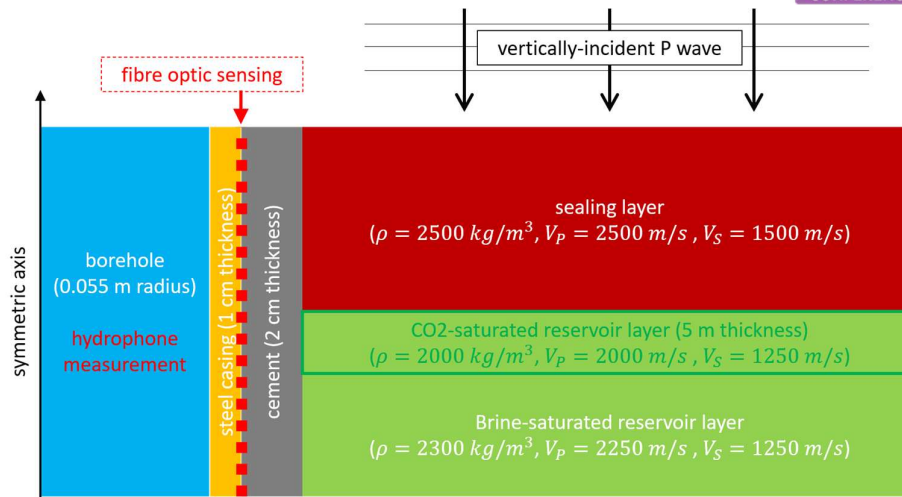


Figure 1. Simple three-layer geological model inspired by Minato et al. (2021). The model is extended to include a cased-well with cement and a CO₂-saturated layer of 5-m thickness. Dimensions not to scale.

Figure 2 presents the results from Models 1, 2, and 3 using the 200 Hz Ricker wavelet. Each column represents a different component of the wavefield response: hydrophone, radial displacement, and vertical strain. The x - and y -axis in each plot is, respectively, time in seconds and z -coordinate (depth) in meters (plotted only from -20 m to +20 m), where 0 m depth is the top of the CO₂ saturated reservoir layer. The colours represent the wavefield component amplitude with white being zero amplitude. The black dashed horizontal line in each plot denotes the interface between the sealing and reservoir layers. The other four dashed inclined lines denote, respectively, the reflected P -wave (blue), the reflected tube wave (red), the transmitted P -wave (yellow) and the transmitted tube wave (green) but only for Model 1, showing how all wave components vary for different models. Comparison of Model 1 and 2 results show that the polarities of hydrophone and radial displacement are opposite between the two models, while the vertical strain is nearly identical for the two models. The phase velocities of the reflected and transmitted tube waves (red and green dashed lines, respectively) at the interface between the seal (upper) and reservoir (lower) formations is (slightly) faster in the cased-well than in the not-cased-well. Furthermore, the tube wave in the radial displacement becomes rather weak in the cased-well, while the pressure response is still noticeable. The results of Model 3 indicate that all three components of hydrophone, radial displacement and vertical strain clearly respond to the 5-m thick CO₂ plume layer (**Figure 2c**). Namely, the phase velocity of the incident P -wave within the 5-m thick CO₂ plume layer slightly decreases, particularly visible in the radial displacement data where an increase in amplitude is also observed. In addition, reflections occur not only at the top of the reservoir, but also at the bottom of the CO₂ plume layer. As expected, the phase velocity of the tube wave reflected at the first interface (i.e., top of reservoir) does not change. However, the amplitude becomes much larger, particularly in the hydrophone response.

Figure 3 compares the simulated responses 10 m above the reservoir (i.e. $z = 10$ m) for the two different frequency Ricker wavelet sources: 200 Hz (a) and 600 Hz (b). We increase the frequency to 600 Hz because the 200 Hz does not indicate a difference between models 3 and 4 (i.e., between competent and degraded cement in 5-m thick CO₂ plume layer). Using the 600 Hz source, the degraded cement in the interval of the 5-m thick CO₂ plume layer (Model 4) shows a clear amplitude increase, but no change in the wave arrival time even though the degraded cement has a 50 % velocity reduction. More importantly, the distinction shows up only in the hydrophone but not in the radial displacement and vertical strain. This implies that VSP data consisting of displacement or strain may not detect the 5-m thick degraded cement interval. Nevertheless, it demonstrates that multi-component measurements (particularly the hydrophone) are desired to detect and/or differentiate any small change or defect in the cased well.

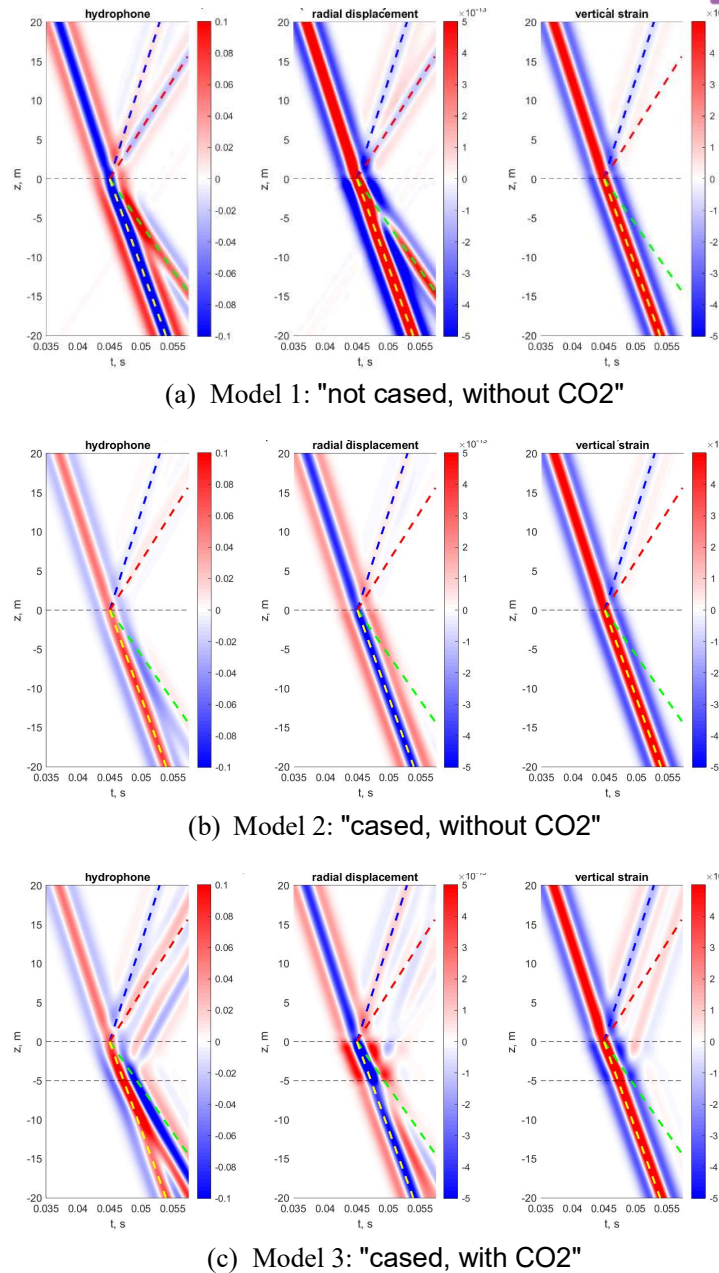


Figure 2. Simulation results for three different scenarios. The three columns are results along the well in terms of hydrophone, radial displacement and vertical strain, respectively. Note: black dashed horizontal lines denote the interface between the sealing and reservoir layers; four dashed inclined lines, respectively, reflected P-wave (blue), reflected tube wave (red), transmitted P-wave (yellow) and transmitted tube wave (green) but only for Model 1.

Conclusions

We simulate wavefield within a VSP survey geometry for a simple geological model containing a fluid-filled cased or uncased borehole, subjected to a vertical incident P-wave of two different central frequencies. We interpret the hydrophone, radial displacement and vertical strain along the borehole. We demonstrate that multicomponent measurements can reveal more information in the VSP survey geometry compared to single component measurements. For example, we can detect and differentiate small changes and defects along wells by jointly interpreting acoustic waves within the borehole (i.e., tube waves) together with elastic waves along cased wells. Therefore, we recommend using geophone or DOFS data together with hydrophone data to interrogate well integrity. Finally, we suggest that one

should also consider a fit-for-purpose seismic source configuration to optimally obtain the information needed for accurate CO₂ monitoring. The vertical incident *P*-wave in the current study is supposed to generate mainly so-called breathing mode. Other incident waves such as *S*-wave and inclined *P*-wave may generate different waveforms, which can also be useful for characterization and monitoring along wells.

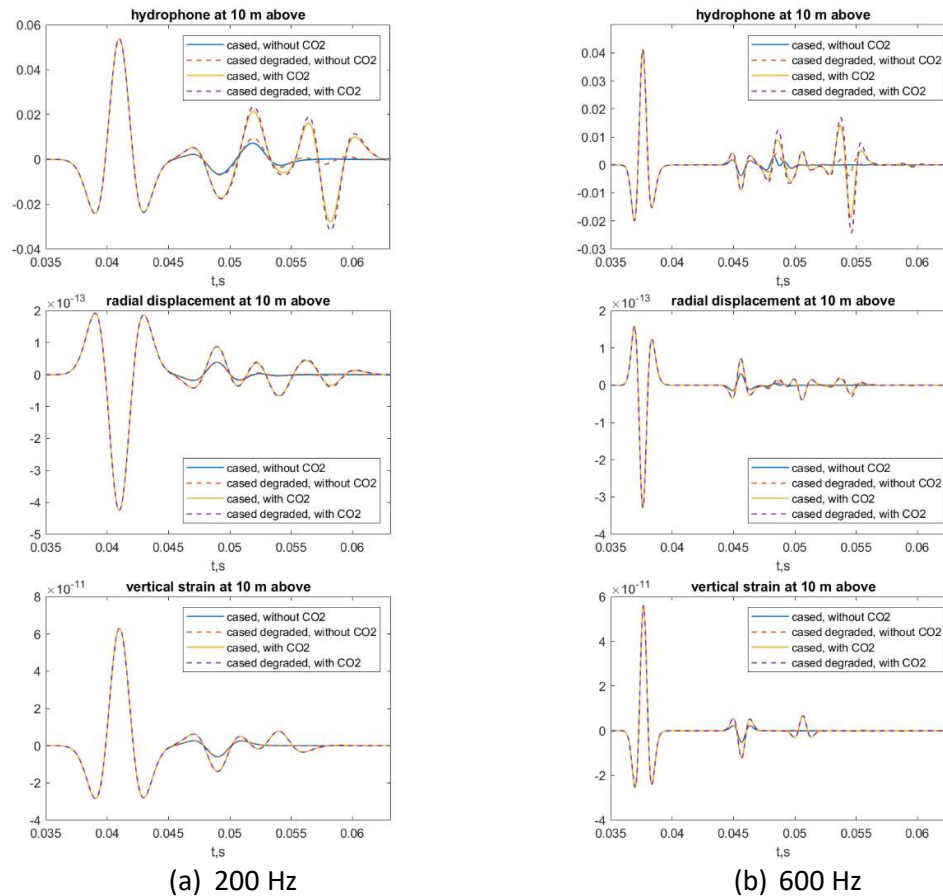


Figure 3. Simulation results at $z=10$ m for (a) 200 Hz and (b) 600 Hz Ricker source wavelets. The three rows are the hydrophone, radial displacement and vertical strain, respectively.

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