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# Time-lapse numerical modeling of the Quest carbon capture and storage (CCS) project: Poroelastic approach

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## Summary

A finite-difference algorithm was developed based on the Biot's equations of motion for modelling wave propagation in poroelastic media. In contrast with the elastic modelling, in the poroelastic approach the properties of the pore fluid are taken into account in the algorithm. Poroelastic modelling could be useful in cases where the fluid content of the rock is of interest, i.e. Carbon Capture and Storage (CCS) projects. We examined our program using a model based on the Quest CCS project in Alberta to investigate the detectability of $CO_2$ after one year of injection. This was done by defining two models for the baseline and monitor scenarios that represented the subsurface before and after injecting $CO_2$, respectively. The difference between the calculated seismic sections for the two scenarios shows that the residual amplitude is comparable with the signal amplitude. With this result, the injected $CO_2$ in the Quest project over a year could be detected providing the data have good bandwidth and a high signal-to-noise ratio. Furthermore, a comparison between the poroelastic algorithm and the elastic algorithm shows that the time-lapse effect in the poroelastic case is smaller than the one in the elastic case. In the fluid saturated media some of the wave energy dissipates due to the traveling wave in the fluid and the poroelastic approach helps us to take this loss into account in the modeling process.

## Introduction

Wave propagation in porous media has attracted attention in the last fifty years since Maurice Biot established his theory on poroelasticity (Biot, 1962). Biot's theory could be used in the oil and gas industry for exploration and monitoring purposes. It could also be used for the detection of $CO_2$ in Carbon Capture and Storage (CCS) projects where $CO_2$ is injected into deep geological formations for permanent storage. A poroelastic medium is composed of two phases. One phase is the porous elastic solid frame, and the other is the compressible viscous pore fluid that can move within the pore space. The relative movement of the fluid with respect to the solid generates a "slow P-wave" that travels with a velocity close to the wave velocity in the fluid. The wave-induced fluid flow leads to energy dissipation in the medium that is often neglected in elastic modelling algorithms. At seismic frequencies the viscosity effects become stronger than the internal effects, and therefore the slow P-wave diffuses in the medium. However, if the viscosity is zero, the slow P-wave is a travelling wave at all ranges of frequency (Carcione et al., 2010).

There have been extensive numerical examination studies of Biot's theory since the fluid content of the rock is always of interest in reservoir characterization and monitoring. Carcione et al. (2010) presented a comprehensive review on the numerical methods used for poroelastic media. For example, Sheen et al. (2006) used a staggered-grid velocity-stress finite-difference for a gas-water interface and Dai et al. (1995) employed a MacCormack finite-difference scheme for simulating the wave motion in poroelastic media. In this work we use a finite difference algorithm similar to that of Sheen et al. (2006) to perform a poroelastic time-lapse modelling study for a carbon capture and storage (CCS) project in Alberta.

## Quest project

The numerical models used in this study are based on the Quest CCS project in Alberta. The purpose of the Quest project is to reduce the $CO_2$ emissions from Scotford Upgrader in Fort Saskatchewan by capturing the $CO_2$ and storing it into the Basal Cambrian Sandstone (BCS) which is a deep saline aquifer within the Western Canadian Sedimentary Basin (WCSB) (Shell, 2010). In an earlier study (Moradi and Lawton, 2012), the in-situ properties of the BCS were extracted from the available well data. These properties are listed in Table 1 as $BCS_1$. In addition, using Gassmann's fluid substitution (Gassmann, 1951), 40% of the in-situ brine was substituted by $CO_2$, and the properties of the new saturated rock were calculated. These properties which are listed in Table 1 as $BCS_2$, are essential for the time-lapse study as they represent the properties of the BCS after injecting $CO_2$.

Table. 1. Physical properties of the BCS

| Property | $BCS_1$ | $BCS_2$ |
|---|---|---|
| $\rho_f$ | 1070 $(kg/m^3)$ | 937 $(kg/m^3)$ |
| $\rho$ | 2400 $(kg/m^3)$ | 2370 $(kg/m^3)$ |
| $V_p$ | 4100 $(m/s)$ | 3800 $(m/s)$ |
| $V_s$ | 2390 $(m/s)$ | 2400 $(m/s)$ |
| $\phi$ | 16% | 16% |
| $\eta$ | 0 | 0 |

## Finite difference poroelastic algorithm

In order to simulate wave propagation in the poroelastic media, partial differential equations in poroelastic media (Sheen et al., 2006) are discretized for the 2D case using a velocity-stress staggered-grid finite-difference approximation. In addition, the perfectly matched layer (PML) method (Berenger, 1994) is employed as the boundary condition to absorb the outgoing waves at the edges of the computational grid. Figure 1a shows the generated snapshot of the solid particle velocity using the poroelastic algorithm. The model consists of two layers based on table 1: $BCS_1$, on the top, and $BCS_2$ at the base. These layers are in fact two sandstones with the same solid properties but different fluid content. The change in the fluid content of the rock leads to a change in the seismic response of the model. As expected from the Biot's theory, a slow P-wave ($P_s$) is generated due to the fluid movement. There are also some wave conversions at the boundary. For example: slow P-wave converted to a fast P-wav ($P_sP_f$), and fast P-wave converted to a slow P-wave ($P_fP_s$). To compare our algorithm with an elastic one, the fluid properties are set equal to zero to perform elastic modelling. Figure 1b shows the elastic snapshot. This figure illustrates how these algorithms simulate the wave propagation differently. In seismic frequencies, the slow P-wave could not be detected unless the viscosity of the fluid is close to zero. In this study we assume that the viscosity is zero, which seems reasonable for $CO_2$.

## Numerical time-lapse modeling

To perform time-lapse modeling, a coarse model is made based on the log data from the Quest project. This model that is shown in Figure 2a consists of four main layers. We assume that all layers except the BCS are elastic. BCS is located between the depths of 2000 and 2050 meters and could not be distinguished from the upper layer due to the low contrast in the velocities of the two layers. This model is used as our baseline model where the properties of BCS are the same as $BCS_1$ in Table 1. For the monitor scenario a $CO_2$ plume is added to the baseline model to simulate a subsurface model after injecting $CO_2$. The properties of the plume are the same as $BCS_2$ in Table 1 which represents the BCS with 40% $CO_2$ saturation. The size of the plume was calculated based on the amount of injected $CO_2$ in one year that is 1.2 million tonnes. Assuming the porosity of 16% for the BCS, and 40% $CO_2$ saturation, the calculated volume of the plume (with cylindrical shape) was $3\times10^7 m^3$. In our 2D model this cylindrical plume appears as an 800 by 50 m block (Figure 2b).

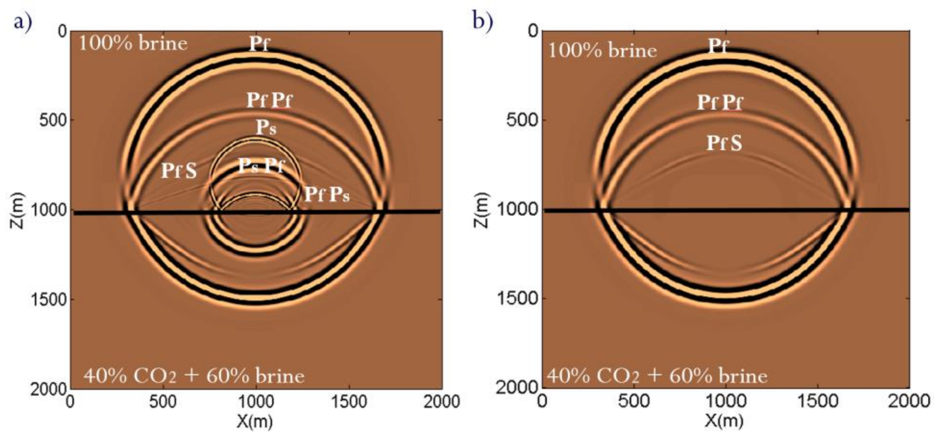


FIG. 1. Snapshots of the solid particle velocity (vertical component) calculated by: a) Poroelastic and b) elastic algorithms.

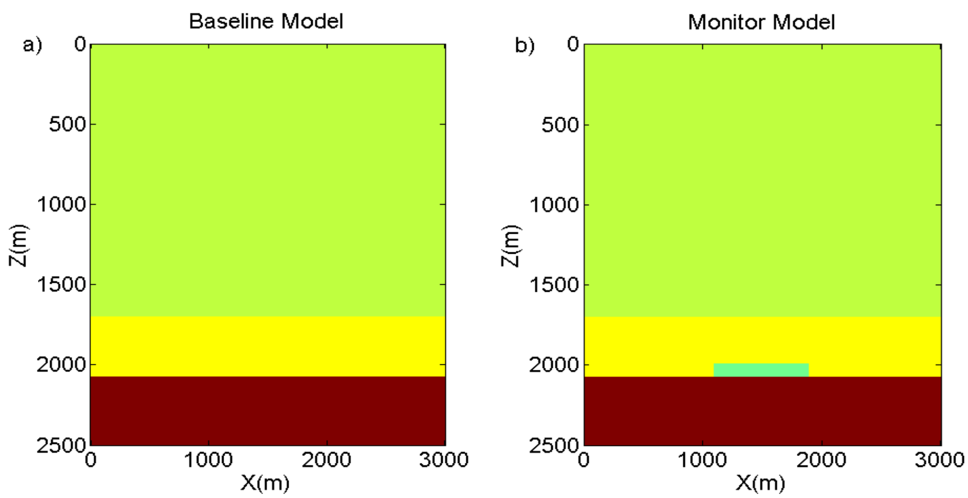


FIG. 2. Baseline (a) and monitor (b) models generated based on the Quest project.

Both models are then used to generate shot gathers. A Ricker wavelet with the dominant frequency of 40 Hz is used as an explosive source. The spatial and temporal spacings are 4 m and 0.2 ms, respectively. The unknowns are the solid and fluid particle velocities and the stresses that are calculated by the program (not shown). Injecting $CO_2$ into the BCS causes a change in the physical properties of the saturated rock. These changes lead to a shift in travel-times of the waves traveling through the plume, and a change in the reflections from the top and the base of the plume. This time-lapse effect could be observed by subtracting the monitor section from the baseline section (Figure 3a). The plume is clearly visible as a residual after subtraction. However, the residual section needs to be migrated since there are some diffractions from the edges of the $CO_2$ plume. Figure 3.b shows the result after applying an elastic Kirchhoff migration. In addition, selected traces from the modeled monitor and the baseline sections are shown in Figure 4. The amplitude of the reflections from the top and the base of the BCS have increased in the monitor scenario due to $CO_2$ injection. There is also a time shift for the reflection from the base of the plume since the wave travels through a slower layer after injecting $CO_2$. The difference between the baseline and the monitor traces (the dotted black curve) shows that the amplitude of the residual trace is comparable with the amplitude of the signal. This means that the $CO_2$ plume could be detected in the seismic data providing the data have good bandwidth and a high signal to noise ratio. Furthermore, an elastic time-lapse study is also carried out and compared with the poroelastic one. Figure 5 shows the time-lapse residual from both elastic and poroelastic algorithms. The residual effect from the base of the

BCS in the poroelastic case is smaller than the one in the elastic case. This is because some of the wave energy in poroelastic media goes to the fluid which is ignored in the elastic case. Amplitudes are very important in time-lapse modeling and poroelastic approach helps us to perform a more accurate modeling especially for cases in which the pore fluid is changing through time.

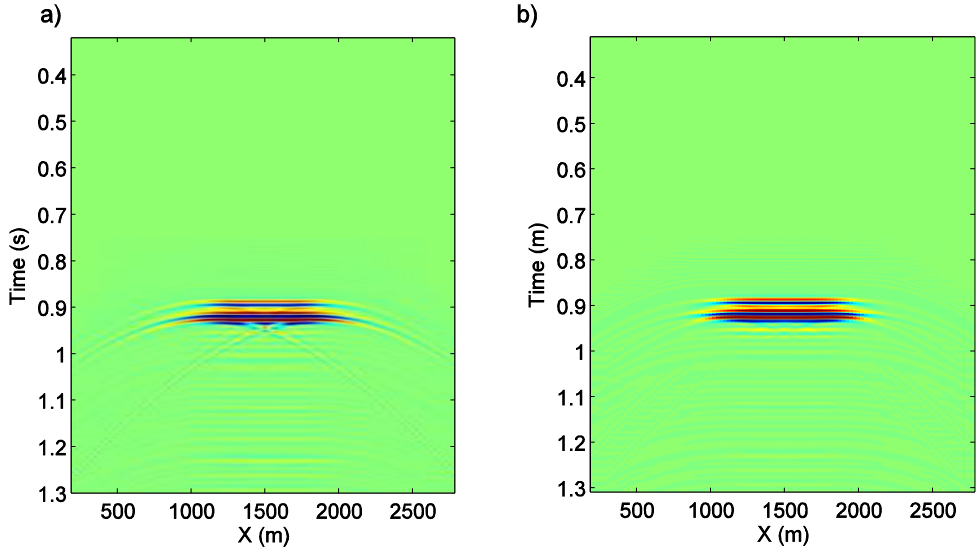


FIG. 3. a) Poroelastic time -lapse residual of the model in figure 2, b) same residual section after migration.

## Conclusions

Model based poroelastic time-lapse modelling was performed for the Quest carbon capture and storage project in Alberta. A finite-difference code was developed in Matlab based on the Biot's theory of poroelasticity in which the properties of the pore fluid are taken into account in wave propagation. Based on the results, the $CO_2$ plume could be detected in the seismic data after one year of injection if the data is of good quality. A comparison between the poroelastic algorithm and an elastic one shows a difference between the time-lapse residual calculated by those two algorithm. This difference reveals the benefits of the poroelastic algorithm for time-lapse modeling in fluid saturated media. By using the poroelastic approach, the changes in reservoir caused by the fluid substitution could be modeled more accurately.

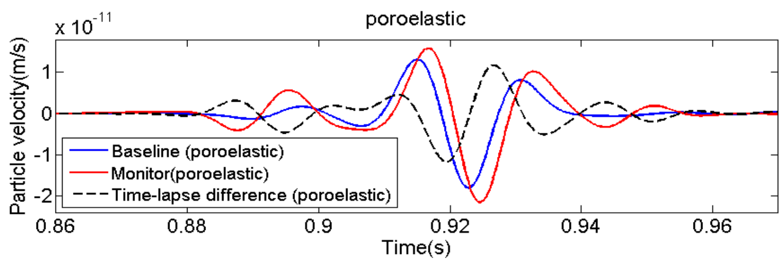


FIG. 4. Selected traces from the zero offset sections of baseline and monitor scenarios along with the difference.

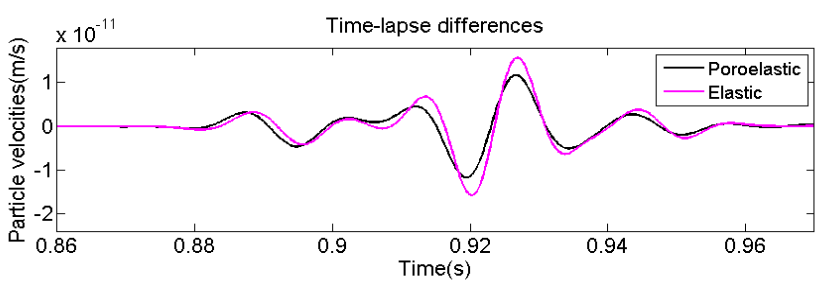


FIG. 5. Time-lapse residuals calculated by elastic and poroelastic algorithms.

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