Modeling of CO_2 storage in aquifers

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Abstract. Storage of CO_2 in geological formations is a means of mitigating the greenhouse effect. Saline aquifers are a good alternative as storage sites due to their large volume and their common occurrence in nature. The first commercial CO_2 injection project is that of the Sleipner field in the Utsira Sand aquifer (North Sea). Nevertheless, very little was known about the effectiveness of CO_2 sequestration over very long periods of time. In this way, numerical modeling of CO_2 injection and seismic monitoring is an important tool to understand the behavior of CO_2 after injection and to make long term predictions in order to prevent CO_2 leaks from the storage into the atmosphere. The description of CO_2 injection into subsurface formations requires an accurate fluid-flow model. To simulate the simultaneous flow of brine and CO_2 we apply the Black-Oil formulation for two phase flow in porous media, which uses the PVT data as a simplified thermodynamic model. Seismic monitoring is modeled using Biot's equations of motion describing wave propagation in fluid-saturated poroviscoelastic solids. Numerical examples of CO_2 injection and time-lapse seismics using data of the Utsira formation show the capability of this methodology to monitor the migration and dispersal of CO_2 after injection.

1. Introduction

Fossil-fuel combustion generates carbon dioxide (CO_2), which is mainly discharged into the atmosphere, increasing its temperature (greenhouse effect). To minimize climate change impacts, geological sequestration of CO_2 is an immediate option [1]. Geologic sequestration involves injecting CO_2 into a target geologic formation at depths typically greater than 1000 m where pressure and temperature are above the critical point for CO_2 (31.6C, 7.38 MPa).

The CO_2 injection operation at the Sleipner gas field in the North Sea, operated by Statoil and the Sleipner partners, is the world first industrial scale CO_2 injection project designed specifically as a greenhouse gas mitigation measure [1]-[2]. CO_2 separated from natural gas produced at Sleipner is currently being injected into the Utsira Sand, a saline aquifer some 26000 km^2 in area. Injection started in 1996 and is planned to continue for about twenty years, at a rate of about one million tonnes per year.

Time-lapse seismic surveys aim to demonstrate storage integrity, provide early warning should any leakage occur and monitor the migration and dispersal of the CO_2 plume. Recent papers [3]-[4] successfully apply seismic modeling for monitoring the spatio-temporal distribution of CO_2 using synthetic generated CO_2 saturation fields. Instead, in this work we employ numerical simulations of CO_2 injection; therefore saturation fields are obtained as a result of the simultaneous flow of CO_2 and brine in porous media.

The final objective is to test that underground storage is a safe and verifiable technology in the long term.

2. The Black-Oil formulation of two-phase flow in porous media

The simultaneous flow of brine and CO_2 is described by the well-known Black-Oil formulation applied to two-phase, two component fluid flow [5]. In this model, CO_2 may dissolve in the brine but the brine is not allowed to vaporize into the CO_2 phase. This formulation uses, as a simplified thermodynamic model, the following PVT data, determined using the Hassanzadeh's correlations [6]: R_s: CO_2 solubility in brine; B_{CO2}: CO_2 formation volume factor, and B_b: brine formation volume factor. The nonlinear system of partial differential equation is,

$$\nabla \cdot (\underline{k}(\frac{k_{rCO2}}{B_{CO2}\mu_{CO2}}(\nabla p_{CO2} - \rho_{CO2} g \nabla D) + \frac{R_s k_{rb}}{B_b \mu_b}(\nabla p_b - \rho_b g \nabla D))) + q_{CO2} = \frac{\partial\left[\phi\left(\frac{S_{CO2}}{B_{CO2}} + \frac{R_s S_b}{B_b}\right)\right]}{\partial t}, \tag{1}$$

$$\nabla \cdot (\underline{k}(\frac{k_{rb}}{B_b \mu_b}(\nabla p_b - \rho_b g \nabla D)) + q_b = \frac{\partial\left[\phi(\frac{S_b}{B_b})\right]}{\partial t}. \tag{2}$$

The unknowns are the fluid pressures p_{CO2}, p_b and saturations S_{CO2}, S_b for the CO_2 and brine phases. The parameters k and ϕ are the absolute permeability and porosity respectively. Also, for $\beta = CO2, b$, the funcions $k_{r\beta}$, μ_β and ρ_β are the relative permeability, viscosity, and density of the β-phase, respectively.

Two algebraic equations relating the saturations and pressures, complete the system:

$$S_b + S_{CO2} = 1, \qquad p_{CO2} - p_b = P_C(S_b), \tag{3}$$

where P_C is the capillary pressure.

The solution of the Black-Oil fluid-flow model was obtained employing the public domain software BOAST [7], which solves the differential equations using IMPES, a semi-implicit finite difference technique [8].

3. Biot's Equations of Motion

Let us consider a 2D isotropic fluid-saturated porous material Ω. The oscillatory motion of Ω at the angular frequency ω subject to external sources $F^{(s)}$ and $F^{(f)}$ obeys Biot's equation of motion [3]

$$-\omega^2 \rho_b u^{(s)} - \omega^2 \rho_f u^{(f)} - \nabla \cdot \sigma(u) = F^{(s)} \tag{4}$$

$$-\omega^2 \rho_f u^{(s)} - \omega^2 g u^{(f)} + i\omega b u^{(f)} + \nabla p_f(u) = F^{(f)}. \tag{5}$$

The unknowns are $u^{(s)}$ and $u^{(f)}$, the time Fourier transforms (FT) of the averaged displacement vectors of the solid and fluid phases, respectively. Also, ρ_f and ρ_b denote the densities of the single-phase fluid and the bulk material, g and b are mass and viscous coupling coefficients, σ_{ij}

is the FT of the stress tensor of the bulk material and p_f is the FT of the fluid pressure. See [4] for the definition of the variables involved in (4)-(5).

Biot's equations were solved with the finite element method, employing a 2D non-conforming finite element space for each component of the solid displacement vector and the vector part of the Raviart Thomas Nedelec space of zero order for the fluid displacement [9].

4. Numerical Experiments

4.1. Idealized model of the Utsira formation

To test the proposed methodology, we consider an idealized geometrical and physical domain consisting of 5 regions as shown in Figure 1. The upper 100 m is region Ω_1, a sand of permeability 60 mD and porosity 0.32. Ω_2 is a sealed shale 2 m thick, the top of the Usira formation. Regions Ω_3 and Ω_5 are the Utsira formation, of permeability 1000 mD and porosity 0.37. We assume that Ω_4 is a sealed shale layer within the Utsira sand. The medium was excited with a compressional point source located at x= 400 m, z= 710 m.

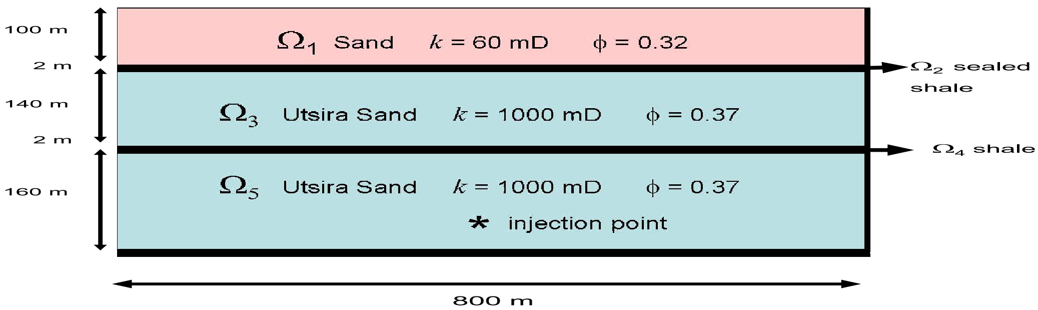

Figure 1. Idealized model of the Utsira formation. The injection point is located at x= 400 m, z= 1060 m.

The Biot model assumes a single-phase fluid, therefore effective fluid density, viscosity and bulk modulus were obtained using the properties of the CO_2 and brine weighted by the corresponding saturations computed by the fluid-flow simulator.

4.2. Injection Modeling

Figure 2 shows the CO_2 saturation distribution after 5 years of injection obtained by the BOAST simulator. A CO_2 accumulation beneath the Ω_4 seal can be clearly observed.

4.3. Seismic Monitoring

Figure 3 displays traces of the vertical component of the particle velocity of the solid phase before (black curve) and after (red curve) 5 years of CO_2 injection. The strong arrival at about 240 ms corresponds to a reflection due to the CO_2 accumulation beneath the seal.

Time histories measured near the surface before (left plot) and after 5 years of CO_2 injection (right plot) are shown in Figure 4.

The first reflection in both figures is due to the direct wave coming from the point source located at x= 400 m, z= 710 m. The second reflection in the time histories after 5 years, not observed before the injection, is generated by the CO_2 accumulations below the thin shale layer at depth z = 940 m.

Figure 5 displays the vertical component of the solid phase velocity before and after 5 years of CO_2 injection at 200 ms. At this time, the waves generated by the point source have generated

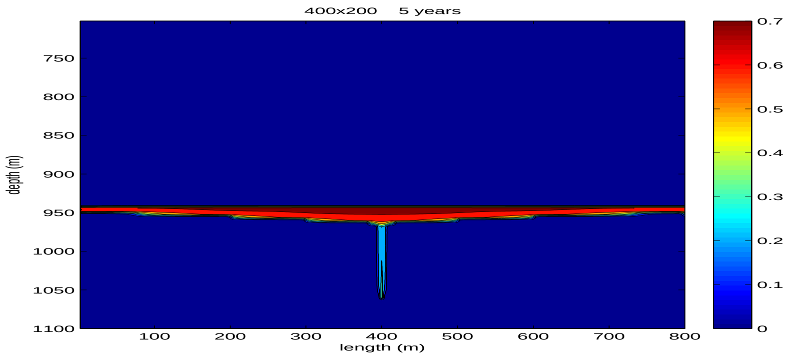

Figure 2. CO_2 saturation distribution after 5 years of injection. The injection point is located at x= 400 m, z= 1060 m.

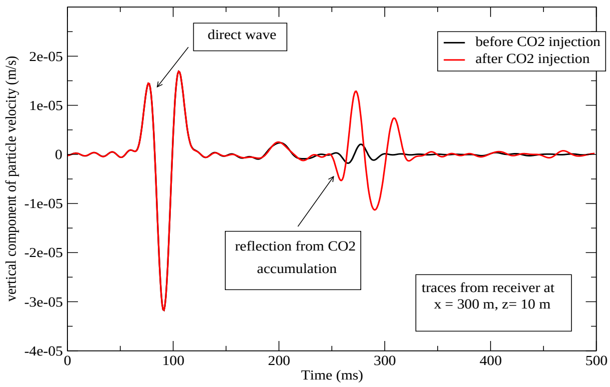

Figure 3. Traces of particle velocity of the solid phase before and after 5 years of CO_2 injection.

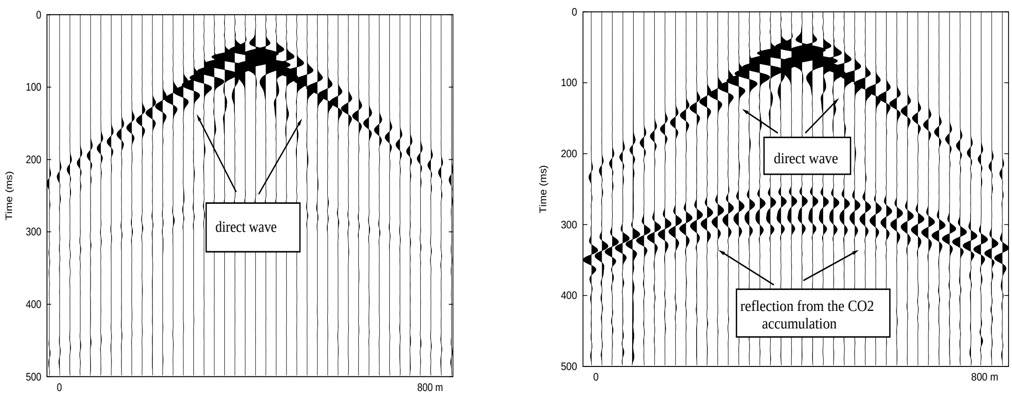

Figure 4. Time histories measured near the surface before and after 5 years of CO_2 injection.

reflected and transmitted waves due to the CO_2 accumulation below the thin shale layer at z = 940 m.

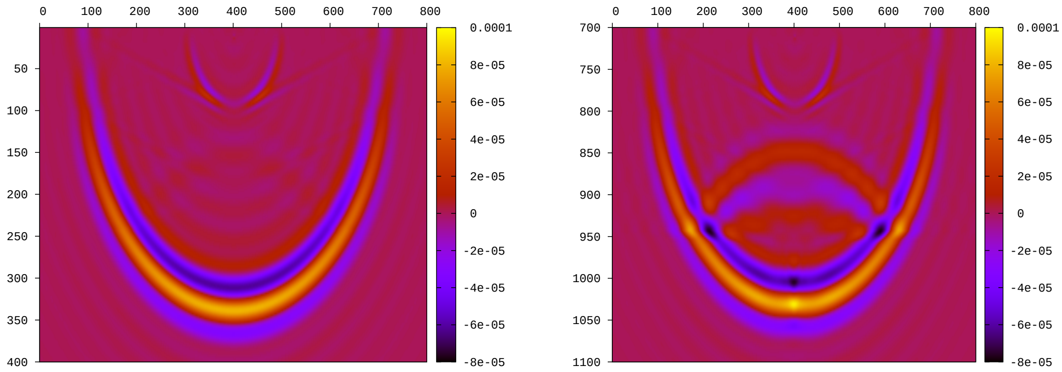

Figure 5. Vertical component of the solid phase velocity at 200 ms before and after 5 years of CO_2 injection.

5. Conclusions

In this work we introduced a methodology to model and monitor CO_2 sequestration using numerical simulations. For that purpose we integrated numerical simulators of CO_2-brine flow and seismic wave propagation. This metodology was tested with a numerical example showing the capability of seismic monitoring to identify the horizontal and vertical accumulations of CO2. Therefore, combining fluid-flow simulations with seismic methods constitute an important tool to analyze storage integrity, provide early warning should any leakage occur, and monitor the migration and dispersal of the CO2 plume.

6. References

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