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A numerical procedure to model and monitor CO_2 sequestration in aquifers

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Abstract. Carbon Dioxide (CO_2) sequestration into geologic formations is a means of mitigating greenhouse effect. In this work we present a new numerical simulation technique to model and monitor CO_2 sequestration in aquifers. For that purpose we integrate numerical simulators of CO_2-brine flow and seismic wave propagation (time-lapse seismics). The simultaneous flow of brine and CO_2 is modeled applying the Black-Oil formulation for two phase flow in porous media, which uses the Pressure-Volume-Temperature (PVT) behavior as a simplified thermodynamic model. Seismic wave propagation uses a simulator based on a space-frequency domain formulation of the viscoelastic wave equation. In this formulation, the complex and frequency dependent coefficients represent the attenuation and dispersion effect suffered by seismic waves travelling in fluid-saturated heterogeneous porous formations. The spatial discretization is achieved employing a nonconforming finite element space to represent the displacement vector. Numerical examples of CO_2 injection and time-lapse seismics in the Utsira formation at the Sleipner field are analyzed. The Utsira formation is represented using a new petrophysical model that allows a realistic inclusion of shale seals and fractures. The results of the simulations show the capability of the proposed methodology to monitor the spatial distribution of CO_2 after injection.

1. Introduction

Storage of CO_2 in geological formations is a procedure employed to reduce the amount of greenhouse gases in the atmosphere to slow down global warming [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 is the world first industrial scale CO_2 injection project [1]-[2]. CO_2 separated from natural gas produced at Sleipner is 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 monitor the migration and dispersal of the CO_2 plume. Recent papers [3]-[4] applied seismic modeling using synthetic generated CO_2 saturation fields. In this work we combine numerical simulations of CO_2 injection and seismic modeling using a viscoelastic model that takes into account attenuation effects due to the presence of heterogeneities in the solid and fluid properties.

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 PVT data: CO_2 solubility in brine (R_s) and CO_2 and brine formation volume factors (B_{CO2}, B_b). They are determined using the Hassanzadeh's correlations [7]. The nonlinear system of partial differential equation is,

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

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

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

Besides, phase saturations add to one and phase pressures are related by the capillary pressure (P_C) relation $p_{CO2} - p_b = P_C(S_b)$.

The solution of the Black-Oil fluid-flow model was obtained employing the BOAST simulator [8], which solves the flow equations with the IMPES finite difference technique [9].

3. A VISCOELASTIC MODEL FOR WAVE PROPAGATION

The propagation of waves is described using a viscoelastic model that takes into account the dispersion and attenuation effects due to the presence of heterogeneities in the fluid and solid phase properties.

The equation of motion in a 2D isotropic viscoelastic domain Ω with boundary $\partial\Omega$ can be stated in the space-frequency domain as

$$-ø^2 \rho u - \nabla \cdot \sigma(u) = f(x, ø), \quad \Omega \qquad (3)$$

$$-\sigma(u)\nu = i ø \mathcal{D} u, \quad \partial\Omega, \qquad (4)$$

where $u = (u_x, u_y)$ is the displacement vector. Here ρ is the bulk density and (4) is a first-order absorbing boundary condition using the positive definite matrix $\mathcal{D}$.

The stress tensor $\sigma(u)$ is defined in the space-frequency domain by

$$\sigma_{jk}(u) = \lambda_G(ø) \nabla \cdot u \delta_{jk} + 2\mu_m(ø)\varepsilon_{jk}(u), \qquad (5)$$

where $\sigma_{jk}(u)$ and $\varepsilon_{jk}(u)$ are the stress and strain tensors, λ_G and μ_m are the complex and frequency dependent Lamé parameters. The Lamé coefficients, computed using White's model [6] for patchy saturation, take into account attenuation and dispersion of waves due to the presence of CO_2 after injection.

The solution of (3)-(4) was obtained using an iterative finite element domain decomposition procedure employing a nonconforming finite element space, since it generates less numerical dispersion than the standard bilinear elements [3] .

4. Model of the Utsira Formation and CO_2 Injection.

We consider a 2D model of the Sleipner field constructed using an initial porosity at hydrostatic pressure and the clay content of the formation. The model has 400 m thickness (top at 700 m and bottom 1100 m b.s.l.). Within the formation, there are several mudstone layers which act as barriers to the vertical motion of the CO_2 and can be observed in Figure 1 (left). The viscosity, density and bulk modulus of CO_2 were obtained from the Peng-Robinson equations as a function of temperature and pore pressure [7].

CO_2 is injected at a constant flow rate of one millon tons per year. The injection point is located at the bottom of the Utsira formation: $x = 400$ m, $z = 1060$ m. Figure 1 (right) shows the saturation field after 2 years of CO_2 injection computed using the BOAST flow simulator.

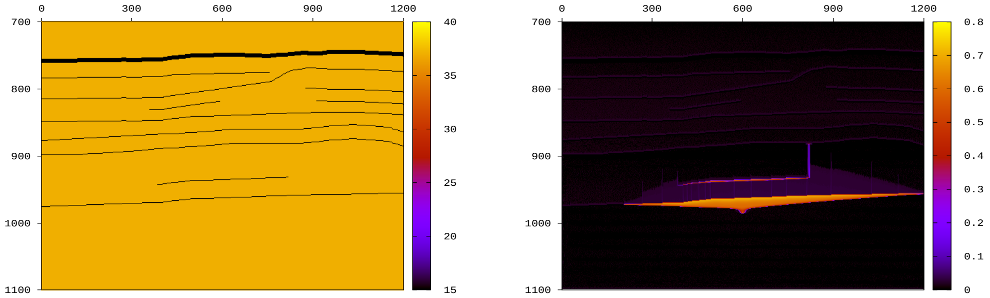

Figure 1. Porosity map (left) and CO_2 saturation distribution (rigth) after 3 years of injection. The injection point is located at x= 600 m, z= 1060 m

5. Time-Lapse Seismic Monitoring

To analyze the capability of seismic monitoring to identify zones of CO_2 accumulation, the media is excited with a compressional point source located at $x = 400$ m, $z = 710$ m before and after 2 years of CO_2 injection. Time histories measured near the surface are shown in Figures 2 before CO_2 injection (left) and after 2 years of CO_2 injection (right). The upper reflection in both figures is due to the direct wave coming from the point source. The other reflection in (b) is due to the CO_2 accumulations below the deepest mudstone layer. Figure 3 displays the traces measured at x= 750 m, z = 710 m shown in Figure 2.

6. Conclusions

In this work we presented a new numerical methodology to model and monitor CO_2 sequestration. For that purpose we integrated numerical simulators of CO_2-brine flow and seismic wave propagation. The numerical experiment shows the capability of seismic monitoring to identify the spatial distribution of CO_2 after injection. Therefore, this approach constitute a valuable tool to analyze storage integrity, provide early warning should any leakage occur, and monitor the migration and dispersal of the CO_2 plume.

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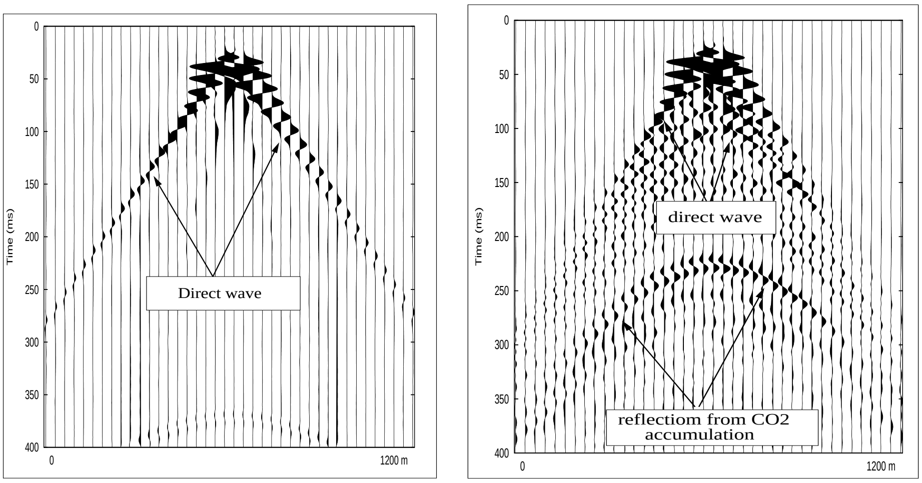

Figure 2. Traces of the z-component of the displacement before (left) and after (right) 2 years of CO_2 injection. The second reflection is due to the deepest CO_2 accumulation .

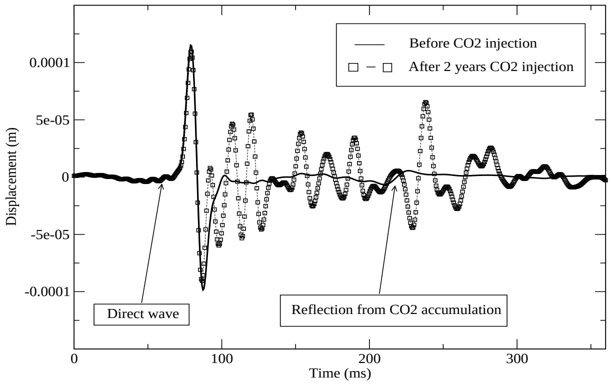

Figure 3. Traces of particle velocity of the solid phase before and after 2 years of CO_2 injection.

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