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Uncertainty quantification for the impact of injection rate fluctuation on the geomechanical response of geological carbon sequestration

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ABSTRACT

We study the effect of random injection rate fluctuations on pressure and geomechanical stresses during geological sequestration of carbon dioxide (CO_2). We first derive analytical solutions for the mean and variance of the pressure of CO_2 in the reservoir. Next, we use the Monte Carlo simulation (MCS) method to obtain the mean and variance of geomechanical deformation stresses and the maximum sustainable injection pressure based on shear-slip failure analysis. The MCS method is validated using the analytical solutions for mean and variance of the pressure. We demonstrate that for any Gaussian distribution of injection rate Q with given mean $\bar{Q}$ and standard deviation ε_Q, the coefficients of variation of the CO_2 pressure ($\epsilon_p = \varepsilon_p/\bar{p}$), deformation ($\epsilon_u = \varepsilon_u/\bar{u}$), and stresses ($\epsilon_\sigma = \varepsilon_\sigma/\bar{\sigma}$) increase linearly with the coefficient of variation of the injection rate ($\epsilon_Q = \varepsilon_Q/\bar{Q}$). We calculate coefficients of variation and show that the fluctuations have the most pronounced effect on the geomechanical stresses and, therefore, on the potential fracturing of the aquifer and caprock layers.

We demonstrate that the maximum sustainable injection pressure can be determined based on shear-slip analysis with a given expected risk due to the injection rate fluctuations. We show that the injection rate fluctuations decrease the maximum sustainable injection pressure.

1. Introduction

Emissions of greenhouse gases have been implicated as a primary contributor to global warming and accelerated climate change (IPCC, 2005). It was estimated that the production of energy-related carbon dioxide (CO_2) accounted for 81.5% of the greenhouse gas emissions in the United States (EIA, 2011). CO_2 sequestration in deep saline aquifers has emerged as a promising mitigation method for reducing the amount of CO_2 emitted into the atmosphere (Vilarrasa et al., 2011). Geological formations in large parts of the midwestern United States can be potentially used to store CO_2 (MIT, 2007; NACAP, 2012). Injection and long-term behavior of CO_2 in aquifers involve a combination of complex physical and chemical processes, such as multiphase flow, multi-component miscible transport, complicated geochemical (Spycher et al., 2003) and geomechanical responses, and nonisothermal effects (Celia and Nordbotten, 2010). Mathematical models and numerical simulation tools will play an important role in evaluating the feasibility of CO_2 storage in subsurface reservoirs, designing and analyzing field tests, and developing and operating geologic CO_2 disposal and geothermal extraction systems (Pruess et al., 2004).

In addition to the complexity of computational models, uncertainty in operating parameters and boundary conditions leads to uncertainty in the geomechanical response during sequestration. In any realistic sequestration scenario, the injection rate is expected to fluctuate due to the supply variations at the compression station and other operational interruptions (Benson, 2006; Sminchak et al., 2009). Moreover, an injection system is designed to control the volumetric injection rate (Nordbotten et al., 2005), but CO_2 density varies with pressure and temperature, so the mass injection rate deviates from the designed or desired average rate (Bachu, 2003). Here, we present a model for uncertainty quantification in CO_2 sequestration due to the fluctuations of the CO_2 mass injection rate.

In geological sequestration, CO_2 is expected to be retained underground in excess of 1000 years (Wilson, 1992; Holloway, 2005). Hence, geological sequestration of supercritical CO_2 intrinsically involves a number of complicated physical and chemical

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processes that occur within large spatial domains and extremely long periods of time. To make the simulation computationally affordable, a numerical model used for CO_2 sequestration must be sufficiently stable to model large time steps and grid sizes. In this study, we use a finite-element numerical model that was shown to be stable and accurate for a time-step interval ranging from a single day to a few years and for grid sizes as large as several hundred meters.

This paper is organized as follows: a hydromechanical model including the governing equations and analytical solutions for a typical injection scenario is introduced in Section 2. In Section 3, we present analytical expressions for the mean and variance of fluid pressure. A numerical model, based on the open-source finite element solver Elmer (CSC-IT, 2011), is introduced in Section 4. Monte Carlo Simulation (MCS) method based on the numerical model is used to compute probability distributions of the geomechanical responses (fluid pressures, displacements, geomechanical stresses, and maximum sustainable injection pressure). Finally, Section 5 presents a method for determining the maximum sustainable injection pressure based on shear-slip failure analysis and given expected risk.

2. Hydromechanical model for geological CO_2 sequestration

Details regarding the hydromechanical model for geological CO_2 sequestration were presented in our previous work (Xu et al., 2012); for convenience and clarity, we briefly introduce the model here. We assume that the hydromechanical response to CO_2 injection in the reservoir can be described by a combination of fluid flow and linear elasticity equations (Terzaghi, 1923; Biot, 1935, 1941, 1955, 1956, 1962):

$$\frac{\partial p}{\partial t} + \frac{1}{\theta\beta}\frac{\partial(\nabla\cdot\vec{u})}{\partial t} = \frac{k}{\theta\mu\beta}\nabla^2 p + \frac{\psi}{\theta\rho\beta}, \tag{1}$$

$$(\lambda + G)\nabla(\nabla\cdot\vec{u}) + G\nabla^2\vec{u} = \nabla p. \tag{2}$$

Eq. (1) is a Darcy flow equation in terms of the pressure-change field p, which is defined as the difference between current pressure (p_c) and initial pressure (p_i), namely $p = p_c - p_i$. In Eq. (1), t is injection time, $\vec{u}$ is the mechanical displacement vector, θ is porosity, β is fluid compressibility, μ is viscosity, k is permeability, ρ is the liquid density, and ψ is the external source term representing the CO_2 injection rate with a unit of $\mathrm{kg\,m^{-3}\,s^{-1}}$. Eq. (2) is a Navier-type elasticity equation in terms of the displacement vector $\vec{u}$. In Eq. (2), for solid rock or soil, G is the shear modulus and λ is Lamé's constant. Eqs. (1) and (2) are valid for arbitrary geometry and boundary conditions. As shown in Fig. 1, a layered subsurface structure (upper rock, caprock, aquifer, and base) in an axisymmetric coordinate system is used as an example to study the hydromechanical response to CO_2 geological injection. Segall (1992) solved a similar problem with homogeneous properties analytically. We assume the caprock and base have zero permeability, so the injected CO_2 is completely constrained within the aquifer. Therefore, the pressure-change field (p) is solved only in the aquifer, where homogeneous properties are applied. By applying Segall's solution (Segall, 1992) and considering the coupling term ($\frac{1}{\theta\beta}\frac{\partial(\nabla\cdot\vec{u})}{\partial t}$), in our previous work (Xu et al., 2012) we analytically solved Eq. (1) in an axisymmetric coordinate system (Fig. 1) as:

$$p(r,t) = \int_0^t \frac{Q(\tau)\mu}{4\pi\rho k}\frac{\exp\left(-\frac{r^2}{4D(t-\tau)}\right)}{(t-\tau)}d\tau, \tag{3}$$

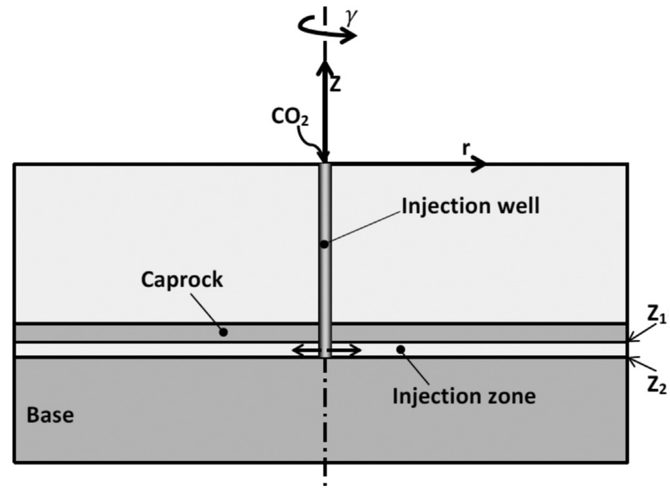

Fig. 1. Geometric configuration of CO_2 injection.

where $Q(\tau)$ is the line injection rate ($\mathrm{kg\,m^{-1}\,s^{-1}}$) and D is the equivalent diffusion coefficent, which includes the coupling effects:

$$D = \frac{k/\mu}{\theta\beta + 1/(\lambda + 2G)}. \tag{4}$$

With a dimensionless number Ω defined as $\Omega = r^2/(4Dt)$, the pressure solution can be simplifiled as:

$$p(r,t) = \tilde{p}F(\Omega), \tag{5}$$

where $F(\Omega)$ is an exponential integral function defined as:

$$F(\Omega) = \int_{\Omega}^{\infty} e^{-\omega}/\omega d\omega. \tag{6}$$

The scaling factor $\tilde{p}$ is defined as:

$$\tilde{p} = \frac{Q\mu}{4\pi\rho k}. \tag{7}$$

We note that Eq. (1) was developed for single-phase flow and is only an approximation of a problem involving CO_2 injection in an aquifer saturated with water (or brine). Fig. 2 shows the comparison between the results from the proposed single-phase flow model (Eqs. (1) and (2)) and the results from a CO_2-brine multiphase subsurface flow simulator, STOMP (Subsurface Transport over Multiple Phases) (White and Oostrom, 2006) for the same geometry and boundary conditions after 1, 5, and 10 years of injection. The layered subsurface structure is a simplified form of a

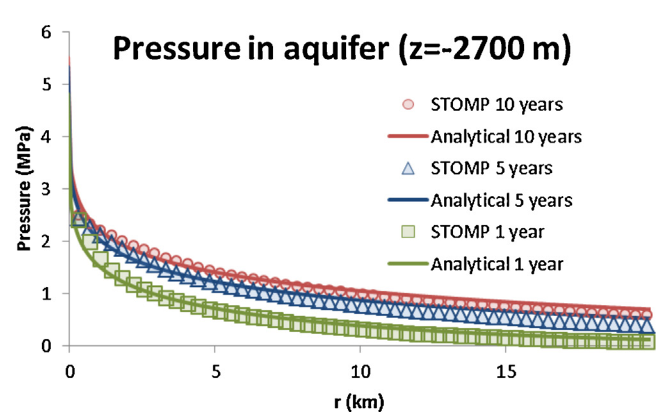

Fig. 2. Comparison of aquifer pressure results achieved with a single-phase model analytical solution and a multi-phase STOMP simulation.