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Full Length Article

Three-dimensional analysis of a faulted CO_2 reservoir using an Eshelby-Mori-Tanaka approach to rock elastic properties and fault permeability

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ABSTRACT

This work develops a three-dimensional (3D) multiscale model to analyze a complex carbon dioxide (CO_2) faulted reservoir that includes some key geologic features of the San Andreas and nearby faults southwest of the Kimberlina site. The model uses the STOMP-CO2 code for flow modeling that is coupled to the ABAQUS® finite element package for geomechanical analysis. A 3D ABAQUS® finite element model is developed that contains a large number of 3D solid elements with two nearly parallel faults whose damage zones and cores are discretized using the same continuum elements. Five zones with different mineral compositions are considered: shale, sandstone, fault damaged sandstone, fault damaged shale, and fault core. Rocks' elastic properties that govern their poroelastic behavior are modeled by an Eshelby–Mori–Tanaka approach (EMTA), which can account for up to 15 mineral phases. The permeability of fault damage zones affected by crack density and orientations is also predicted by an EMTA formulation. A STOMP-CO2 grid that exactly maps the ABAQUS® finite element model is built for coupled hydro-mechanical analyses. Simulations of the reservoir assuming three different crack pattern situations (including crack volume fraction and orientation) for the fault damage zones are performed to predict the potential leakage of CO_2 due to cracks that enhance the permeability of the fault damage zones. The results illustrate the important effect of the crack orientation on fault permeability that can lead to substantial leakage along the fault attained by the expansion of the CO_2 plume. Potential hydraulic fracture and tendency for the faults to slip are also examined and discussed in terms of stress distributions and geomechanical properties.

1. Introduction

Safe and long-term storage of carbon dioxide (CO_2) in deep underground reservoirs has been sought to be a viable approach to reduce atmospheric emissions of greenhouse gases. Properly sited and managed geologic carbon storage in deep saline formations remains a safe option to mitigate anthropogenic climate change (Vilarrasa and Carrera, 2015). However, injecting large amounts of CO_2 in the subsurface of the crust poses important challenges and technical issues that need to be solved to ensure efficient long-term injection and storage of CO_2 while addressing public concerns on the risks related to CO_2 sequestration (Chen et al., 2015). The main risks involve site-induced seismicity and CO_2 leakage through natural pathways or as a result of rupture of the caprock seal or fault reactivation. Numerical analyses have been very helpful to understand the physical processes involved and have provided insights of the controlling parameters governing the formation geomechanical responses. Over the past decade, there have been many studies that developed models to simulate the CO_2 flow in reservoirs and predict the resulting stresses, strains and potential fracture due to hydraulic fracturing or shear failure of the faulted formation (Rutqvist and Tsang, 2002; Rutqvist et al., 2002, 2007; Comerlati et al., 2006; Lucier et al., 2006; Jha and Juanes, 2007; Chiaramonte et al., 2008). Previous analyses helped understand the evolution trends of the governing parameters as well as the mechanisms involved that could cause rupture of the reservoir or trigger the reactivation of a fault. Among the many factors that impact the reservoir integrity and CO_2 leakage are formation flow and transport attributes, the pressure buildup and the

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geomechanical stresses due to injection. Many of the previous models were very generic regarding some critical aspects, and below appear the limitations:

(1) The modeling domains were often very simple, many were two-dimensional (2D) and with a few alternating layers.
(2) The analyses were almost based on assumed geomechanical and flow properties.
(3) Faults were modeled as discrete surfaces or continuous media with assumed uniform flow and geomechanical properties.

Actual selected sites for CO_2 storage are very complex multilayered formations with varying flow and geomechanical properties. While simplified models could be developed with a limited number of layers, these models cannot capture realistic magnitudes of stresses, strains, and pressure buildups that impact the flow properties, and geomechanical properties and response. The uncertainties are higher with the use of assumed flow and material properties in the models. Faults are complex and heterogeneous geologic systems, which strictly speaking, do not correspond to discrete surfaces or continuous media with uniform properties as already postulated by many authors in their models. Typical fault structures contain one or multiple fault cores surrounded by fault damage zones (Faulkner et al., 2010). While the width of the fault core is small with orders of magnitude from centimeters to meters, the width of the damage zones is substantially larger (from tens of meters to a few hundreds of meters). Samuelson and Spiers (2012) conducted direct shear experiments on simulated fault gouges relevant to a proposed carbon capture and storage site, and found that fault strength is strongly related to bulk clay content of the gouge material, but is not significantly influenced by the presence of CO_2. Tillner et al. (2014) investigated the mechanical impact of industrial-scale CO_2 storage at a prospective Danish site by coupled three-dimensional (3D) hydro-mechanical simulations and stated that the introduced fault zone implementation in the hydro-mechanical model allows for localization of potential leakage pathways for formation fluids along the fault plane. Faults can act as barriers or flow paths (sealing faults vs. leaking faults) depending on the permeability of the fault zone. Recently, Mbia et al. (2014) modeled the pressure propagation due to CO_2 injection and the effect of fault permeability on the pressure buildup in a case study of the Vedsted structure in Northern Denmark. In their model, faults were modeled as continuous media with uniform permeability and thickness (200 m), and a range of permeability values from literature were considered to represent sealing faults to open faults.

In this paper, we have made a first step to address the above-mentioned limitations of the current modeling approach by proposing a multiscale analysis, in which the properties computed at a lower scale accounting for the rock microstructure are judiciously fed into an upper scale model to predict the geomechanical response of a complex representative CO_2 storage formation. First, based on a review of fault zone architecture and fluid flow properties, a conceptual model for such a complex CO_2 storage reservoir is proposed. There exist few sites where a full suite of mineralogical, mechanical and fluid flow properties was available. Thus, we select a few studies, mostly of the San Andreas and other nearby faults close to the Kimberlina site, as a basis for assembling a representative conceptual model containing alternating layers with typical zones including sandstone and shale layers, fault damage zones (i.e. damaged sandstone and damaged shale) and fault core. For each zone, the mineralogy and fluid flow properties based on literature findings are then formulated and gathered for subsequent analyses. Second, the Eshelby–Mori–Tanaka approach (EMTA) (Eshelby, 1957; Mori and Tanaka, 1973) previously used by Nguyen et al. (2016) is applied to compute the homogenized elastic properties for each zone based on its mineral composition. We then extend the EMTA model to predict the elastic properties of the fault damage zones affected by preexisting cracks according to given crack orientation distributions and volume fractions. An EMTA model for the permeability enhanced by preexisting cracks is also developed to predict the permeability of the fault damage zones as functions of the crack volume fraction and orientation state. Finally, from the conceptual model, a 3D model of a complex and representative CO_2 storage formation is developed to analyze the injection and flow of CO_2 in the formation. This model that captures all the features of the conceptual model serves as a basis to investigate flow in the reservoir, pressure buildup, stress distributions in different zones, pathways for leakage, and potential reservoir fractures. The modeling approach is demonstrated through CO_2 injection analyses of such a model reservoir containing two inclined faults with different crack pattern situations. It involves the coupled process between geomechanics and flow in porous media. In the fully coupled approach, the coupled nonlinear system of equations is discretized and solved simultaneously, typically using a Newton–Raphson's scheme. On the other hand, there are sequential approaches, which couple flow to geomechanics sequentially or iteratively, and can also offer as accurate solutions as the fully coupled approach if tight convergence criteria are prescribed (Jha and Juanes, 2007). As the sequentially coupled approach solves separately in a sequential way the fluid flow equations and the mechanical problem (e.g. Rutqvist and Tsang, 2002; Rutqvist et al., 2007), it offers the flexibility to use separate simulators for each sub problem. For practical reasons, we have developed a sequentially coupled multifluid flow/geomechanical approach to analyze prototype CO_2 reservoirs to determine stress and strain distributions as well as the risks associated with fault reactivation. The developed capability uses STOMP-CO2 multifluid flow simulator (White and Oostrom, 2006; White et al., 2012) that is interfaced with the ABAQUS® finite element (FE) packages. In this paper, STOMP-CO2 handles flow solutions while ABAQUS® performs geomechanical modeling.

2. Conceptual model for a representative CO_2 storage reservoir

2.1. Fault zone architecture and fluid flow properties

A review of recent developments concerning the structure, mechanics and fluid flow properties of fault zones was conducted by Faulkner et al. (2010). Typical fault zone structures are composed of two distinct components: a fault core where most of the displacement is accommodated and strain is localized, and an associated damage zone, mechanically related to the growth of the fault zone. A fault zone can have multiple cores surrounded by the fracture damage zone. The fault core generally consists of gouge, cataclasite or ultracataclasite (or a combination of these), and the damage zone generally consists of cracks over a wide range of length scales and subsidiary faults. The amount and distribution of fault cores and damage zones control fluid flow within and near the fault zone. Caine et al. (1996) noted that the fluid flow properties of the fault core and fault damage zone may change over time. For example, the fault core may act as a conduit during deformation and as a barrier when open pore space is filled by mineral precipitation following deformation. These authors further noted that fracture density in the fault core is usually significantly less than that in the damage zone, and thus, the permeability of the fault core may be dominated by the grain-scale permeability of the fault