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Multi-scale simulation of thermal pressurization of fault fluid under CO_2 injection for storage and utilization purposes

Kimia Mortezaei, Farshid Vahedifard*

Dept. of Civil and Environmental Engineering, Mississippi State University, Mississippi State, MS 39762, USA

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ABSTRACT

We investigated the impact of thermal pressurization (TP) on temperature and pore pressure changes within the shear zone of a slipping fault under supercritical CO_2 injection. As a weakening mechanism, TP of fault fluid during slip tends to reduce frictional resistance by increasing pore pressures along the fault shear zone. We employed a multi-scale modeling approach in which the CO_2 injection was simulated in a large-scale model of reservoir and the results were then exported into a micro-scale model of the fault shear zone which incorporates the TP effect. A poroelasticity finite element model was created in the large-scale model to determine the stress and pressure changes in the reservoir and within the fault zone during CO_2 injection. The fault slip, pressure, and stresses obtained from the large-scale model were fed into the small-scale model to define hydraulic and mechanical boundary conditions of the shear zone of the fault. Two small-scale models were developed to compare the response of the fault shear zone with and without considering the TP. For the model with the TP effect, a simple constitutive law was implemented to couple pore pressure changes with temperature rise due to frictional heating. The results indicated that, in general, TP can lead to a significant increase of pore pressure build up due to CO_2 injection. The effects of hydraulic diffusivity, slip velocity, shear zone thickness as well as injection rate on pore pressure, temperature and fracture energy prediction were evaluated. It was found that temperature and pore pressure rise decrease significantly by decreasing the slip velocity and increasing the shear zone thickness. For the values which were examined, hydraulic diffusivity was found to have insignificant effect on pore pressure and temperature changes which can be attributed to high compressibility of CO_2. Findings of this study can be used and further expanded in future studies for more accurate assessment of induced seismicity potential due to CO_2 injection.

1. Introduction

There are several unanswered questions regarding the potential for induced seismicity associated with CO_2 injection for storage purposes, primarily due to lack of large-scale injection experience and some unique characteristics of Carbon Capture and Storage (CCS) operations.[1] When CO_2 is injected, the pore pressure in the reservoir increases and the effective stress decreases. The changes in effective stress and pore pressure can cause expansion in the reservoir leading to deformation of the reservoir and overburden.[2,3] This phenomenon may threaten the storage integrity of the reservoir by creating new fractures and/or reactivating existing faults.[3,4] In the presence of an existing fault combined with favorable injection characteristics, fault slip might occur which can increase the risk of leakage and induced seismicity.[1,5]

Once fault slip initiates, two mechanisms with opposite impacts compete to control the magnitude and rate of slip.[6] On one hand, shear-induced dilatancy of the fault core tends to increase the fault permeability helping the fault zone to be increasingly drained and consequently, to decrease the fluid pressure. On the other hand, if the fault slip occurs fast enough, it becomes harder for the fluid flow to keep up with dilatancy. Consequently, frictional heating is generated leading to heating-induced weakening mechanisms which increase the fault fluid pressure and decrease frictional resistance within the fault shear zone.[6,7] A seismic event occurs if the thermal weakening process during the fault's early slip takes over the shear-induced dilatancy due to the release of tectonic stress driving the fault motion.[8]

While seismic imaging techniques can detect major faults and some fractures, they cannot locate smaller faults and potential leakage pathways such as blind faults, whose lengths are small comparing to the reservoir thickness.[9,10] Therefore, CO_2 can possibly be injected in the vicinity of such minor or blind faults. Further, several studies have recently been performed to explore the feasibility of CCS operations in faulted areas.[11,12] There is very limited, if any, information on the

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* Corresponding author.

E-mail addresses: km1745@msstate.edu (K. Mortezaei), farshid@cee.msstate.edu (F. Vahedifard).

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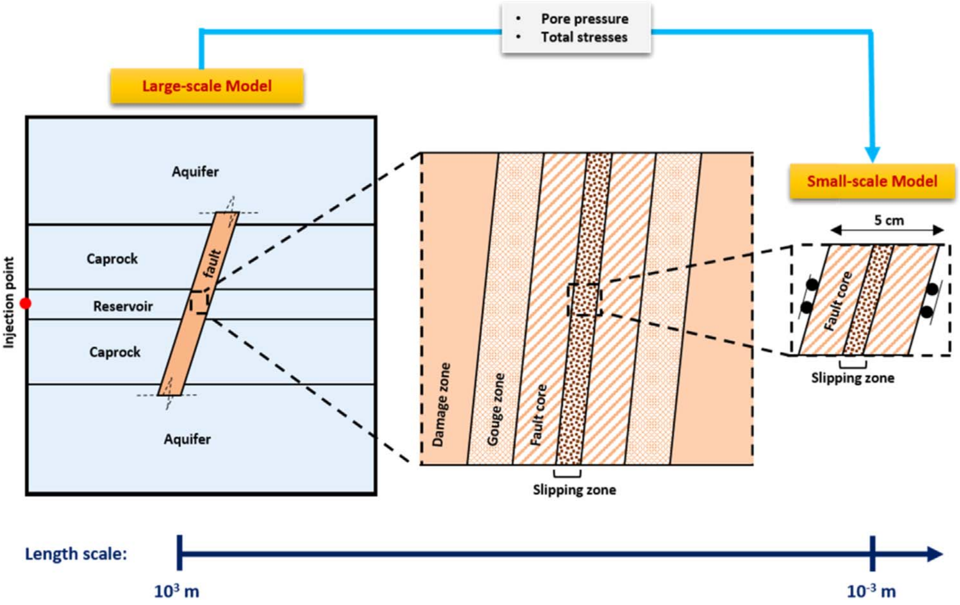

Fig. 1. Schematic representation of a multi-scale model used in this study.

impact of thermal weakening on the response of fault shear zone during CO_2 injection in the vicinity of a stressed fault.

2. Thermal-induced fault weakening during fault slip

Two thermal weakening mechanisms, referred to as flash heating and thermal pressurization (TP), can weaken the fault and decrease frictional resistance along the fault.[7] Flash heating occurs in rapid slips and mostly depends on the slip rate.[7] This mechanism deals with highly stressed micro-scale contacts during slip and decreases the fault friction coefficient. The real contact area (i.e., slip surface) is the sum of contact areas of all the asperities which is a small fraction of the macroscopic contact area. Since the stress supported by the asperities is larger than the stress carried by the fault surface, sliding leads to a large heat production and weakening of the contact.[7,13–17]

Frictional heating generated during slip can lead to another heat-induced fault weakening mechanism referred to as thermal pressurization.[7,18,19] When shear sliding happens, the fault fluid expands in volume much more than the surrounding rock. This is due to the thermal expansion coefficient of the fluid being greater than the shear-induced dilatancy of the rock matrix. Consequently, frictional heating increases pore pressure which decreases the effective normal stress and the coefficient of friction and thus, reduces fault strength.[7,18–22] Mase and Smith[21] pointed out that the fault response depends on the relative magnitude of two time scales: slip duration and thermal pressurization time. Moreover, the mechanical response of the fault is controlled by the width of the fault and hydraulic characteristics of the fault zone and adjacent medium.[21]

Generally, the evolution of pore fluid pressure influences both slip behavior and the coefficient of friction. Some studies have only considered the fluid pressure changes on the slip behavior by assuming a constant frictional coefficient[7,19] whereas other studies incorporated both changes into their models.[22,24,25] Andrews[24] developed a one-dimensional model coupling heat and fluid and calculated the pore pressure increase due to frictional heating in a dynamic rupture. He used a linear integral equation for calculating pressure changes in a three-dimensional fault model governed by a time-weakening friction law. Andrews[24] ignored the advective term, assumed friction and hydraulic diffusivity to be constant and the porosity variation to obey Biot's theory. Bizzarri and Cocco[22] investigated the role of TP on propagation of a three-dimensional crack on a planar fault by evolution of the effective normal stress. They considered changes in normal stress in terms of fault friction and in the case of rate- and state-dependent laws. Rice[7] derived analytical expressions for TP assuming a constant frictional coefficient. He considered two cases and proposed an analytical solution for each case. In one case he assumed the shear zone to be infinitely small (i.e., slip on a plane), and for the second case he assumed a long slip distance implying an adiabatic undrained solution. Miller[26] used a simple constitutive law with two levels of friction with no thermal effect and studied the influence of fluids on earthquake and faulting. Noda et al.[27] implemented rate-state friction and TP of pore fluid into a spectral boundary integral equation code for elastodynamic rupture propagation, and reached to a good agreement between the model ruptures and natural earthquakes.

3. Objective and scope

The main objective of this study is to quantify the impact of TP on the response of the shear zone of a stressed fault which is triggered by CO_2 injection. The problem imposes a complex problem coupling thermal, hydrologic, and geomechanical processes at different scales, which may require a certain set of approximations to tackle the problem at each scale. That is, CO_2 injection occurs in a multi-kilometre reservoir-scale domain whereas TP happens in the shear zone of the fault which is very narrow (e.g., a few millimetres). Consequently, we employed a multi-scale modeling approach to properly simulate CO_2 injection in the reservoir as well as TP in the fault shear zone. As schematically demonstrated in Fig. 1, a large-scale model (Fig. 1, left) is used to simulate CO_2 injection in the reservoir, and a small-scale model (Fig. 1, right) is then used to simulate the fault slipping zone. We adopted a 2-D poroelasticity model to numerically simulate stress changes and fault slip due to CO_2 injection into the reservoir. We assumed that there is a limited-dimension fault at the site and it is critically oriented with a normal faulting stress regime. Once the slip due to CO_2 injection initiated in the stressed fault, the injection was ceased and the induced stresses and pore pressures computed from the large-scale model were passed to the small-scale model as initial conditions to examine the impact of TP. Moreover, comparative studies were performed between two sets of models for each parameter of interest: one set without TP and the second set with TP. For the model including the TP effect, a simple TP constitutive law developed by Andrews[24] was implemented to couple pore pressure changes with temperature rise due to frictional heating. Further, parametric studies were performed to investigate the effects of hydraulic diffusivity,