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Research Paper

A two-scale hydromechanical model for fault zones accounting for their heterogeneous structure

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ABSTRACT

Fault zones show generally hetergeneous structures constituted of a fault core surrounded by damaged zones containing different fracture families. Taking into account this hetergeneous architecture of fault zones on their hydromechanical response to a pore pressure increase in their vicinity is the main goal of the present paper. The hydromechanical behavior of a fault running across a reservoir during a CO_2 injection scenario has been modeled by a two-scale model. At the fault zone scale, statistically distributed fractures are considered to evaluate the equivalent permeability of the fault zone. At the site scale, a specific fault model that takes into account the permeability of different parts of the fault zone is used. The change of the permeability of each damage zone due to the pressure build-up within the reservoir is taken into account. Finally, the proposed model is used to perform large-scale simulations of the injection operation through a multilayered geological site. The model permits to simulate brine flow through the fault zone. The failure reactivation risk can also be estimated through the failure criterion of the fault core's materials, here considered following an elastic perfectly plastic Drucker–Prager criterion.

1. Introduction

The geological storage of carbon dioxide (CO_2) into permeable aquifers has been suggested as an important potential method to reduce the emission of greenhouse gases to the atmosphere [1]. The hydro-mechanical behavior of fault zones is a predominant challenge in view of reliable modeling of the safety and efficiency of this technology. In the last two decades, there has been an increasing interest in the analysis of coupled hydromechanical response of faulted zones and fractured rocks. Characterization of hydraulic conductivity for fractured rock masses, however, is one of the most challenging problems for reliable modeling of coupled processes in faulted zones and fractured rocks.

Evaluation of the sustainable injection pressure is an important part of the safety study of a CO_2 storage site. A fault zone generally has a different permeability comparing to the neighboring rock matrix. If the fault zone runs across the reservoir and the caprock, it may create a potential leakage path leading to the contamination of the aquifers located in upper layers. Even if the reactivation of large faults due to CO_2 injection operation is not very likely, the decrease of effective stress (soil mechanics convention) in the vicinity of smaller or not-detected faults, due to the gas injection, may lead toward the failure of the fault, creating induced seismicity and preferential leakage pathways. Recent works (e.g. [2]) have shown that the storage capacity of a given reservoir is limited by the sustainable overpressure created by the injection (from a safety point of view for the overlying/underlying seals) more than by the available pore-space. Quick assessment methods are always conservative and may lead to severe limitation of the injection flow rate, and thus bias the site selection process.

One simple way for evaluating the fault response is to model the effective stress field in the reservoir, to compute shear and normal stresses of a cohesionless fault as function of the fault dip and to compare them to a fault reactivation criterion (e.g. [3–5]). However, this approach does not allow taking into account the effects of the presence of the fault on the stress and pressure field in the surrounding rock matrix. More accurate modeling strategies are developed recently. A coupled hydromechanical fault-permeability model based on Tough-FLAC^{3D} simulator is presented by Cappa and Rutqvist [6]. The coupled simulations are performed using the finite-thickness elements with the isotropic elasto-plastic constitutive mechanical model. The obtained results show that the permeability changes during fault reactivation is strongly

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dependent on the type of fault and its architecture. Morris et al. [7] presented a large-scale simulation of CO_2 injection within a faulted aquifer. In this study the faults are simulated by introducing directional weakness into the elements of the model that are part of the fault. The obtained results show that development of robust relationships for permeability evolution in reactivated fault zones is fundamental because of the direct link between the permeability along fault zones and the evolving pressure distribution in the reservoir. The importance of *in situ* stress and the geometry of faults are also highlighted [7].

More recently, attempts have been done to taking into account the effect of the internal architecture of the fault zone on its hydromechanical behavior. Seyedi et al. [8] proposed a two-scale equivalent model for the fault behavior. In this model, hydromechanical couplings are taken into account through joint elements located on the both sides of the fault core. However, the choice of relevant parameters for the joint elements represents a practical difficulty. Moreover, joint elements cannot reproduce the heterogeneous character of the fault zone. Rinaldi et al. [9] investigated the effects of fault-zone architecture on induced seismicity and leakage due to CO_2 storage in a deep aquifer through 2D calculations. The fault core is modeled by a ubiquitous-joint element and is surrounded by a damage zone. The differences in the internal architecture of the fault zone result in different pressure distribution in the vicinity of the fault core and affect the reactivation time with different slip and rupture along the fault at the time of reactivation. Rohmer [10] studied the reactivation possibility of a blind normal fault affected by CO_2 injection through 2D hydromechanical simulations. The numerical results show that the presence of a thick fractured hanging wall's damage zone with a decreasing Young's modulus due to the presence of the fractures strongly controls the magnitude of the seismic event induced by the rupture. Pereira et al. [11] investigated the uncertainties related to the fault reactivation analysis using an evidence theory based approach. The total plastic work criterion in the fault zone is considered to estimate the maximum sustainable injection pressure. Aforementioned researches point out the important influence of the fault geometry and architecture, the permeability and mechanical parameters of different segments of the fault zone on its hydraulic role and on the reactivation risk.

The main goal of the present paper is to provide an appropriate modeling approach for accurate simulation of existing faults' behavior during and just after the CO_2 injection phase. A particular attention is paid to accurate evaluation of the permeability of the damaged zone and its evolution due to pressure build-up through a new coupled pressure-permeability model based on homogenization method. In this setting, a two-scale approach is followed. At the fault zone scale, damage zones are modeled as porous media containing statistically distributed fractures. The Equivalent permeability of each zone is calculated considering several families of fractures. The effect of the pressure change on the fracture aperture increase is accounted for through a hydromechanical coupling scheme. At the site scale, an equivalent fault model consisting of a fault core surrounded by equivalent damage zones is considered. Finally, the developed numerical process is applied to evaluate the brine leakage through the fault zone and the fault reactivation risk considering a hypothetical but realistic multi-layer storage site.

2. A hydromechanical model for the fault zone

Faults and their effects on the flow of hydrocarbons have been largely studied in petroleum engineering. Classical model of a fault consists of an inner fault core made of fine materials, often impermeable, and an outer damage zone that acts as a hydraulic pathway. Faults are therefore highly anisotropic and heterogeneous bodies. Faults' structure depends also on the surrounding geological formation. Although the number of observations of deep fault structures is small, the available exposed faults provide some information on their deep structure. A fault "zone" consists of several smaller regions defined by the style and amount of deformation within them. The core material (i.e., gouge) is composed of very fine-grained material that behaves like clay and represent always a largely smaller permeability regarding to the surrounding damage zones. Surrounding the central zone is a region across that contains abundant fractures. Outside that region is another that contains distinguishable fractures, but much less dense than the preceding region. The thickness of the damage zone may vary according to the process by which the fault has grown. Other models involve the formation of a damage zone by linkage of different fractures, that are offset each other. The damage zone represents then patches of rocks that become damaged due to shear between two sliding interfaces [12].

In the present paper, the fractured zones around the fault core (Fig 1a) are replaced by equivalent porous media (Fig 1b) to model the hydromechanical response of the fault zone. The main focus is to improve the estimation of the hydraulic permeability of the fault zone and its evolution during the storage operations, as the main parameter controlling its hydraulic role. In this setting, it is assumed that the permeability of the core, as a clayey fine-grained material, is small with respect to the permeability of the damaged zone. A specific numerical tool, based on the singular-integral-equations method, is developed to calculate the equivalent permeability of dense fracture networks embedded within a porous matrix. The pressure build-up in the vicinity of the fault zone due to the injection operation may increase the hydraulic aperture of the fractures affected by this pressure increase. Developed procedure enables us to calculate the equivalent permeability of the damaged zone and its evolutions due to the pressure build up that will be then used in the fault model.

At the site scale, an equivalent fault model is used to represent its hydromechanical behavior [13,8]. The fault core is represented by a low-permeable porous media (red area on Fig. 1b). An elastic-perfectly plastic constitutive law based on Drucker–Prager failure criterion is assigned to the fault core. Outside the core, equivalent porous media are considered to represent the damaged zones. The porous materials allow the representation of the equivalent permeability of different parts of the fault zone, i.e., the fault core and damaged zone. A small value will be assigned to the permeability of the fault core.

3. Equivalent permeability of the damaged zone

From a hydrogeological point of view, a geological damaged zone (e.g., damage zone around the fault core) can be represented by a statistically distributed fracture network embedded within a porous matrix. The inherent uncertainty in the knowledge of the fracture networks especially in deep formations, such as what is expected in a fault zone potentially in contact with a storage reservoir, requires appropriate statistical treatment usually based on stochastic calculations. Moreover, performance and safety studies in the context of CO_2 geological storage requires long term and large scale computations that renders the use of direct calculations based on discrete fracture networks inappropriate. In this section, an effective medium model is presented to estimate the permeability of fractured porous media adapted to the studies in the context of deep geological fluid injection.

Let us consider a porous domain Ω with a uniform permeability tensor $\boldsymbol{k}$, containing several fractures Γ^m, prescribed by a constant pressure gradient on its boundary, i.e., $p(\underline{x}) = \underline{A} \cdot \underline{x}$ with $\underline{x} \in \partial\Omega$. The