Evaluation of the fault reactivation dynamics using fully coupled hydro-mechanical models

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Abstract

Geological Carbon Storage (GCS) is widely considered as one of the key pillars that will facilitate the energy transition towards Net-Zero Emissions (NZE) targets. The International Energy Agency’s NZE scenario estimates a CO2 storage target of, at least, 1.9 Gt CO2 per year by 2050 (IEA, 2021). This scenario implies significant challenges if we consider that the present-day operational levels (approximately 40 Mt per year are captured and stored worldwide) are equivalent to about 0.1 per cent of the global CO2 emissions. While the next decade is likely to see a huge growth in terms of the number of GCS projects, NZE ambitious goal will not occur without the mitigation of geological risks, as the injection of large volumes of fluid into the subsurface may cause significant overpressure at reservoir and basin scales. The scientific community has already raised some concerns about the Geomechanical challenges associated with storage integrity and induced seismicity, especially due to the existence of faults and fractures (Zoback and Gorelick 2015). Unfortunately, industrial tools that would permit to predict and quantify geological risks are mostly based on fit-for-purpose techniques which address needs in the context of Oil and Gas (O&G) operations. Although these tools have interesting options, they do not necessarily cover all of the simulation needs in the GCS context. When compared with O&G, GCS models tend to require higher-resolution modelling approaches, which are computationally demanding and frequently time consuming or impractical when used together with the standard O&G workflows. The need for new standards (and more advanced simulation features) to quantify Geomechanical risks associated with fluid injection in areas where active faults are present has been recommended also for gas storage projects (Juanes et al 2017).

This paper seeks to advance higher-resolution modelling and simulation approaches that take into account realistic hydromechanical (HM) effects caused by fluid injection in the presence of faulted zones and fracture networks. To validate our modelling and simulation approach, we first studied a recent mesoscale scientific experiment involving controlled injection of fluids in the proximity of a fault surrounded by a low-permeability shale rock (Guglielmi et al, 2021). Data from the 2020 fault stimulation experiment conducted in the Opalinus Clay at Mont Terri, Switzerland was collected from the public literature (Shadoan et al, 2021). For the geomodelling tasks we used the Petrel platform (Schlumberger, 2020). For the simulation tasks we used the COMSOL Multiphysics\textsuperscript{®} software (COMSOL, 2020), which provides modelling workflows to create physics-based models by means of a general-purpose Finite Element Method (FEM) solver, an unstructured mesh generator, and advanced visualization techniques.

A fully coupled HM model that permits to represent fracture re-opening and fluid leakage into the caprock was implemented. The main fault is represented using 3D geometrical objects exported from a realistic geological model, which was built from a complete characterization dataset. The faulted region is composed of an intact rock, a discrete fracture network, and a faulted damaged zone structure. The fractures are modelled using thin structures, acting as high permeability pathways that strongly influence the HM

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response. We use thin elastic boundary conditions, which provide a way to account for the mechanical effects of high-aspect ratio objects without modelling the fracture thickness explicitly. This approach significantly reduces the computational cost of the simulations. The mechanical model relies on the classical Poroelasticity theory, which associates fluid flow in porous media with the equilibrium mechanics equations. The FEM solver has the ability to handle complex geometries and Multiphysics coupling. Once the flow and fault behavior were validated at the mesoscopic scale, a multiphasic field-scale model was developed to investigate geomechanical effects under typical CO2 storage conditions. The procedure here described is based on the following features: 1) the fractures are simulated using thin 2D structures, which is an efficient approach that avoids heavier computational costs incurred with explicit 3D fractures; 2) the geological structure of the main fault was smoothly integrated into the FEM analysis using parametric surfaces and interpolation functions; and 3) an unstructured FEM mesh allowed to accommodate the geometrical complexity of the different model regions. Future work will concentrate on model extensions to evaluate fault slip scenarios using Contact Mechanics algorithms, a multiscale simulation approach for having dedicated models coupling larger-scale phenomena such as the CO2 plume evolution with local-scale phenomena such as fault slip, and the incorporation of thermal expansion effects.

We have devised a procedure which permits to build more realistic models by leveraging advanced simulation options readily available in state-of-the-art Multiphysics solvers. We have obtained satisfactory results proving that the procedure is suitable for solving the numerical challenges imposed by the fault stimulation dynamics. On one hand, results from the mesoscale model indicate that the well observations (flowsrates, downhole pressures, and local displacements) only can be matched using coupled HM simulations. On the other hand, results from the field-scale model confirm that the maximum injection pressure should be constrained to moderate local displacements around the near wellbore and at the reservoir-caprock interface. We believe that this modelling approach would benefit the GCS community from the advance of more representative simulations. Our investigations in this area are still ongoing and seem likely to confirm our hypothesis that it is possible to simulate more realistic representations that will permit to quantify more accurately geological risk scenarios in the context of CO2 storage projects.

References


Figure 1: Illustrations of the meso-scale geological model created in Petrel: (a) geometrical objects (fault surface, model boundary, faulted zone, tunnel galleries and wellbores); and (b) structural objects used in the HM model: faulted region, top and bottom horizons, and well trajectories.

Figure 2: Illustrations of the meso-scale model created in COMSOL: (a) geometrical objects (fault top, mid and bottom surfaces, well perforations, simulation domain); (b) unstructured mesh in the hanging and foot walls; and (c) unstructured mesh in the faulted zone.

Figure 3: Illustrations of the FEM results: (a) S3 principal stress at initial time; and (b) pressure contours at final time.

Keywords: Fault reactivation; CO2 Storage; Coupled Hydro-Mechanical Modelling.