Modelling leakage risk along a fault using Modified Discrete Elements

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Abstract

Understanding fault behaviour is vital to de-risk and optimize CO₂ storage in a chosen site¹. Indeed, if the site is bound by isolating faults and sealing caprock on top, the pore pressure in the reservoir may at some point bring the shear stresses close to the faults to critical slip value. When this happens, the fault permeability may dramatically increase and become conductive, causing the occurrence of a leakage across or along the fault².

Traditionally, faults are implemented as 1D lines in 2D geomechanical software packages (2D planes in 3D codes). Most simulations use some variant of the finite element method, coupling reservoir simulation and geomechanical model³-⁶. However, geological description of faults shows that they are much more complex, with structure evolving outwards from a thin core to a process zone with fractures⁷. Recent more advanced models have started looking at the structure in and around the fault. Such approaches include for example using the Cosserat continuous medium⁸.

The SINTEF MDEM code is based on a triangular finite element grid, to which a failure criterion is associated. At failure, the elements are redefined from a Voronoi tessellation of the basis triangular elements. These clusters are used to define contact lines (in 2D, planes in 3D) potentially failing to create fractures. The code was successfully used to simulate extended leak-off tests⁹. Fluid flow is calculated by coupling MDEM to SINTEF’s MRST reservoir simulator. Fracture permeability can be monitored by tracking fracture aperture in both tensile and shear mode. The hydraulic aperture is calculated as a function of the mechanical aperture that can be decomposed into its initial aperture, the aperture due to normal opening and the aperture due to shear-induced dilatancy. The upscaled permeability of a failed element is a function of the hydraulic aperture¹⁰.

MDEM is primarily a fracturing numerical tool. The goals of the ongoing modelling effort are to run simulations capable of monitoring the evolution of permeability along a fault; this is the principal risk for loss of CO₂ containment in the intended reservoir. Since the process zone near the fault core is a region with existing fractures, this can be a zone where fracture connectivity could be established as the normal effective stresses decrease with increasing pore pressure due to continuous CO₂ injection in the reservoir.

In this work, one fault linking two reservoirs separated by a shale layer is simulated. For the first simulations, the fault core was modelled as a 0 permeability, one-element thick layer with the same chosen properties as the shale layers. Two options were considered for the damage or process zone of the fault: either populate a narrow band to the side of the fault with pre-existing fractures, or simply assign the narrow band weaker strength and stiffness than the other lithologies, to facilitate fracturing there. The output of the simulations follows fracture connectivity evolution with increasing pressure...
in the lower reservoir until a percolation threshold is passed and pressure increase starts to be monitored in the upper reservoir. An equivalent process zone permeability is mapped to the corresponding input parameters such as fault orientation, reservoir thickness and permeability, shale and sandstone mechanical properties and eventually, pore pressure variation history of reservoir (and hence accompanying stress hysteresis in the whole system\textsuperscript{11}).

A simulation where pore pressure was increased monotonically at the injection point, showed that the model is indeed capable of initiating fractures in the weakened zone around the fault. Another simulation, where depletion of the lower reservoir was first carried out, did not reach fracture initiation threshold in the weakened zone (Figure 1). Varying the properties of the layers in the simulation will yield a range where fracturing is likely to occur and pressure communication risks being established. Once these properties are known, an upscaling can be performed, such that a permeability along the fault as a function of stress state can be established and exported to more complex cases using standard finite element methods.

![Figure 1](image.png)

**Figure 1.** Top left: shear stress distribution, top right: horizontal effective stress; bottom left: vertical effective stress and bottom right: pore fluid pressure in a simulation with injection from a well in a depleted reservoir.

References

1. Bohloli, Bahman, Elin Skurtveit, Lars Grande, Geir Ove Titlestad, Marion Børresen, Øistein Johnsen, and Alvar Braathen. 2014. ‘Evaluation of reservoir and cap-rock integrity for the Longyearbyen CO\textsubscript{2} storage pilot based on laboratory experiments and injection tests’.