Investigation of caprock integrity due to pressure build-up during high-volume injection into the Utsira formation

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Abstract

The Utsira formation is a large offshore saline aquifer in the North Sea that is considered a likely candidate for large-scale injection of regional CO₂ emissions. Currently, the Utsira formation is host to the longest operating CO₂ storage project, the Sleipner project, which is injecting produced CO₂ from a deeper hydrocarbon reservoir. Approximately 14 million tons of CO₂ have been injected since 1996, and the operation has demonstrated that CO₂ injection in the Utsira formation is safe and effective. The Utsira formation as a whole has an estimated storage capacity of 15 gigatons (Gt), based on static capacity estimates, which would be comparable to 300 projects equivalent in size to the Sleipner project in simultaneous operation for the next 50 years. Injectivity into the Utsira is exceptionally good, and no significant pressure increase has been observed at the Sleipner project. The formation is over 100-m thick and is comprised of unconsolidated sand with high porosity and permeability, 30-40% and 1-3 Darcy, respectively. The Utsira sand is highly compressible, as much as 10 times more compressible than typical sandstone reservoirs. The sealing layer is the Nordland shale, which has been characterized as a high-quality seal that is regionally thick, extensive and absent of significant faults. Analysis of shale samples taken near the base of the seal indicates a relatively ductile material that is likely softer at shallower depths.

Full utilization of the Utsira storage capacity would result in injection rates of hundreds of megatons per year (Mt/y), which requires a significant scale-up from the current Sleipner injection rate of 1 Mt/y. Despite the lack of pressure effects currently monitored in the Sleipner project, it is likely that higher injection rates will lead to significant pressure build-up in the Utsira formation. This will impact the storage capacity because the pressure must be limited to the mechanical constraint of the caprock, which is here defined by the least compressive stress. Relatively little is known about pressure build-up in the Utsira and the resulting impact on storage capacity and caprock integrity with high-volume injection. No mechanical studies have been done previously at these large scales. The magnitude and extent of the pressure footprint depend on mechanical parameters based on a very limited mechanical dataset. The shale and sand may be heterogeneous and subject to non-uniform deformation over large scales. Another issue is that the sand properties have been measured under compression, which may not be applicable to an unconsolidated material that expands significantly under injection-induced pressurization. The uncertainties in mechanical properties are investigated in this study.
The computational problem is also complex, involving multiphase flow and mechanical deformation of the storage reservoir and the surrounding formations, and covers very large spatial scales, ranging several hundred kilometers in lateral extent. There are significant challenges in applying coupled hydro-mechanical simulators to problems of this scale. The computational effort required to solve such a system with the appropriate resolution is prohibitively high, and therefore efforts to reduce the complexity of the model are often needed. In this study, simplified modeling approaches are investigated. Reduced order multiphase flow models can be coupled with geomechanical models for greater efficiency. Similarly, fully coupled hydro-mechanical models can be applied assuming single-phase flow conditions. Both approaches are applied to the Utsira and compared under a variety of injection scenarios and boundary conditions.

Large-scale pressure build-up and subsequent impact on storage capacity and caprock deformation are quantified for the Utsira formation for high-volume injection rates. The main finding of this study is that uncertainty in mechanical properties leads to significant variation in pressure build-up (both localization of the pressure pulse and magnitude). This results in large differences in estimated storage capacity. In addition, parameter uncertainty also impacts caprock deformations at both the reservoir top and at the sea floor, which has implications for long-term monitoring. This study also quantifies the differences in model approaches, showing that simplified mechanical modelling and coupling approaches gives sufficiently accurate estimates of pressure build-up and deformation, which can significantly reduce the computational effort required to model pressure build-up over large aquifers extending several hundreds of kilometres in spatial extent.