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Use of rock mechanics laboratory data in geomechanical modelling to increase confidence in CO_2 geological storage

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ABSTRACT

One of the many challenges facing carbon capture and storage will be to provide convincing evidence of the geomechanical integrity of any proposed geological storage site. Contrary to storage in depleted hydrocarbon fields, storage in saline aquifer presents many more unknowns in this respect because there will probably be no known previous pressure response history or rock property characterisation. The work presented here was carried out as part of a project investigating the improvement in levels of confidence in all aspects of site selection and characterisation that could be expected with increasing data availability for saline aquifers. Attention here was focused on geomechanical modelling and the rock mechanics data used to populate these models. The models initially used generic geomechanical property data and the potential for shear failure of the intact rock and (fault) reactivation of fractured rock investigated. The models were then updated with laboratory measured rock mechanical properties for actual rock from the proposed storage system locality. The modelled results were changed marginally but did not identify any significant issues of criticality because of the relative geomechanical "benignness" of the storage site.

1. Introduction

Carbon capture and storage (CCS) faces many challenges – among them the validation of safety and quantification of risks associated with any geological storage element. To quantify those risks a thorough understanding of the subsurface chemico-physical processes involved is required together with a capability to simulate them for storage evaluation and design purposes. Although much information can be gathered from other geo-engineered and natural subsurface production/storage activity, the validation of CO_2 geological storage brings together requirements at the forefront of many disciplines. This is particularly so in the area of reservoir simulation, where the once considered sufficient hydrogeological flow modelling for hydrocarbon reservoirs, must be augmented by the modelling of both geochemical and geomechanical processes. In many CO_2 geological storage projects the current methodology is to investigate these processes independently. However they are intrinsically linked and the goal in reservoir simulation for CO_2 geological storage must be to develop modelling methods and techniques that capture the interdependence of all processes involved including flow, thermal, geochemical and geomechanical effects.

Geomechanical effects are recognised as being significant in the behaviour of many producing hydrocarbon reservoirs as dramatically illustrated by the compaction and subsidence in fields such as the Wilmington oilfield in California and Ekofisk in the North Sea. An extensive literature documenting reservoir geomechanics has developed and geomechanical modelling is now recognised as integral part of characterising and simulating the behaviour of many producing hydrocarbon reservoirs. As effort continues to extend the scope of reservoir simulation for CO_2 geological storage it will also be necessary to incorporate geomechanical modelling capabilities for the particular requirements of this type of geo-engineering.

When CO_2 is injected into a porous and permeable formation, it will be forced into the rock pores at a higher pressure than is present in the surrounding rock. This causes changes to the stress state of the rock mass leading to deformation and possible failure of the reservoir and/or seal rock. Pre-existing fractures or faults may be opened up and/or new fractures or faults created, potentially providing conduits for leakage. The conditions under which this may happen are site specific and depend on the injection pressures utilised, the characteristics of the host formation, the in situ stress regime and the production history of the reservoir.

The most immediate risk to leakage in CO_2 geological storage is posed by breaching the caprock. However reactivation may also take place on faults within and transecting the reservoir. An important observation as regards modelling is that the geomechanical domain or region of influence will be much greater than that influenced by just the CO_2 plume itself or indeed any induced pressure

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changes, so a geomechanical model based on just the flow domain alone may not capture all deleterious effects. Some geomechanical effects may not necessarily pose risks to storage integrity if they occur remotely from the contained CO_2 or migration pathways.

Although reservoir simulation is a well established tool in the exploitation of hydrocarbon reservoirs, geomechanical modelling is less practised. In the past, reservoir geomechanics was not considered a priority, with many reservoirs considered technically straight-forward and having undergone only limited depletion and/or pressure support. However, declining resource volumes and increasing oil prices have prompted operators to seek less accessible prospects in formations with higher pressures, higher temperatures and in potentially tectonically active regions. The modelling tools developed in these situations can usefully be applied to CO_2 geological storage.

CO_2 storage in depleted hydrocarbon fields – through enhanced oil and gas recovery projects – has provided the precursor to the CO_2 geological storage industry, but storage in saline aquifers will likely be the main focus of attention in the future due to the significantly greater potential storage capacities they provide. The most extensive theoretical study to date, modelling geomechanical effects in relation to saline aquifer storage has been carried out by Rutqvist and others (Rutqvist et al., 2007, 2008; Rutqvist and Tsang, 2002). The potential for fracture initiation and reactivation of existing fractures was analysed in different in situ stress regimes, commencing with isotropic and normal faulting (extensional) and then extending to a reverse faulting (compressional) regime in a multilayered system. The type of initial stress is a key parameter that determines whether fracturing or shear slip take place sub-horizontally or sub-vertically and in which location. Rutqvist also provides a comprehensive review of the major factors related to geomechanics in the CO_2 storage in deep sedimentary formations (Rutqvist, 2012).

A large body of work in (hydrocarbon) reservoir geomechanics is described in terms of “geomechanical modelling”, “mechanical earth modelling” or other similar terms. A mechanical earth model has been defined as a logical compilation of relevant information about earth stresses and rock mechanical properties based on geomechanical studies and geological, geophysical and reservoir engineering models (Jimenez et al., 2005). It is important to understand that a model in these terms may not specifically refer to modelling in the sense of the simulation of reservoir geomechanical behaviour using numerical modelling software. The geomechanical model may be more accurately described as a geomechanical characterisation, although a degree of analytical modelling may be incorporated in the process. It is in this latter category that a significant amount of work has been done in relation to the geomechanical modelling of subsurface CO_2 storage. A good example of the development of a geomechanical model (or characterisation) of a storage site using the methods described above is given in (Lucier et al., 2006). The paper describes in detail the determination of the in situ stress state from well logs using the methodology given by (Zoback et al., 2003).

Australia’s GEODISC research program into the safe storage of CO_2 in saline aquifers and depleted hydrocarbon reservoirs has also concerned itself with geomechanical modelling (Streit and Hillis, 2003, 2004; Streit and Siggins, 2005; Streit et al., 2005) and focused on the maximum sustainable formation pressures that will not reactivate existing faults or induce new fractures. The methodology used is also based on the Mohr–Coulomb failure criterion and was originally developed as an algorithm for estimating fluid pressures that can induce fault reactivation during depletion in hydrocarbon reservoirs (Streit and Hillis, 2002, 2003).

Recent activity in the area of geomechanical modelling of CO_2 storage in saline aquifers has focussed on the In Salah project in Algeria (Ringrose et al., 2009). The project is distinctive in that ground surface (uplift) deformations measured by satellite airborne radar interferometry (InSAR) can be directly linked to the injection of CO_2 through three horizontal wells. The project is providing a test bed for different modelling approaches from various investigators with efforts being made to match both the magnitude and pattern of surface displacements(Bissell et al., 2011; Morris et al., 2009, 2011; Preisig and Prévost, 2011; Rutqvist et al., 2009, 2010). Recent concerns have been raised over the potential triggering of human detectable seismic events (Cappa and Rutqvist, 2011), as has been observed in some hydraulic fracturing and other gas storage projects.

One of the main challenges of geomechanical modelling is the gathering and assessment of rock mechanical data. A limited appraisal of a particular site can be made using generic data but to increase confidence in safety and security, site specific data are required. The work described here investigates this process.

2. Geomechanical models

There are various approaches to reservoir simulation incorporating geomechanical effects. A coupled analysis whereby there is feedback from the geomechanical model to the flow model is now considered the preferred method. The stress and strain state of the geomechanical model is used to modify the hydraulic properties (porosity and permeability) of the flow model according to (usually) empirical relationships. The exchange of data between the two simulations can be scheduled to take place at different times according to the magnitude of say, the pore pressure changes taking place. A fully coupled analysis all conducted within the same code in which the flow and deformation calculations are solved simultaneously is the most rigorous type of simulation but there may be a heavy computational requirement. The former method was used here.

The geomechanical models were developed from reservoir simulation models of sub-surface CO_2 injection into a saline aquifer at a hypothetical storage site based on the geology to be found just onshore the North Sea coast of Lincolnshire, England. The target storage aquifer formation was the Sherwood Sandstone Group (average porosity 20% and permeability 500 mD) with thicknesses up to 300 m, overlain by the Mercia Mudstone Group as caprock, and underlain by the Roxby sealing formation. Injection of supercritical CO_2 was projected to take place at a depth of around 1200 m i.e. below the 800 m threshold that any phase change to free gas might occur. The CO_2 plume was anticipated to migrate up-dip to the SSW through gently dipping beds, with the primary trapping mechanism expected to be residual, with some structural trapping at sealing sub-vertical faults. The reservoir models themselves were developed as part of a multi-disciplinary project CASSEM (CO_2 Aquifer Storage Site Evaluation and Monitoring) covering all aspects of the CCS chain (Smith et al., 2011).

The reservoir modelling methodology and models were progressed in various stages according to data availability and modelling complexity (Pickup et al., 2011). The geomechanical models are described here as “preliminary models”, referring to the use of published geomechanical property data together with the intermediate stage reservoir models of the CASSEM project, and “updated models” referring to the use of site specific laboratory derived geomechanical property data, together with the final stage reservoir models of the project. The VISAGE coupled reservoir geomechanical simulation software was used for the geomechanical modelling (Schlumberger, 2009).

The reservoir models of the aquifer/caprock CO_2 geological storage system were developed from a Petrel geological geo-cellular model using the ECLIPSE 300 compositional reservoir simulator. The geo-cellular model covered a study area approximately 50 km × 18 km and incorporated surfaces (significant strata