Geomechanical modelling of CO_2 geological storage with the use of site specific rock mechanics laboratory data

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Abstract

Many diverse challenges – political, economic, legal and technical – face the continued development and deployment of geological storage of anthropogenic CO_2. Among the technical challenges will be the satisfactory proof of storage site security and efficacy. Evidence from many past geo-technical projects has shown the investigations and analyses that are required to demonstrate safe and satisfactory performance, will be site specific. This will hold for the geomechanical assessment of saline aquifer storage site integrity where, compared to depleted hydrocarbon fields, there will be no previous pressure response history or rock property characterisation data available.

The work presented was carried out as part of a project investigating the improvement in levels of confidence in all aspects of saline aquifer site selection and characterisation that could be expected with increasing data availability and in-depth analysis. Attention focused on the geomechanical modelling and the rock mechanics data used to populate models of two storage sites in geological settings analogous to those where CO_2 storage might be considered. Coupled geomechanical models were developed from reservoir simulation models initially incorporating generic rock mechanical properties and then laboratory derived site specific properties. The models were run in various configurations to investigate the effect of changing the rock mechanical properties on the geomechanical response of the storage systems.

Modelling results showed that the pressure response at one site due to low injectivity caused significant potential for fault reactivation. Increasing the number of injection wells, thereby reducing the individual rates needed to deliver the target capacity, reduced the injection pressures and ameliorated, but did not eliminate this adverse response.

Keywords

1. Introduction

Geological storage is the final stage of the capture, compression, transport and storage of anthropogenic CO_2 – the carbon capture and storage (CCS) chain. In this process, supercritical CO_2 is injected under pressure into geological formations in a dense fluid state, displacing native pore fluids. Sedimentary basins consisting of alternating layers of coarse (sandstone) and fine-textured (clay, shale, evaporites) sediments are the prime locations for CO_2 geological storage. The sandstone formations – saline aquifers where the pore fluid is brine – provide the storage reservoir and must have sufficient thickness, porosity and permeability to permit adequate quantities of CO_2 to be injected and stored. The shale or evaporite formations with very low permeability act as seals to prevent CO_2 from escaping to the surface or other undesirable locations.

Naturally occurring CO_2 reservoirs exist worldwide, demonstrating that CO_2 can be stored underground for millions of years or longer. Many hydrocarbon reservoirs contain large quantities of CO_2 confirming that they can store CO_2 over geologic time-scales. Ultimately the fate of any sequestered CO_2 will be influenced by many interdependent factors depending on the characteristics of the receiving formations. Experience and data is currently being obtained from injection and storage sites worldwide, with many new projects being proposed and planned (SCCS, 2011).

CCS faces many technical, economic and political challenges. Among them is the validation of safety and quantification of risks associated with the 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 hydro-geological 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 characterizing and simulating the behaviour of many producing hydrocarbon reservoirs (Cook et al., 2007; Settari and Sen, 2007). 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 CCS geo-engineering.

In this study, we look at the differences in geomechanical response at two hypothetical saline aquifer CO_2 storage sites. The geomechanical assessments were part of a wider project investigating the integration of all elements of CCS full chain connectivity from, capture and transport to injection, storage and monitoring. In the project the two sites had quite different features: one was onshore, the other offshore; one had "simple" geology of thick uniform sandstone, the other a "complex" faulted and folded structure; with different levels of legacy subsurface data available. The geomechanical modelling sought to integrate the results of rock mechanical testing carried out on proxy rock core with reservoir models developed for the sites, leading to an assessment of the risk of geomechanical failure affecting storage integrity.

2. Geomechanical model for CO_2 storage: background

When CO_2 is injected into a porous and permeable formation, it will be forced into the interstitial pore space at a higher pressure than exists in the host rock. This causes changes to the stress state of the rock mass which leads 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 utilized, 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 (IPCC,2005). However reactivation for example may also take place on faults within and transecting the reservoir. Because the pressure affected domain is usually more extensive than the CO_2 plume, deleterious geomechanical effects may take place in locations not directly associated with the CO_2 migration pathways, so it is important to be able to predict both the fluid flow and geomechanical behaviour. Some geomechanical effects may not necessarily pose risks to storage integrity, if they occur remotely from the contained CO_2 for example but may still be undesirable e.g. induced seismicity.

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. Failure to be aware of the geomechanics in these circumstances can have severe consequences in terms of compaction, subsidence, wellbore stability, fault reactivation etc.

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.

Saline aquifer storage

Of the types of geological formations suitable for CO_2 storage, saline aquifers provide the most promising targets, given their anticipated large capacities. The most extensive theoretical study to date, modelling geomechanical effects related to CO_2 storage in saline aquifers has been carried out by Rutqvist and others (Rutqvist et al., 2007; Rutqvist et al., 2008; Rutqvist and Tsang, 2002). Their work uses coupled flow/geomechanical simulations of the TOUGH2 code from Lawrence Berkley National Laboratory and Itasca's FLAC3D (Rutqvist et al., 2002).

The complexity of the aquifer models was gradually increased as the studies by Rutqvist et al. progressed, starting as a simple 1D geological column of a single aquifer/caprock system through to 2D models of multi-layered aquifer/caprock systems. The work utilized the concept of "pressure margins" P_{fm} and P_{sm}, or proximity of the fluid pressure P to critical pressures P_{fc} (fracture) and P_{sc} (shear slip). The pressure margins are derived from simplified failure criteria, for the initiation of hydraulic fracturing and the onset of slip on pre-existing faults respectively. The potential for fracture initiation and reactivation of existing fractures is 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.

Observations are made on the differences in the pressure response to injection of single and multilayered aquifer-caprock systems and the authors draw attention to the important conclusion that in a CO_2 storage project much more attention should be paid to the stress field than is current practice for oil and gas exploration and should encompass the entire region affected by mechanical stress changes which is generally more extensive than just the region of fluid pressure change e.g. stress arching in the overburden. Coupled numerical analysis is required for more precise evaluation of sustainable injection pressure which has the advantage that it can be fully integrated with the multiphase fluid flow simulation of the site and can be used for design and optimization of injection/withdrawal operations.

Geomechanical modelling methods

A large body of work in (hydrocarbon) reservoir geomechanics is described in terms of "geomechanical modelling", "mechanical earth modelling" (MEM) 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). 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 and may be more accurately described as a geomechanical characterization.

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 of the above type (Streit and Hillis, 2003, 2004; Streit and

Siggins, 2005; Streit et al., 2005), with attention again 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).

A good example of the development of a geomechanical model (or characterization) 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.

An alternative to the analytical approach described above is to combine the mechanical earth model data derived from wells (1D MEMs) into a full 3D mechanical description of the CO_2 injection site. This and other geophysical data can then be exported to both a reservoir simulator and a mechanical simulator enabling coupled analyses to be carried out. The outline of an example of this is shown in Bérard et al., 2007 which features the use of the VISAGE code.

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., 2011; Morris et al., 2009; Preisig and Prévost, 2011; Rutqvist et al., 2009, 2010).

CO_2 storage in depleted oil and gas reservoirs is complicated by the fact that the reservoir will have undergone a geomechanical history and the prediction of the effects of injection will need to take into account the previous effects of production. There is also the issue of geochemical effects with mineral dissolution and/or precipitation which may alter the geomechanical properties of the rock matrix. These effects will potentially take place over a range of temporal and spatial scales e.g. drying out at the near wellbore within say hours of injection commencing to mineral precipitation in the far field residual plume taking place over millennia after CO_2 injection ceases. Deriving the necessary experimental data to incorporate in to a chemo-mechanical coupled model was considered beyond the scope of the project. In this study we look at the differences in geomechanical response at two hypothetical CO_2 storage sites with models based on site specific laboratory rock mechanics data without the complications of a past pressure history and geochemical effects.

3. Geomechanical models

The geomechanical models were based on reservoir simulation models of CO_2 injection into a saline aquifer. 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). CASSEM adopted the use of two hypothetical exemplar CCS schemes to constrain the parameter and operating factors of surface activities that influence subsurface CO_2 storage site selection. The project exemplars were the Ferrybridge Power Station in Yorkshire, England and the Longannet Power Station in Fife, Scotland. The two schemes included the CO_2 emitted, the capture plant, transportation infrastructure, injection facilities and geological storage. The schemes were modelled to include a new power plant, post-combustion capture plant, pipeline transportation and a store located within 75 km of the CO_2 source. The models used in this paper are for the hypothetical storage sites chosen, one onshore in Lincolnshire, and the other offshore in the Firth of Forth.

The reservoir modelling methodology and models were progressed in various stages according to data availability and modelling complexity (Pickup et al., 2011). Within the reservoir modelling project work package, the idea was to start with very simple models at minimal cost in terms of data, time and money, and then move through in stages to a more complex level of modelling, using more complex simulation tools and techniques, acquiring more site-specific data with which to better constrain the modelling. The objective was that by the third stage, a detailed simulation model would be available that may be used as reliable input for a risk assessment process.

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, 2009b, c)

The models of the aquifer/caprock CO_2 storage site systems were developed from Petrel geological geo-cellular models incorporating surfaces (strata horizons) and faults. The geology was interpreted from a combination of 2D, 3D seismic and well log data as described in Ford et al., 2009 and Monaghan et al. 2009. The Lincolnshire model was relatively straightforward with gently dipping beds of 1 – 2° inclination to the horizontal. The presence of a group of minor sub-vertical faults with throws of the order 10 to 50 m was interpreted in the central region of the model. The Firth of Forth model geology was much more complex with a combination of antilclinal and synclinal structures bounded and intersected by major faults. The geological models are shown in Fig. 1.

The reservoir models were developed using the ECLIPSE 300 compositional reservoir simulator. The study area chosen for the Lincolnshire reservoir model was approximately 50 × 18 km and for the Firth of Forth model 20 × 19 km. The reservoir models were populated with representative stochastic distributions of porosity and permeability based on well log data from within the study areas. In the case of the Lincolnshire site this could be satisfactorily done using data interpolated from 6

boreholes within the modelling area whereas for the Firth of Forth site this had to be carried by extrapolating data from a single borehole outside the area. For the Lincolnshire model distributions were required for three zones – a caprock consisting predominantly of mudstone (Mercia Mudstone Group), the target storage aquifer consisting of sandstone (Sherwood Sandstone group) and a basal formation (Roxby Formation). The faults in the central region of this model, with modest offsets, were treated as transmissibility barriers. In the Firth of Forth model the formations modelled were the Ballagan Formation acting as a seal, the Kinnesswood and Knox Pulpit Formations – the target aquifer and the Glenvale Sandstone Formation as an underburden. Again faults, in this region with more substantial offsets, were treated as transmissibility barriers. The reservoir simulation models are shown in Fig. 2. Note that the sub-layering of the geological units (caprock, aquifer etc.) in the reservoir models was chosen to best capture the flow characteristics of the system.

The ECLIPSE 300 models were run using the CO2STORE option (Schlumberger, 2009a), treating the displacement and solubility interaction of the CO_2 with the brine consisting of dissolved salts sodium chloride, calcium chloride or calcium carbonate. Numerical aquifers – large pore volumes of additional water of the same brine – were connected to the grids to simulate an "open" or extended storage system. CO_2 injection was through a single well in both models, down-dip near the E corner of the Lincolnshire model and on the SW flank of the Forth anticline in the case of the Firth of Forth model. An injection rate of 15 Mt/year over a 15 year period was used, after which the well was shut in for both sites.   In reality, 15 Mt/year could not be injected through a single well and a rate of the order 1 – 2 Mt/year would be more reasonable for these sites. The simulations here therefore represent CO_2 injection through a cluster of wells.

The simulations were run initially up to ~9000 years to check the extent of CO_2 migration. Typical results for CO_2 migration are also presented in Fig. 2 which shows the CO_2 gas saturation in the top layer of the aquifer after ~7000 years. The simulations results confirmed that the free gas was concentrated at the well, spreading away at the end of the injection phase but then continued to migrate very slowly up dip with residual trapping taking place. In the case of the Lincolnshire model structural trapping occurs at the faults in the middle of the model which transect the general migration direction. The up-dip migration is more rapid in the case of the Firth of Forth model. At this site the model also shows some pronounced dissolution of the CO_2 as indicated by the mole fraction distribution plot, where part is seen slumping in to the Leven Syncline. After ~7000 years the trapped gas was still contained within the areal extent of the model.

Various geomechanical models of the storage sites were developed. The first model undertaken was a fine grid model of the Lincolnshire site with an areal cell size 400 × 400 m (96,480 cells). However, the geomechanical model proved to be slightly onerous on computing resources and it was decided to also work with coarser grid models. In the case of the Lincolnshire site this was with an areal cell size of 1000 × 1000 m (21,285 cells) and the Firth of Forth model an areal cell size of 500 × 500 m (21,760 cells). The input data files for the reservoir models were imported into the VISAGE pre-processing program.

The models were prepared for coupled geomechanical analysis. This involves various steps the first of which is to "embed" the model i.e. surround it on all sides, underneath and on top with extra cells which will constitute the side-, under- and over-burdens respectively. Geomechanical embedding of the reservoir model is a method by which the necessary mechanical boundary conditions can be suitably imposed on the reservoir model grid. Essentially specified uniform restraints and tractions set up at a distance removed from the reservoir, will have their effect transferred to the reservoir model through the "uniform" embedding material to the geomechanical model. The idea is that the heterogeneities and geometric irregularities of the reservoir model itself will not unduly influence these effects.

Embedding is a relatively straightforward process but needs to be done carefully to ensure an adequate but not excessive number of cells are added, that there is a smooth gradation in cell size to the model boundaries and that cells sizes are not excessively large or small. The embedded Lincolnshire model was 66,975 cells and the Firth of Forth model 66,240 cells. Overall the geomechanical model extended from the surface at 0 m to 2000 m depth in the case of the Lincolnshire model and 7000 m depth in the case of the Firth of Forth model. The model grids are shown in Fig. 3. Within the active reservoir cells there was a wide range of cell thicknesses. The range was 0.76 to 173 m in the Lincolnshire model and 0.46 to 499 m in the Firth of Forth model. The reservoir embedding (inactive) cells had a considerably wider range of thicknesses.

Mechanical properties

The second stage in the development of the geomechanical models was to assign appropriate geomechanical properties to the various regions of the model. The geomechanical properties were derived from published data, developing correlations of both elastic deformation parameters – Young's modulus E and Poisson's ratio ν – and (Mohr-Coulomb) failure parameters – cohesion S_o and angle of internal friction ϕ – against porosity. Two groups of correlations were developed, one for the aquifer layers in the models assumed to be sandstone and another for the caprock layers, assumed to be mudstone. For the aquifer layers of the models the correlations were based on extensive sandstone data (Edlmann, 2001) and for the caprock on the more limited North Sea shale data (Horsrud et al., 1998, Horsrud, 2001) and are given in Table 1. Note that because of the way the sandstone correlations have been developed that when modelled, failure of the intact rock will be dependent on porosity.

The following transformations are applied to convert the data to in situ Mohr-Coulomb failure parameters required for model input data:

$$S_o = \frac{C_{o\,in\,situ}}{2\sqrt{k}}$$

$$\tan\phi = \frac{k-1}{2\sqrt{k}}$$

$$\text{where } C_{o\,in\,situ} = \frac{C_o}{f}$$

where the failure parameters are given in terms of uniaxial compressive strength C_o and triaxial stress factor k (both as measured in the laboratory) and f is the in situ strength factor (Wilson, 1983). These transformations essentially scale the predictions obtained from experiment based correlations (small scale), to the reservoir scale.

The shale data is not quite so straightforward, as the correlations are not all against porosity. The failure parameters are given in terms of uniaxial compressive strength C_o and failure angle β. These require the following transformations to be applied:

$$S_o = \frac{C_{o\,in\,situ}}{2\tan\beta}$$

$$\phi = 2\beta - 90°$$

again where $C_{o\,in\,situ} = C_o / f$

The factor f – taken as an integer – will vary according to the rock type and degree of fracturing or jointing in situ. Values range from unity for massive unjointed sandstone or siltstone to 6 or 7 for weak rock in a fault zone (Wilson, 1983). A value of 5 was used for f for both the caprock and aquifer, as suggested by Wilson as a general figure or where the precise in situ conditions are unknown.

Stress initialization

The geomechanical analysis calculates effective stresses, where the effective stress is the total stress minus the pore pressure. In a coupled analysis the pore pressure changes calculated by the reservoir simulation are used to modify the stresses starting from an initial effective stress state that must be set up in the geomechanical model. The simplest method of stress initialisation was used for the models whereby the initial stress state is specified and taken as being in equilibrium, rather than induced by external loadings.

Taking the VISAGE Modeler (Schlumberger, 2009c) defaults, the vertical effective stresses were set using a total stress gradient of 22.6 kPa/m (1.00 psi/ft) and a pore pressure gradient of 10.0 kPa/m (0.44 psi/ft). Using this method, for the purposes of the coupled analysis, the absolute value of these gradients is not strictly important. It is the difference in these gradients which determines the initial effective stress gradient, which in this case was 12.6 kPa/m (0.56 psi/ft). The orientation and magnitude of the maximum and minimum horizontal stress components can be further specified. For these components the total stresses are specified in terms of multipliers of the vertical stress. In the absence of actual site borehole data, the World Stress Map – WSM (Heidbach et al., 2009) was referred to.

The Lincolnshire site area (Fig.1) has some limited data shown in Fig. 4(a). Although not definitive, from the orientation of nearby unclassified stress regime data it would appear reasonable to assume the maximum horizontal stress azimuth is in a direction of N 35° E, which is approximately parallel to the strike of the general trend of the dipping bed formations going out into the North Sea. Further, on the basis of other slightly remoter data it has also been assumed that the stress regime at this site is strike-slip.

The Firth of Forth site has no nearby WSM data. However at a regional scale it is likely that the in situ stress regime will be highly influenced by the presence of the Leven Syncline and its geological origins. In the absence of definitive data as to the type of in situ stress regime a strike-slip regime was also assumed. However two options were treated for the orientation of the maximum horizontal stress azimuth, one in the direction of the CO_2 migration path and the other at right angles to the migration path, as illustrated in Fig. 4(b). The following stress ratios were assumed at both sites: $S_{Hmax} = 1.5 \times S_V$ and $S_{hmin} = S_V$.

The geomechanical time step dates of the coupled simulations were chosen at suitable time intervals – initially closer together then lengthening – to track the changes in the aquifer pressure history. The initial reservoir pressures were ~95 bar and ~290 bar in the Lincolnshire and Firth of Forth models respectively. The "field" pressure changes reported by the simulator during the injection phases were 1–2 bar and ~10 bar, again respectively, although much higher pressure changes were predicted in the vicinity of the injectors.

Stress regime modelling

Fracturing of the intact rock can be analysed directly by examining a property termed the "failure value". This property is a measure of the proximity of the stress state at a particular location to the failure envelope. The failure value is a large negative number when the stress state is remote from the failure envelope and becomes less negative the closer the stress state is to the failure envelope. At failure the value is zero.

A simple criterion for fault (fracture) reactivation through shear slip can be derived from the Mohr-Coulomb criterion. For cohesionless faults with a coefficient of friction of 0.6 (field observation lower value, Zoback 2007) this can be expressed as:

$$\sigma'_1 = 3\sigma'_3$$

i.e. shear slip would be induced wherever or whenever the maximum principal effective stress σ'_1 exceeds three times the minimum principal effective stress σ'_3 on preferentially orientated faults. The quotient ($\sigma'_1/3\sigma'_3$) can be calculated, which will be unity at failure. These features are illustrated in Fig. 5.

4. Rock mechanics laboratory data

A suite of rock mechanical property tests were performed on twelve, 1½ inch diameter samples cut from whole core from each of the two target formations near the proposed storage sites. The tests carried out are summarised in Table 2.

Ten aquifer samples (Sherwood Sandstone) and two caprock samples (Mercia Mudstone) were cut from the Lincolnshire site core. Nine aquifer samples (six Knox Pulpit and three Kinneswood sandstone) and three caprock samples (Ballagan Mudstone) were cut from the Firth of Forth site core. The samples were trimmed, using a diamond-tipped blade, to the recommended tolerances for triaxial testing, dried overnight to a constant weight and the sample dimensions and weight measured. The samples varied in length from 1.7 to 3.1 inches and on average were around 2.5 inches long. The ambient porosity of each sample was determined

using a Boyle's Law Helium porosimeter and the liquid equivalent permeability (Klinkenberg) measured using a nitrogen gas permeameter.

For the Lincolnshire site the porosity ranged from 8.9% to 29.7% for the aquifer samples (Sherwood Sandstone) and 1.5% to 5.2% for the caprock samples (Mercia Mudstone). The permeabilities ranged from 0.9 mD to 3546 mD for Sherwood Sandstone however the Mercia Mudstone proved to be impermeable. For the Firth of Forth site the porosities covered a lower range from 2.7% to 15.6% for the aquifer samples and 0.03% to 6.1% for the caprock samples. The permeabilities ranged from 0.03 mD to 16.3 mD for the aquifer samples and 0.01 mD to 0.03 mD for the caprock samples. The measured porosity and permeability values for samples from the two storage sites are shown in Table 3.

To determine the length and diameter changes during the triaxial tests, electrical strain gauges were bonded to the outside of the samples. The strain gauges were supplied in a rosette consisting of two gauges aligned at 90° to each other. The rosette was bonded to the surface of the sample at the mid-point of its length using epoxy resin. Diametrically opposed, a second rosette was bonded to the surface. Thus four strain gauges were bonded to the surface of the sample, two aligned vertically and two aligned horizontally. The electrical connections of the gauges were soldered to plastic coated electrical foil and the whole assembly coated with epoxy resin to protect the gauges and connections.

To investigate the effect of increasing stress on the static and dynamic elastic constants the samples were placed in a Hoek cell (Hoek & Franklin, 1968), with acoustic platens either end, and the whole assembly positioned within the stiff testing machine. The loads applied to the sample were generated by a servo-controlled ram rated to 1000 kN. Associated with the stiff testing machine was a pressure intensifier that controlled the pressure within the annulus of the Hoek cell, which applied the confining pressure to the radial surface of the samples. The stress was increased hydrostatically until the first stress level was reached 6.9 MPa (1000 psi). The axial load was then varied by approximately 3 kN to produce a response in the vertical and horizontal strain gauges. The confining pressure was held constant during this variation in load. The changes in axial and radial stress and strain were then used to determine the static elastic constants (Young's Modulus and Poisson's ratio). The acoustic platens were used to generate a compressional and shear wave through the sample and this captured using an oscilloscope. The arrival of the waves was then picked from the waveform and this used to calculate the compressional velocity (V_p), shear velocity (V_s). The dynamic elastic constants (Young's Modulus and Poisson's ratio) were then calculated using V_p, V_s and the sample bulk density. The procedure was repeated in 3.5 MPa (500 psi) stress steps to 27.6 MPa (4000 psi), the stress reduced to zero and the sample unloaded from the Hoek cell.

To investigate the effect of increasing stress on the porosity, permeability and dynamic elastic constants of the aquifer samples the samples were saturated to 100% pore volume saturation. No attempt was made to saturate the caprock samples due to their very low permeability. Brines for both the Lincolnshire and Firth of Forth were prepared to recipes reported for each formation and the viscosity and density of the brines measured before use in the saturated tests. The samples were

saturated to 100% pore volume saturation using a vacuum saturator and stored under brine until required for testing.

The samples were loaded into the Hoek cell and porous acoustic platens placed either end of the samples. Due to the design of these platens the strain gauges could no longer be used for the static elastic constants measurements. The Hoek cell was positioned in the servo-controlled stiff testing machine and the stress increased to 1.4 MPa (200 psi). At this point several pore volumes of formation brine were pumped through the samples to ensure 100% sample saturation. Brine flow through the sample was collected in a vessel mounted in an electronic, gravimetric balance. The weight of the expelled brine was used to determine the volume of expelled brine during the tests. Brine flow was stopped and the stress was then increased hydrostatically to the first stress level and the pore volume squeeze-out allowed to reach a constant value. When a constant squeeze-out was reached brine was flowed through the samples until a constant differential pressure (ΔP) was reached, the values of ΔP and flow rate were recorded. The porosity and permeability of the samples was determined using the pore volume squeeze-out data and the brine flow date, respectively. The acoustic system was then used to produce the P and S waves, the velocities determined and elastic constants calculated, as in the dry tests. The stress was then increased hydrostatically to the next stress level and the procedure repeated.

The saturated samples and the dry caprock samples were then tested to (shear) failure using the multi-failure state method. These tests were used to determine the failure criteria describing the development of rock strength with increasing confining pressure. The tests were driven using axial load and axial deformation outputs recorded in real time.   At the particular confining pressures the axial load was permitted to increase and stopped when near failure was detected (as indicated by a rapid reduction in the rate at which the load increased). The confining pressure was then increased to the next level and the axial load allowed to increase and then stopped, as before. The tests were terminated at the maximum confining pressure of the loading cycle by allowing the sample to fail. A plot of axial stress versus confining stress at failure enables a straight line fit to be made, from which the UCS and triaxial stress factor are the intercept on the axial stress axis and slope respectively.

Site specific geomechanical properties

The laboratory measurements were analysed and compared to the geomechanical property correlations derived from generic data. The analysis of the measurements was carried out in three parts: (elastic) deformation properties, failure properties and the permeability sensitivity to stress (aquifer rock only). The term failure as used here is the permanent deformation of the rock material through the formation of crushed zones, fracture planes and faults as opposed to elastic deformation which is largely reversible. The former is typically characterised by the failure properties cohesion and angle of internal friction, and the latter by the elastic (here termed deformation) properties Young's modulus & Poisson's ratio derived from the strain gauge measurements on the rock samples. The details of the procedure used to derive the geomechanical properties are described elsewhere (Olden et al., 2012). Due to the vagaries of laboratory testing the complete suite of tests described above was not carried out on all the samples.

The generic property correlations and laboratory measurements are shown in Fig. 6 (aquifer elastic deformation properties), Fig. 7 (caprock elastic deformation properties) and Fig. 8 (aquifer and caprock failure properties). In these figures the left hand side plots (a) relate to the Lincolnshire samples and the right hand side plots (b) to the Firth of Forth samples.

As noted above, the Lincolnshire aquifer samples covered a good range of porosity. The laboratory measurements showed typical differences to be expected depending on the property/condition of the rock i.e. dynamic Young's modulus values are higher than static values and are also higher with brine pore fluid. The Firth of Forth samples covered a narrower and generally lower porosity range. The values actually required for the geomechanical modelling – static, brine saturated condition – were not explicitly available from the laboratory data, but the generic Young's modulus correlations looked generally satisfactory, whereas the Poisson's ratio correlations looked as if they would under-estimate values. The proposed modifications are shown in Fig. 6.

There were very limited measurements for the few caprock (mudstone) samples – the porosities being at the low end of the scale, covering a very narrow porosity range. However, the Young's modulus preliminary correlations again appeared satisfactory, whilst the Poisson's ratio correlations may also again under-estimate values. The proposed modifications are shown in Fig. 7. For the deformation properties then of both the aquifer and caprock material, only changes were made to the Poisson's ratio correlations of both the aquifer and caprock – these would be expected to have a limited effect on the overall geomechanical response of the models to pore pressure changes because they primarily affect displacements.

The rock failure properties were taken from the multi-failure state testing data on the brine saturated samples. The calculated Mohr-Coulomb cohesion values were again adjusted to in situ cohesion values using an in situ strength factor of 5. The values of in situ cohesion and angle of internal friction could then be compared to the generic correlations as shown in Fig. 8. Again, there were limited points, particularly for the caprock samples, however there was reasonable agreement with the generic correlations for in situ cohesion of the caprock material and angle of internal friction of the aquifer material. The derived in situ cohesion values of the aquifer material from the laboratory measurements – where there was a reasonable spread of porosity values in the case of the Firth of Forth samples – indicates that the generic correlations may under-estimate this, whereas the angle of internal friction of the caprock material has been over-estimated. Increasing the in situ cohesion will have ameliorating effects on failure of intact rock in the aquifer, but reducing the angle of internal friction is likely to have detrimental effects i.e. increasing likelihood of failure of intact rock in the caprock.

For the failure properties then, the in situ cohesion values of the aquifer material were increased (this would reduce the potential for failure) whilst the angle of internal friction of the caprock material was decreased (increasing the potential for failure). The latter correlation was tentatively modified (on the basis of very limited laboratory data), as small changes to the angle of internal friction can make large differences in the potential for geomechanical (shear) failure.

Permeability stress sensitivity

The triaxial tests on brine saturated (aquifer) sandstone samples enabled permeability stress sensitivity curves to be generated as also described elsewhere (Olden et al., 2012). The curves were used to calculate permeability reduction factors depending on mean effective stress, deriving initial in situ permeabilities for the updated geomechanical models depending on the initial mean effective stresses.

5. Modelling results

The coupled geomechanical models were run in two configurations – first using the generic geomechanical property correlations and then using the modified (site specific) correlations. The modelling results are presented as time sequenced areal plots of failure and slip calculation values for various caprock layers and the upper aquifer layers (other layers were examined but are not discussed here as the main effects were in these layers). Again, note that the layers referred to here are sub-layers of the basic geological units (caprock, aquifer etc.) of the storage system. For simplicity and to aid interpretation a reduced subset of the geomechanical timesteps has been plotted and the location of the injector in the plots is indicated by "INJ1".

Fig. 9 shows the initial failure value results for the Lincolnshire model indicating the potential for incipient fracture (shear failure) in the caprock bottom layer, as predicted by the Mohr-Coulomb failure criterion. The results can be interpreted as follows: blue – non-failed, red – at or near failure. It can be seen that there is very little difference between the results using the generic correlations (a) and the site specific geomechanical property correlations (b). There is marginally more indication of shear failure potential in the latter case because of the reduction in internal angle of friction but actual failure prediction is very sparse. The results show that some regions are closer to failure than others. This is due to the stochastic nature of modeled porosity distribution.

The slip calculation results – potential for (strike-slip) fault reactivation in the upper aquifer layer are shown in Fig. 10. The results can be interpreted as follows: blue – non-slip, red – calculation value unity i.e. slipping on preferentially aligned fracture and faults. An initial perturbation occurs in the region of the injector (light blue area) in the early stage of injection but as the aquifer pressure increases and the principal effective stress magnitudes change this disappears and the main effect is seen in the up-dip part of the model (green trending towards the bottom left hand edge as shown in the figure). Again, as the pressure response equilibrates throughout the aquifer/caprock system – the faults are not continuous barriers to flow – this effect also disappears. Spatially these effects are not so localised as the failure value results because they don't depend on the intact rock failure properties. In this case, although reactivation of faults is predicted by the model the region where this occurs is remote from the CO_2 plume and therefore does not pose a threat to storage integrity – compare the green region in Fig. 10 (increased potential for fault slip) to the migration plume in Fig 2(a). There is virtually no difference between the models with different correlations essentially because the pore pressure distributions are the same for each model. These and the intact rock failure results indicate the relative benignness of this site for CO_2 geological storage as regards geomechanical integrity.

The Firth of Forth models were run with two orientations of azimuth S_{Hmax} – N 15° W and N 75° E. All the above models were run with a single injection well with a target injection rate of 15 Mt/year of CO_2. A further case of the Firth of Forth model was run with multiple vertical injection wells – 16 wells injecting at a rate of ~1 Mt/year each.

The results for the two different orientations of S_{Hmax} were very similar – only those for the S_{Hmax} – N 15° W case are shown here. The intact rock failure results for the aquifer top layer are shown in Fig. 11. For this site it can be seen that the rock

failure is concentrated at the well location and its greatest effect is at the end of injection for the case with the generic correlations. For the case with the site specific correlations the effect is reduced because of the increase in in situ cohesion has increased the rock strength. No general intact rock failure occurs throughout the model because the higher injection pressures required have concentrated the effects at the well location.

The slip calculation effects for this site are much more extensive with the very strong potential for fault reactivation as shown in Fig. 12. The potential is again hardly changed by the correlations used and is very extensive at the well location in the aquifer top layer as shown. There is also significant potential for fault reactivation in the caprock layers (not shown here). This would suggest that injecting CO_2 at a rate of 15 Mt/year at this site could pose a threat to storage integrity.

In order to reduce the injection pressure associated with injection through a single well a model of the Firth of Forth site was run with 16 vertical injection wells spaced ~1 km apart replacing the single injector. For this case only the site specific geomechanical property correlations were used. The results for this case are shown in Fig. 13. For the intact rock failure this was now only observed in the caprock bottom and middle layers, having been eliminated from the aquifer layers. For the slip calculation results the potential for fault reactivation was eliminated in the aquifer layers, but still remained in the caprock layer although ameliorated when compared the single well injection cases. This result again indicates that this site could pose geomechanical challenges for CO_2 storage.

6. Conclusions

Proof of the geomechanical structural integrity of storage sites will be an important factor in the successful deployment of CCS. Given the uniqueness of potential storage sites this will need to be assessed on a case by case basis. Coupled reservoir simulation and geomechanical modelling will be one of the techniques used to achieve this. Simulation methods currently used in hydrocarbon extraction provide suitable techniques, but these will need to be adapted for CO_2 geological storage with an emphasis on compositional reservoir simulation, the potential for geomechanical effects out with the reservoir flow domain and in the case of depleted oil and gas reservoirs, pre-injection pressure history. These modelling techniques will require the gathering of site specific rock property data, including the measurement of geomechanical properties. Although not considered here, geochemical alterations of geomechanical properties may also need to be treated.

The work reported here endeavoured to explore this process. The geomechanical modelling was carried out on two hypothetical storage sites with different characteristics. The first site had simple geology with gently dipping formations (where storage could be expected to be primarily by residual trapping) whilst the second site had a more complex synclinal/anticlinal geology (where structural trapping would be expected to dominate). Faults were present at both sites, providing some structural trapping at the first site and adding to the geological complexity at the second site.

The geomechanical models were developed using generic and site specific correlations between rock deformation and failure parameters and porosity. The site

specific correlations were derived from laboratory rock mechanics data. Assumptions were made about the in situ stress state and modelling results were used to make predictions about the likely timing and extent of both failure of the intact rock and reactivation of faults within the layers comprising the aquifer and caprock of the potential storage sites.

Predictions of failure of the intact rock and reactivation of faults in the models show different characteristics. Failure of the intact rock is closely associated with regions of weak rock (high porosity) within the models together with the lesser influence of depth (which determines the relative magnitudes of the in situ stresses). These characteristics are in turn influenced by the porosity realisations generated in the underlying geological model and the in situ strength factor used to scale up laboratory UCS to reservoir (in situ) UCS. The porosity realisations were generated stochastically in the models, based on mean and standard deviations from well data. Although the actual porosity distribution is unknown, the results indicated that there are likely to be locations which are more prone to failure than others. A factor of 5 was used to scale the laboratory UCS to the reservoir value. This value is an assumption which ideally should be investigated with a separate sensitivity study.

Reactivation of faults is independent of the failure (porosity) characteristics of the models and is primarily determined by the relative magnitudes of the minimum and maximum effective stresses which are directly related to the in situ stress regime and spatial and temporal changes in pore pressure.

The model results showed that the Forth site intact fault reactivation potential was significant. The main reason was the pressure response of the system with low injectivity which resulted in very high injection pressures to achieve the target CO_2 injection rates. Increasing the number of wells, thereby reducing the individual well injection rates needed to deliver the same total CO_2 injection, reduces the injection pressures and ameliorated although did not eliminate this adverse response.

The most important conclusion that can be drawn from the geomechanical modelling is the significance of realistic and accurate pressure response prediction on the induced geomechanical response of the storage system. Further a potential storage site may be wrongfully selected or rejected on the basis of inappropriate geomechanical data.

On the basis of the geomechanical modelling results the Forth appears to be the less suitable site geomechanically due to greater injection pressures necessary to achieve the storage requirements with corresponding greater risk of loss of geomechanical integrity. It is also recognized that a limited geomechanical analysis was carried out which did not consider the effects of faults and fractures modelled more directly, to achieve a feedback in the flow response to strain induced permeability changes on faults. However, this requires further geomechanical data, and the capability to simulate these effects.

Acknowledgements

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