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The impact of geomechanics on monitoring techniques for CO_2 injection and storage

Tom Lynch[a,b]*, Doug Angus[b], Quentin Fisher[b], Piroska Lorinczi[b]

[a]Low Carbon Technologies DTC, Faculty of Engineering, University of Leeds, UK
[b]CiPEG, School of Earth and Environment, University of Leeds, UK

Abstract

Surface seismic and vertical seismic profile (VSP) time-lapse surveys have demonstrated the capability of temporally and spatially tracking the storage of CO_2 within the subsurface geological formation, however quantitatively linking changes in seismic attributes to fluid flow remains problematic. This study uses coupled geomechanical-fluid flow models to generate seismic attributes and compares the impact of geomechanics on seismic attributes to non-coupled models. Prediction of seismic data may be important in predictive modelling of fluid flow properties for CO_2 storage projects and aid in the design of monitoring programs, and the calibration of predictive models. Incorporating geomechanical impacts on seismic attribute predictions will increase the level of sophistication of fluid flow models and may improve the predictive capabilities of such model. Future work will involve the analysis of seismic attribute prediction using a full study of material, geometric and fault properties in the existing model, and extension of this work to a full field North Sea depleted field model, using the initial work as a benchmark.

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Keywords: Coupled; geomechanics; seismic prediction; geomechanical simulation; seismic attributes

1. Introduction

Seismic methods have been used as a tool to monitor the flow and storage of injected CO_2 for various carbon capture and storage (CCS) pilot studies. Surface seismic and vertical seismic profile (VSP) time-lapse surveys have demonstrated the capability of temporally and spatially tracking the storage of CO_2 within the subsurface geological formation (e.g., Daley et al, [2] at Frio, Chadwick et al, [3] at Sleipner; White [4] at Weyburn). Microseismic monitoring has been used to monitor the injection of CO_2 and the integrity of the cap rock (e.g., Urbancic et al, [5], Verdon et al, at Ostego; [6] at Weyburn). Although

* Corresponding author. Tel.: +44(0)113-343-2556; fax: +44(0)113-246-7310.
E-mail address: pmtol@leeds.ac.uk.

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these techniques have demonstrated capability to track the flow and containment of CO_2, quantitatively linking changes in seismic attributes (e.g., reflection amplitude) to fluid-flow properties (e.g., volume and saturation) is often difficult and uncertain.

The coupling of fluid-flow simulators to geomechanical modelling software allows the impact of geomechanical deformation of the reservoir to be considered, which may have a significant impact on the reservoir pressures, and mechanical behavior of the reservoir. Furthermore, coupled approaches enable the assessment of reservoir deformation in the overburden and hence quantify the security of containment. Verdon et al, have shown the benefits of integrating coupled flow-geomechanical simulation with seismic observations using a poroelastic model [7]. In this study, we use a poroelastoplastic constitutive material model and a model geometry representing a simple faulted graben style sandstone reservoir to investigate the seismic and geomechanical attributes of a CO_2 injection scenario, using both coupled and non-coupled fluid flow simulations. The aim of the study is to generate comparisons of predictions of P and S wave velocities and reflection amplitudes using both simulation techniques.

2. Method

1.1. Coupled fluid-flow and geomechanical simulation

Although formulations exist for fully coupled fluid flow and geomechanical simulation, their computational expense in terms of simulation time make iteratively or loosely coupled schemes more attractive approaches [8]. Furthermore, since there are various commercial fluid flow and geomechanical simulation packages already available, there has been an interest in developing coupling techniques and workflows to link these various industry software packages for improved "in–house" reservoir modeling. We use an algorithm that links the TEMPEST™ (ROXAR) reservoir flow simulator with the geomechanical simulator ELFEN™ (Rockfield Software Ltd.). An extensive study on the influence of reservoir geometry and material properties on stress path during production using coupled fluid-flow and geomechanical simulation has been carried out using this workflow [9].

The fundamental principle behind the coupling technique is illustrated schematically in Figure 1. The process is controlled by the ElfenRS module, this handles the exchange of information between the two programs using message passing interface (MPI) protocols. The initial grid and porosity of the reservoir model are passed to Elfen, Elfen then maps this information onto the geomechanical grid, which is much larger, representing the overburden and under and side burden surrounding the reservoir. For each step Tempest passes the calculated fluid pressures to Elfen, Elfen computes the modified pore volume based on the calculated deformation and passes the modified pore volume back to Tempest.

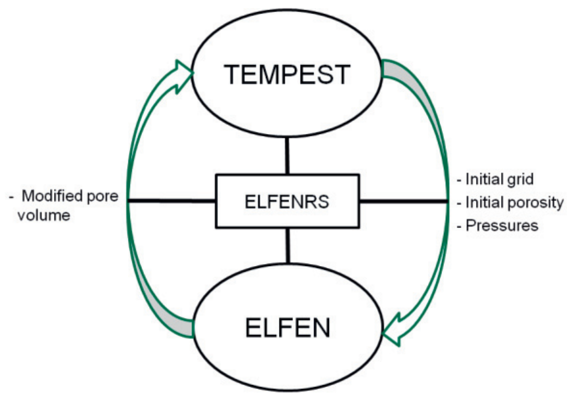

Figure 1 - Schematic diagram of Tempest-Elfen fluid-flow geomechanical simulation.

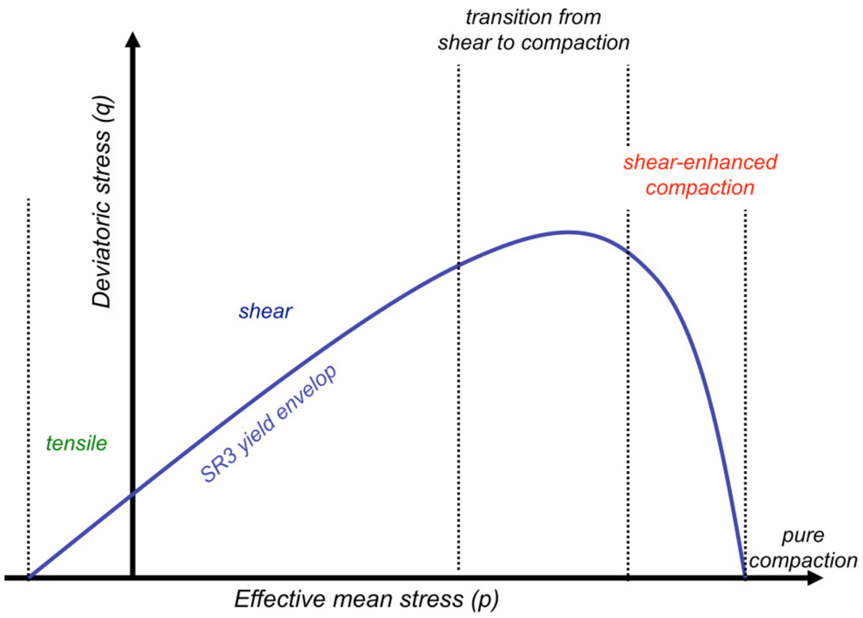

Figure 2 – From Angus et al 2010, SR3 non-linear yield function in p-q space, defining the transition from elastic to plastic irrecoverable deformation. The failure modes represented by the model, tensile, shear, shear-enhanced compaction and pure compaction are highlighted [1].

1.2. Constitutive Model

The constitutive model used in for the geomechanical model is the SR3 (standing for soft rock 3) model, developed by Crook et al, [10], the model is discussed in previous studies using the same coupling technique e.g. Angus et al. [1]. The model is based on critical state soil mechanics and utilises triaxial data for calibration, the main features of the SR3 model are the non-linear yield function, unification of shearing and consolidation properties and the ability to model material hardening and softening behaviour [1], this allows the geomechanical model to capture a range of material behaviours dependent on the stress path. Figure 2 shows the elliptical failure/yield surface in p-q space.

1.3. Rock physics modelling

To predict the seismic response based on the results of the reservoir simulator as well as the coupled fluid-flow/geomechanical simulator, rock physics models are required that map changes in fluid saturation, pore pressure, and effective stresses into seismic stiffness. The workflow used to build the dynamic elastic model is based on constructing an aggregate elasticity starting from the micro-scale (e.g., intrinsic anisotropy) and working up to the macro-scale (field-scale fractures) [11]. Such a model should account for intrinsic rock properties and microstructural fabrics [12], stress-dependent seismic velocities

[13], and fluid substitution effects either at low frequency [14] or including dispersive effects induced by squirt-flow [15]. The influence of coherent fracture sets is modelled using Hudson et al. and Schoenberg & Sayers [16, 17].

In this study, we use Gassmann's equation to predict the influence of fluid saturation on seismic velocity and for the coupled fluid-flow and geomechanical simulation we also map the influence of stress perturbations onto seismic velocity changes. To do this we adopted the microstructural model of Verdon et al. because it represents a conceptually attractive approach to describe the stress dependence of seismic velocity and anisotropy [13], the seismic anisotropy is presented using Thomsen parameters, ε, δ and γ [18]. The microstructural model assumes that a fraction of the total porosity of the rock can be considered compliant. Although negligible in volume, the compliance of these features, sometimes referred to as microcracks, dominates the nonlinear stiffness response. As stresses increase, these features are forced closed, increasing the seismic velocity and reducing the stress-sensitivity, matching the nonlinear response that is empirically observed.

1.4. Scenario Comparison

In this study two CO_2 storage scenarios are investigated, single well injection into a saline aquifer, and natural gas depletion and CO_2 re-injection, the latter forms part of the investigation into stress path hysteresis presented elsewhere in this volume by the authors. The flow models use black oil formulations to represent the CO_2 fluid, and the depletion-injection scenario uses restart files to adjust the gas properties for injection. The saline aquifer scenario involves bottom hole pressure controlled injection of the CO_2 into a saline aquifer, and the depletion-re-injection scenario involves depletion of the natural gas reservoir to a minimal value, and rate controlled CO_2 reinjection to initial reservoir pressure. The coupled and non-coupled solutions to the scenarios, and the derived seismic parameters, are compared in each case.

In order to make the non-coupled solutions comparable, the compressibility specified in the flow model was matched to the parameters of the coupled model using the rock compressibility parameter in Tempest. The rock compressibility is the only geomechanical parameter that can be specified in the Tempest, and determines the volume change of the reservoir due to pressure changes, this in turn changes the pore volume, the parameter is uniform across the reservoir. The relationship show in Equation (1) was used to calibrate the geomechanical parameters of the coupled model and the rock compressibility in the non-coupled models [19]; E is Young's Modulus, φ is porosity and ν is Poisson's Ratio from the coupled model.

$$C = \frac{1}{\varphi}\frac{1}{E}\frac{(1+\nu)(1-2\nu)}{(1-\nu)} \tag{1}$$

3. Model Geometry and Parameters

The model we used to study the geomechanical impact of CO_2 injection on predicted seismic attributes has been used in previous studies. Angus et al, presented initial results from the coupled flow-geomechanical simulations to show the effect of fault transmissibility due to production on various seismic attributes [20]. For the high transmissibility example, travel-time anomalies for both the overburden and reservoir are observed over the lateral extent of the reservoir and indicate that the two normal faults may act as a stress guide. As fault transmissibility is reduced, the travel-time anomalies become more localized. Shear–wave splitting shows similar patterns [20]. Angus et al, predict production induced microseismicity and show, that for this reservoir geometry, fault movement as well as fluid extraction can influence the spatial, temporal and scalar moment of microseismicity [1]. For non-sealing faults, failure occurs within and surrounding all reservoir compartments and significant distribution located near the surface of the overburden. Movement of faults leads to increase in shear-enhanced compaction events within the reservoir and shear events located within the side-burden adjacent to the fault. The moment magnitude distributions of shear events show low values near the surface, moderate values near the faults and high values along the reservoir boundary. Overall, the results from the study indicate that it may be possible to identify compartment boundaries based on the results of microseismic monitoring.

The model consists of a sandstone reservoir with two normal faults subdividing the reservoir into three compartments (see Figure 3). The surrounding shale rock and reservoir sandstone are initially seismically isotropic. The bounding model is a rectangular volume having lateral dimensions of 18.6 km x 9.3 km, and depth 3.72 km. The reservoir has lateral dimensions of 7 km x 3.5 km, thickness 76 m and is located at a depth of 3.048 km. Four coupled flow–geomechanical simulations are performed; two varying the fault transmissibility multiplier from high (0.98) to zero (0.00001), and two varying the fault plane coefficient of friction from a high value (μ =0.750) to a low value (μ=0.375). For the injection only simulations, CO_2 is injected at a maximum rate controlled by the fracture pressure/bottom hole pressure, and for the depletion-reinjection scenario the CO_2 injection is rate controlled, with a maximum bottom hole pressure equal to the initial reservoir pressure, so that pre-depletion and post-injection states are comparable in terms of pressure.

4. Results and Discussion

Initial results are presented for the model with high fault transmissibility and low fault plane friction

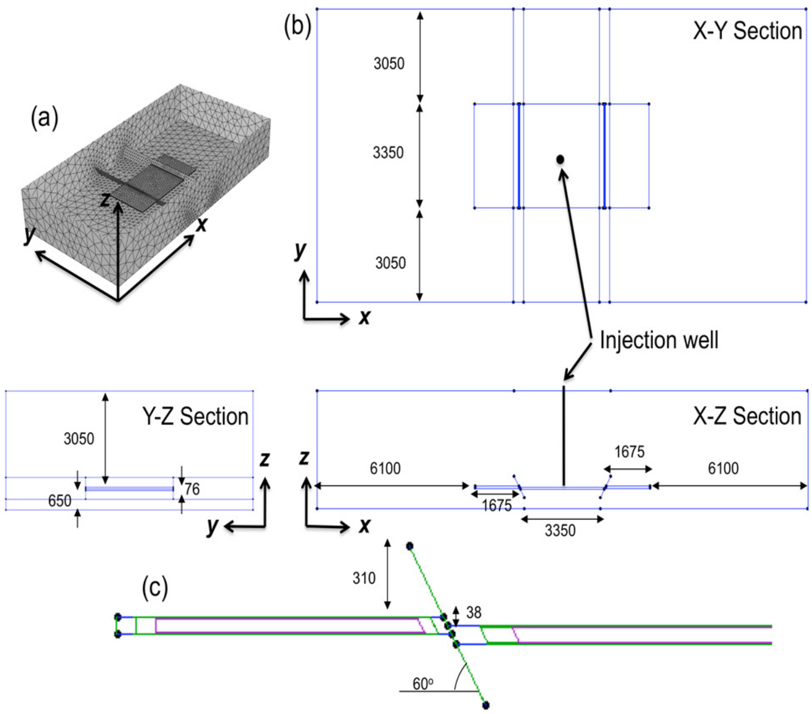

Figure 3 – a) Triangular mesh version of geomechanical model from Elfen. b) Plan and cross sections of model illustrating dimensions of flow and geomechanical models, the flow model is surrounded by the much larger geomechanical model representing the overburden and side and underburden. c) Fault geometry.

coefficient. In this case the fault is non-sealing for flow across the fault and there is potential for deformation to be accommodated by fault movement. The model does not simulate fault plane flow, and so cannot model leakage of CO_2 vertically along the fault, or leakage from the reservoir into the caprock.

Figure 4 and Figure 5 show some initial results from this study, the figures are plots of the fluid saturation and P-wave velocity generated in Tempest, the plots compare the non-coupled (Tempest analysis only) and coupled solution using geomechanical analysis with Elfen. In this case the gas storage total in the coupled solution was 1000 MScf higher than the non-coupled solution, this difference between the two solutions can be detected in the profiles of saturation shown in Figure 4, however the differences are more pronounced in the P-wave velocity profile shown in Figure 5 as even small saturations will affect the Gassmann's solution of P-wave velocity. In this case the reservoir compressibility modeled using the single equation in the non-coupled solution does not accurately model the behaviour of the full system and underestimates the volume injected in the coupled solution by ~6.5% of the total. The differences could result from the fault movement or the mechanical behaviour of the sandstone/shale reservoir system, or a combination of the two. Flow models of reservoirs are likely to be a key method by which CO_2 storage projects are assessed prior to actual test injections and full scale injection, the may be employed both to estimate the commercial sustainability of a project and to assure regulators of the safety and feasibility of the project. As part of the reservoir assessment seismic monitoring may be used, and the generation of synthetic seismics to model the predicted observations once injection operations start (in order to ground truth/calibrate the model) is likely. In this case it will be important to understand the impact of geomechanical factors on the seismic data observed at the surface, something that is currently not generally taken into account in flow models, and which cannot be modeled sufficiently in many cases with flow models alone.

Using the coupled geomechanical-fluid flow modelling approach allows seismic attribute predictions to be generated from the stress analysis performed by the geomechanical software. Figure 6 shows some initial results, the figure shows plots of seismic anisotropy and Thomsen parameters during the production phase of the model. The plots show the development of anisotropy around the reservoir, and in the cap rock above the reservoir, anisotropy is indicative of non-hydrostatic stress development and can indicate stress arching above the reservoir. Stress arching causes stress changes to occur predominantly in the overburden rather than in the reservoir [9] and may therefore affect fluid flow within the reservoir, depending upon the reservoir stress arching may be an important factor in CO_2 storage as it may have an unexpected impact upon the reservoir conditions.

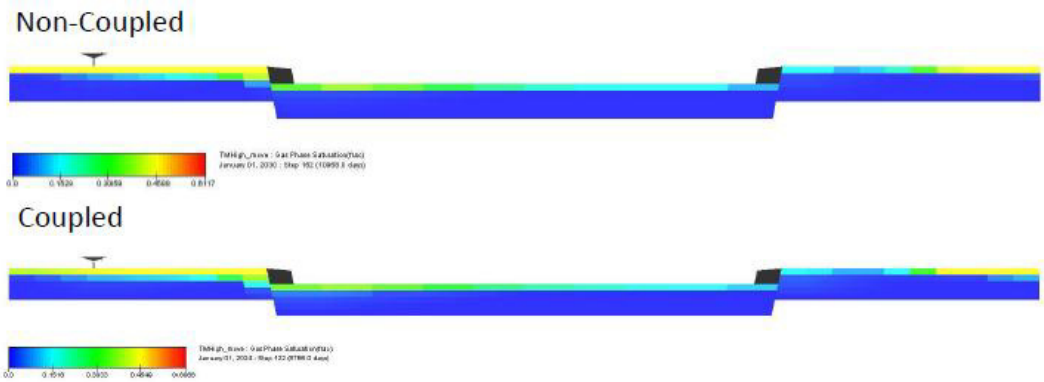

Figure 4 - Comparison of final gas saturations after depletion-reinjection cycle for the non-coupled and coupled, high transmissibility, low friction fault case. The main difference that can be noted is the higher concentration of gas (CO_2) in the middle layer on the well side fault, and in the right hand compartment.

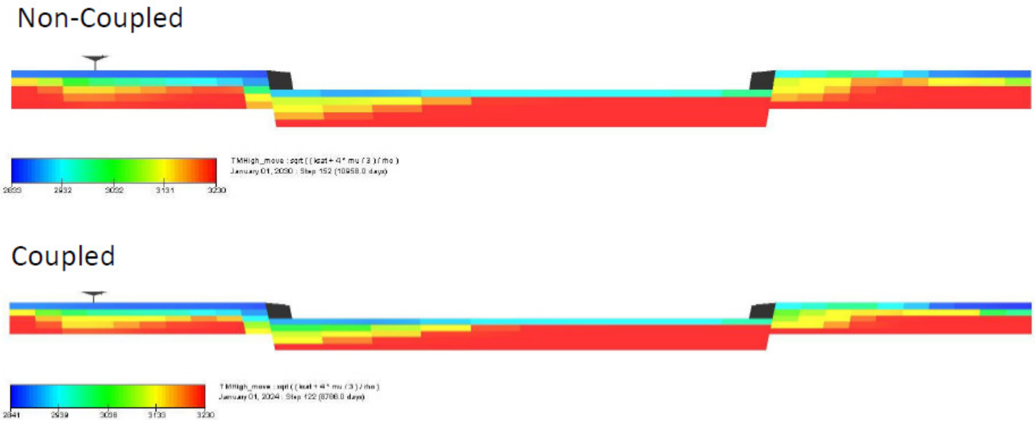

Figure 5 - Comparison of final P-wave velocity after depletion-reinjection cycle for the non-coupled and coupled, high transmissibility, low friction fault case. The decrease in P-wave velocity associated with CO_2 saturation is more pronounced in the coupled model, with the velocity decrease evident across all 5 layers at the well side fault, and to a greater depth at the well and in the right hand compartment.

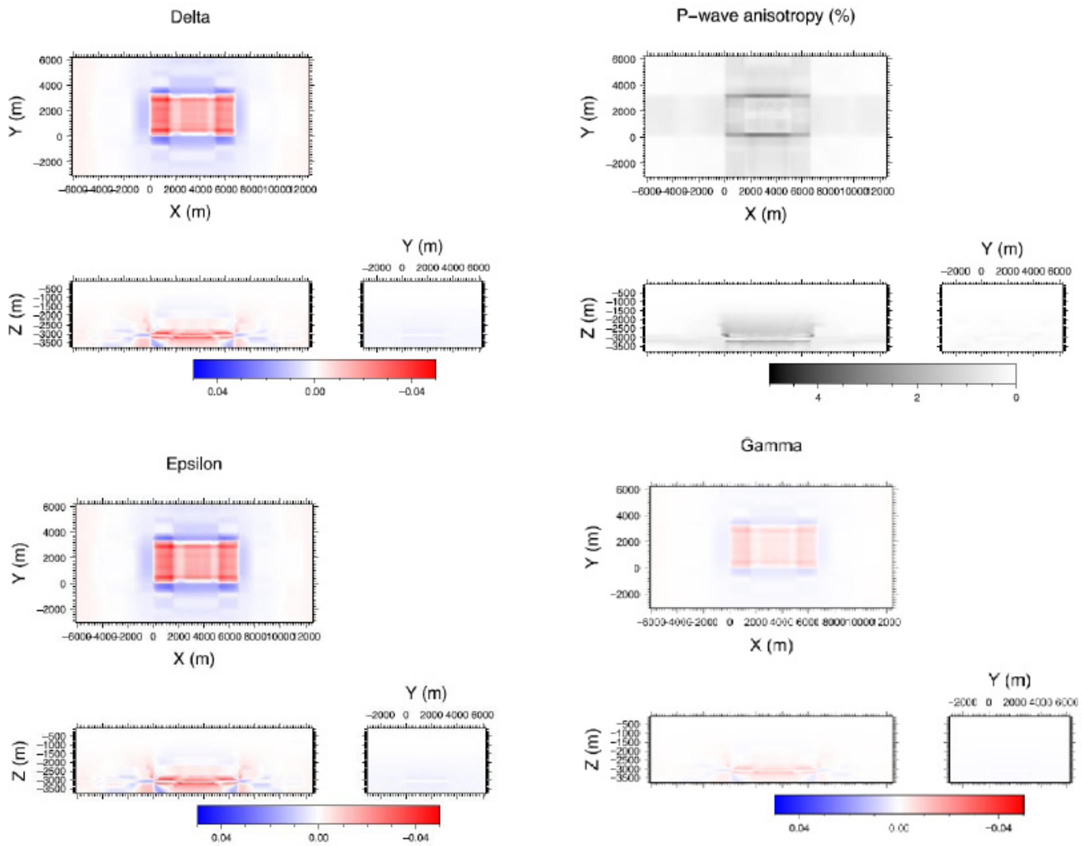

Figure 6 - Plots of Thomsen parameters, delta (δ) gamma (γ) and epsilon (ε), and P-wave anisotropy for the production phase of the model.

5. Conclusions

Geomechanics may be an important consideration when modelling injection activities for CO_2 storage projects, the mechanical behavior of the overburden and reservoir may have a significant effect on the fluid flow properties of the reservoir. Predicting the potential seismic response of a CO_2 injection scenario could be important in designing monitoring programs and ground truthing/calibrating models of storage systems; this study shows that geomechanics can have an impact on the observed seismic response, and may be important in generating predictive synthetic seismics for future projects. Further work in this study will include the generation of seismic attributes for more injection scenarios (low transmissibilities, high fault friction and the injection stage of the injection-depletion cycle), the aim is to use this initial study as a benchmark for the study of a full field model of a North Sea history matched depleted field, using the coupled methodology, this study will incorporate analysis of stress path hysteresis in the full field which is discussed in elsewhere in this volume.

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