CATO-2 Deliverable WP3.03-D02

Results of preliminary simulations of the impact of CO_2 injection on generic models

(1st Year Progress Report, 2010)

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1 Executive Summary (restricted)

Geomechanical analysis of the impact of CO2 injection is a crucial part in validating suitability of subsurface reservoirs for long-term CO2 storage and optimizing injection scenarios. Leakage of CO2 to the surface may occur if breach of fault and top seals occurs as a result of changing stress conditions associated with CO2 injection.

This report (deliverable WP3.3-D02) describes results of preliminary geomechanical simulations of the impact of CO2 injection on generic models. Numerical models are commonly used to model thermo-hydro-mechanical effects of CO2 injection because they can account better than analytical models for structural complexity of the reservoirs, non-linear behaviour and spatial variability of different geomaterials present in the subsurface.

We choose to use different numerical techniques in geomechanical simulations: finite element (FEM), finite difference (FDM) and discrete element method (DEM). The different numerical techniques are incorporated into two separate workflows for geomechanical modelling currently under development. The workflows are based on (i) a continuous (macro-scale) approach (FEM/FDM) and (ii) a discontinuous (micro-scale) approach (DEM).
The continuous approach to geomechanical modelling is based on uncoupled flow-stress simulations. This is a frequently used way of combining fluid flow modelling and stress modelling in oil and gas industry applications. In continuous approach we use the finite element code DIANA coupled to an industry-standard reservoir simulator. FE analysis results allow evaluating the dynamic effects of CO2 injection which determine how the sealing integrity of top seals and faults will evolve during the period of CO2 injection into the target reservoir.
The discontinuous approach uses local stress conditions from the FE analysis to investigate fracture initiation and propagation in generic reservoir-seal models. It specifically aims to investigate the long-term effects of CO2 injection on fault and top seal integrity. Effects of reactive flow on the mechanical evolution of reservoir-seal systems are also investigated by explicitly modelling volume changes, alteration of rock mechanical properties and fracture propagation associated with reactions between CO2-rich fluids and reservoir-, fault- and caprock.

Distribution List

(this section shows the initial distribution list)

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Document Change Record

(this section shows the historical versions, with a short description of the updates)

Version	Nr of pages	Short description of change	Pages
2010-08-30	10	Initial report by TNO	1-10

Table of Content

2 Applicable/Reference documents and Abbreviations

2.1 Applicable Documents

(Applicable Documents, including their version, are documents that are the "legal" basis to the work performed)

	Title	Doc nr	Version date
AD-01	Beschikking (Subsidieverlening CATO-2 programma verplichtingnummer 1-6843	ET/ED/90780 40	2009.07.09
AD-02	Consortium Agreement	CATO-2-CA	2009.09.07
AD-03	Program Plan	CATO2-WPD-3.03-D.02	2009.09.29

2.2 Reference Documents

(Reference Documents are referred to in the document)

	Title	Doc nr	Version/issue	Date

2.3 Abbreviations

(this refers to abbreviations used in this document)

3 General Text

3.1 Introduction

Fault or top seals around subsurface storage sites for CO2 can be breached as a result of changes stress conditions associated with CO2 injection. If seal are breached leakage of CO2 to the surface may occur. Analyse the impact of CO2 injection is therefore a crucial part in assessing if potential subsurface storage sites are suitable for long-term CO2 storage and in determining the effects of specific injection scenarios. Numerical models can account for structural complexity of the reservoirs, non-linear behaviour and spatial variability of different geomaterials present in the subsurface and are best equipped for such analysis.

This is a first year progress report on "*Results of preliminary simulations of the impact of CO2 injection on generic models".* This report is a deliverable D02 of the WP3.3 *"Caprock and Fault Integrity"* of the CATO-2a project. The report covers the period from project start 2009.04.15. until 2010.08.31 and addresses task T3.3.1 related to "*Geomechanical evolution of the reservoir-seal system and induced deformation*". The objective is to develop numerical modelling capability allowing prediction of the stress-strain evolution in and around a generic reservoir-seal system. This will be applied to specific sites to evaluate reservoir deformation (heave vs. compaction), caprock deformation and ground deformation at the surface, as well as the reactivation and seismic risk potential of pre-existing faults. The work to be performed under the task T3.3.1 comprises *"Generic modelling/simulation of the evolution of reservoir deformation, caprock deformation, surface deformation, cap rock and fault seal integrity (permeability), and fault reactivation/seismic risk, based on integration of site-relevant experimental data with numerical modelling of thermo-hydro-chemo-mechanical effects of CO2 injection and reactive flow".*

Preliminary simulations of the impact of CO2 injection were performed looking at (1) stress paths of the reservoir rock and potential for shear failure and fault reactivation in a generic finite element model of a reservoir-fault-caprock system (i.e. the continuous approach), (2) fracturing in reservoir and caprock due to changes in volume and rock mechanical properties associated with reactions between anhydrite caprock and CO2-rich fluids in a generic discrete element model of a reservoir-caprock system (i.e. the discontinuous approach).

The deliverables achieved in the 1st year of the project are in agreement with the project plan.

3.2 Background: Geomechanical effects associated with CO2 injection

CO2 injection will change the stress-strain field in a reservoir-seal system due to various dynamic phenomena:
- poro-elastic effects caused by changes in pore fluid pressure;
- buoyancy effects caused by changes in pore fluid density;
- thermo-elastic effects caused by changes in pore fluid temperature; and
- chemical effects caused by changes in pore fluid chemistry (water-CO2-rock interaction).

As a result of induced stress changes top seals can be damaged, pre-existing sealing faults and fractures can be re-activated allowing fluid flow. Besides this CO2 injection could also induce ground movement, which can be either aseismic in nature- in the form of ground surface uplift, or (micro-)seismic - caused by a sudden slip on pre-existing discontinuities and faults.

Geomechanical effects associated with CO2 injection can conveniently be assessed by using analytical and numerical geomechanical models. Analytical solutions for stress changes and displacement exist for simple reservoir geometries. These are typically used for preliminary assessment of induced geomechanical effects related to CO2 injection in geological reservoirs. Numerical models are more commonly used to model thermo-hydro-mechanical effects of CO2 injection because they can account (better than analytical models) for structural complexity of the reservoirs, non-linear behaviour and spatial variability of different geomaterials present in the subsurface.

Considering the advantages of numerical modelling, we choose to use different numerical techniques in geomechanical simulations: finite element (FEM), finite difference (FDM) and discrete element method (DEM). The different numerical techniques are incorporated into two separate workflows for geomechanical modelling, which are currently under development. The workflows are based on:
- a continuous (macro-scale) approach (FEM/FDM) and
- a discontinuous (micro-scale) approach (DEM).

3.3 Simulations using continuous (FEM/FDM) models

Continuous approach to geomechanical modelling is based on uncoupled (i.e. staggered) flow-stress simulations. This is a frequently used way of combining fluid flow modelling and stress modelling in oil and gas industry. In this approach a reservoir simulator is used first to compute the entire time history and forecast of pressure. This time history and forecast are then used as input to the stress modelling and a transient stress solution is found. Although these two calculated time histories/forecasts of pressure and stress are independent, the procedure is often used because the conventional modelling tools for (multi-phase) fluid flow simulation and stress analysis can directly be used, without any modification.

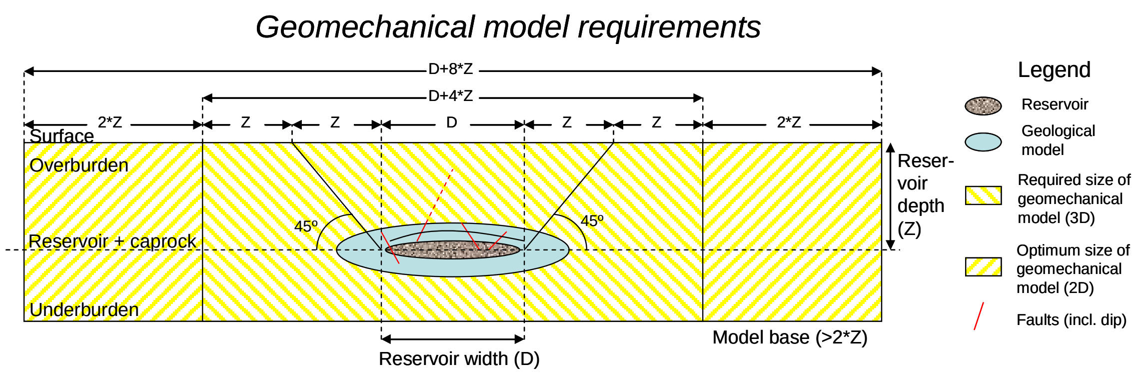

Figure 1. *Schematic cross-section showing the spatial extent of reservoir simulation model, geological model, created for the purpose of reservoir modelling, and geomechanical model. Creation of extended geological models of selected sites, required for derivation of geomechanical models, is under development in WP3.1.*

Geomechanical models of specific sites are derived from geological models and reservoir engineering models. Geological models are typically created to derive reservoir simulation grids which represent the reservoir layers and supporting aquifers (in the case of injection in depleted fields), or the aquifer system (in the case of aquifers). Such a geological model covers only a small part of the volume of interest required to be interpreted for the purpose of geomechanical modelling (Figure 1). Geomechanical models must include the intermittent reservoir layers not included in reservoir models and must be extended far from the reservoir to include the surrounding rock up to the ground surface, deep below the reservoir and far enough in lateral directions to avoid influence of boundary conditions on geomechanical modelling results. Hence, geomechanical modelling of selected sites requires extended geological models currently under development in WP3.1.

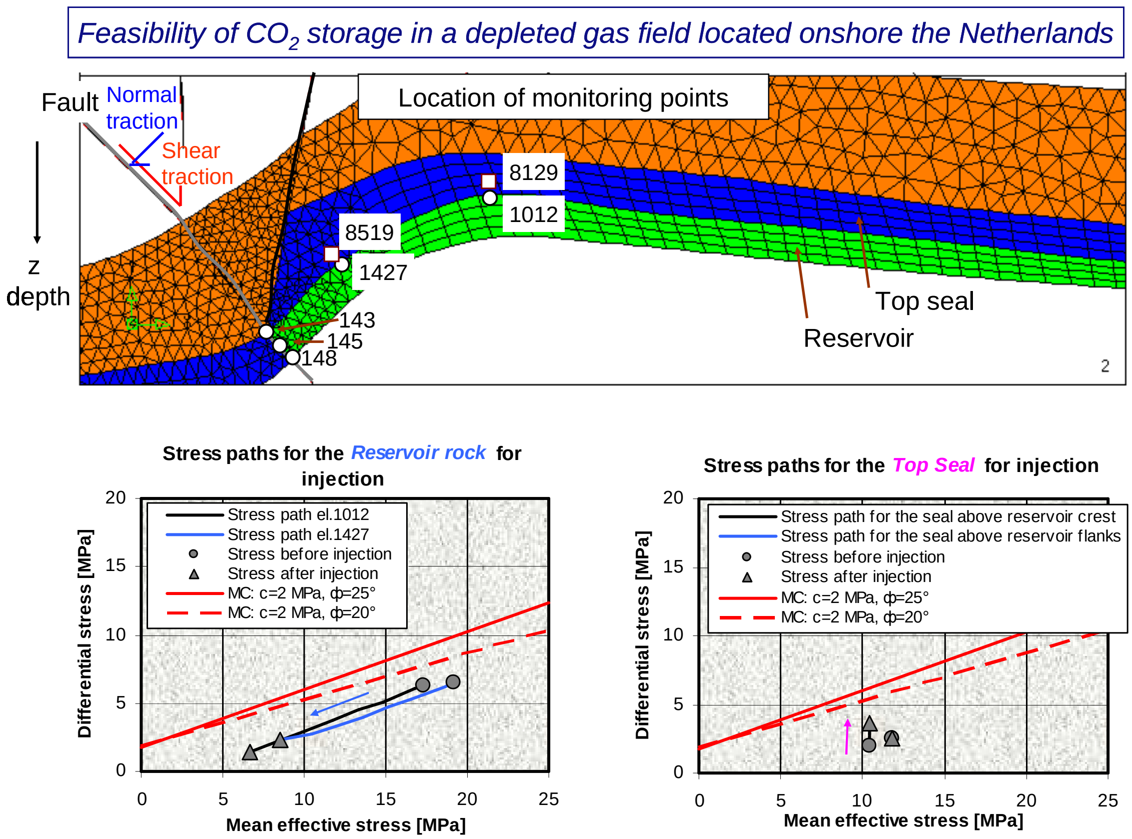

Figure 2. *Stress changes in the reservoir rock and top seal resulting from CO_2 injection in a depleted hydrocarbon field. The reservoir average pressure increase amounts to 12 MPa.*

- *a) Part of the finite element model of the storage site showing locations of the elements used to present the results of geomechanical analyses.*
- *b) Stress changes in the reservoir rock shown by stress path diagrams. The stress paths not converging towards the Mohr-Coulomb failure envelope indicate a non-critical stress development with respect to shear failure.*
- *c) Stress changes in top seals are much smaller than in the reservoir - in many cases by two or more orders of magnitude. However, the stress development due to injection is critical as the state of stress moves towards the failure envelope.*

In continuous approach we use the finite element code DIANA coupled to an industry-standard reservoir simulator (e.g. ECLIPSE). FE analysis results allow evaluating the dynamic effects of CO2 injection which determine how the sealing integrity of top seals and faults will evolve during the period of CO2 injection into the target reservoir, as illustrated in Figure 2. Detailed description of the workflow and the results obtained from synthetic and real reservoir models are presented in one published paper (*Orlic, 2009*) and another paper in preparation (*Orlic et al., 2010*).

3.4 Simulations using discontinuous (DEM) models

For the discontinuous (micro-scale) approach to geomechanical modelling, PFC2D (Particle Flow Code in 2 dimensions) is used. Two-dimensional porous aggregates are generated by filling a required space (reservoir/caprock) with rigid circular discs of different radius. The package has the advantage that it can be used to model fracture propagation (i.e. breaking of bonds between neighbouring discs), porosity evolution (by rearrangement of discs due to sliding of discs past one another), fluid flow (by considering pressure changes in domains of discs due to fluid flow over disc-to-disc contacts) and chemical reactions (by changing the area and mechanical properties of discs representing volume changes and mineral alteration) as a result of changing stress conditions in the model .

CO_2 may interact with anhydrite caprock and form calcite. Although this process is very slow (hundreds-thousands of years), the geomechanical strength of the caprock may be affected and fractures may be created. Fractures formed may further induce reactions in the caprock through an increase in fluid flow. This process of chemical reactions, fluid flow and fracturing could be self progressing and eventually cause leakage of CO_2 through a network of fractures.

This research is a first attempt to couple the geochemical and geomechical aspects of the reaction between CO_2-rich fluids and anhydrite caprock and examines the effects on reservoir and caprock deformation in time. Preliminary simulations are performed aiming at developing algorithms for chemical-mechanical coupling and testing the workflow. Therefore, small (sample) scale models are generated to limit computation times. Development of larger scale models and upscaling of sample scale models is planned in year 2 of the CATO-2 programme.

We consider a Rotliegend reservoir (clean sand; quartz) with anhydrite caprock (Figure 3). The reaction of CO2 with this caprock will introduce calcite, which has a 20% lower volume.
The model is 1.6 cm x 4 cm large; with the anhydrite seal the upper part and the clean reservoir sand (quartz) the bottom part. We calibrated the anhydrite and quartz separately to ensure the correct macro parameters (Young's modulus, Poisson's ratio, and unconfined strength) for the micro parameters used (Young's modulus, friction, Poisson's ratio, stiffness ratio, parallel bond strength). After calibration we performed a biaxial test on the material, with a confining stress of 10 MPa, to obtain the strength of the material. A stress of 98.5 MPa was needed to fracture the material. The fractures are predominantly situated in the reservoir (Figure 3c).

After establishing the initial strength of the material, we exchanged one element of anhydrite for one element of calcite (Figure 3b). The calcite is 20% smaller in volume than anhydrite. This causes the increase in pore space.

Figure 3. *Reservoir-caprock model with in yellow the clean sand reservoir, in red the anhydrite caprock and in blue calcite (a, b). View of the fractures in the reservoir after performing biaxial tests on the model to determine model strength with in green calcite, in red normal fractures and in green shear fractures (c, d).*

Figure 3d shows the fractures formed during a biaxial test. A stress of 61.6 MPa was needed to induce fractures in the material. This is a decrease in strength of 36.9 MPa. To determine whether this change is significant we performed biaxial tests on the same material but with different packing. The range in strength needed was 105.2 MPa ± 9.3 MPa. The value of 61.6 MPa is more than four standard deviations away from 105.2MPa. Therefore we conclude that the difference in strength of the material with or without calcite is significant. The material with calcite formed is weaker than the material without calcite. Most fractures are formed in the reservoir part. Only one fracture formed in the seal directly above the calcite.

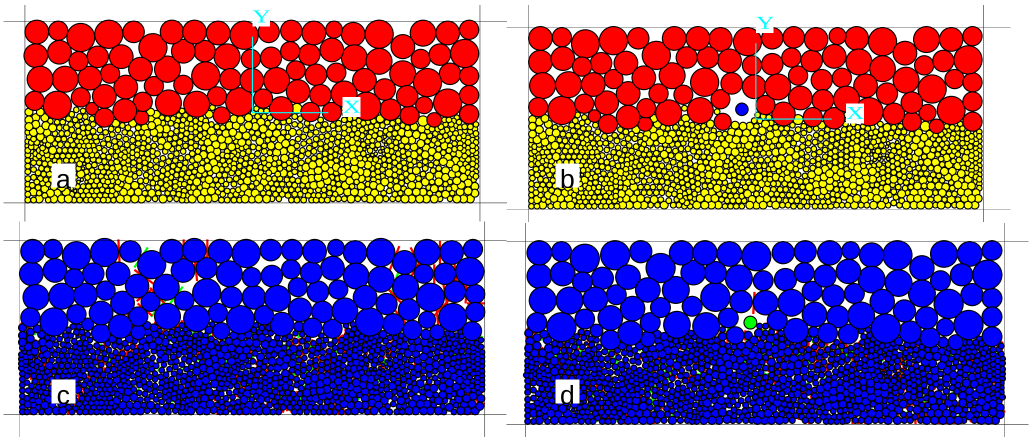

Figure 3. *Reservoir-caprock model with in yellow the clean sand reservoir, in red the anhydrite caprock and in blue calcite (a, b). View of the fractures in the reservoir after performing biaxial tests on the model to determine model strength with in green calcite, in red normal fractures and in green shear fractures (c, d).*

The research will now focus on the actual coupling of the geochemical and geomechanical models, including effects of (lack of) fluid flow in the caprock. First, we will simulate anhydrite being replaced by calcite in time while experiencing different in situ stress conditions and monitor fractures that may be formed and their effect on fluid penetration in the caprock. Later, we will exchange information on the formation of calcite and fractures in between the geomechanical (PFC2D/PFC3D) and reactive flow (TOUGHREACT) models and couple these processes.

3.5 Dissemination & Communication

Nr	**Type** interview, presentation, paper, etc	**Author(s)**	**Title**	**Event/journal**	**Date**
1	Paper	Orlic, B.	Some geomechanical aspects of geological CO2 sequestration	Korean Journal of Civil Engineering, 2009, 13(4), 225-232	2009
2	Participation in the workshop and poster presentations	Orlic, B.	Assessing the mechanical impact of CO_2 injection on faults and seals	Workshop on Seals and Caprocks in Geologic Carbon Sequestration, organised by the Global Climate & Energy Project (Stanford University) and US Geological Survey)	12-15 January 2010
		ter Heege, J., Wassing, B., Orlic, B.	Discrete element modelling of clay smear development and permeability evolution in simulated fault zones: A workflow to assess the long term integrity of fault and top seals during CO2 storage in depleted gas fields		
3	Paper in preparation	Orlic, B., ter Heege, J., Wassing, B.	Assessing the integrity of fault- and top seals at CO2 storage sites	International Conference on Greenhouse Gas Technologies, GHGT10, Amsterdam, 2010	19-23 September 2010

3.6 References

Orlic, B., 2009. Some geomechanical aspects of geological CO2 sequestration. Korean Journal of Civil Engineering, Vol. 13, No. 4, 225-232.

Paper in preparation: Orlic, B., Wassing, B., ter Heege, J., 2010. Assessing the integrity of fault- and top seals at CO2 storage sites. International Conference on Greenhouse Gas Technologies, GHGT10, 2010, Amsterdam.