Geomechanical evaluation of a depleted chalk reservoir for CO2 storage

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Publication date: 2022

Document Version
Publisher's PDF, also known as Version of record

Link back to DTU Orbit

Citation (APA):
Geomechanical evaluation of a depleted chalk reservoir for CO2 storage

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Abstract

Carbon capture and storage (CCS) is the process of capturing carbon dioxide (CO2) before it enters the atmosphere and storing it for centuries. Depleted hydrocarbon fields represent an opportunity for CO2 storage because of already installed facilities and equipment and available subsurface data recording during the lifetime of the reservoir. With starting CO2 injection in depleted chalk formations that have experienced elastic and visco-plastic deformation during production, two main processes can occur simultaneously under visco-plastic deformation condition. First, reservoir expansion is often expected as reservoir pressure builds up and effective stresses drops. The second is the reservoir compaction that continues due to viscous deformation even after the cessation of hydrocarbon production. As a result, the reservoir top tends to go up because of build-up pressure which may be limited at the same time with viscous deformation that had induced from the production phase. Taking advantage of these two effects, this study investigates the safest scenarios for CO2 injection in depleted chalk formation to minimize geo-mechanical deformation. For this purpose, a rate dependent constitutive model is utilized to calculate deformation in 1D simulation during depletion and injection phases. The constitutive model is calibrated for pelagic chalk from the North Sea and takes into account the water weakening effect. The simulation uses experimental and well log data obtained along two wells in Harald East field. We evaluate the impact of various operational conditions for CO2 injection in depleted reservoirs on long-term deformation of the storage sites.

Keywords: depleted reservoirs, CO2 injection, creep, geomechanic, chalk

1. Introduction

CCS projects traditionally targeted mostly high permeability sandstone formations. Because of the reactivity between calcite minerals and CO2 saturated water, chalk formations, characterized by high porosity and low permeability, have been previously portrayed as infeasible CO2 storage sites. However, chalk fields have been recently considered for CCS project in several studies [1]. Among others, depleted chalk reservoirs represent an opportunity for CO2 storage due to the existing infrastructures and subsurface data recorded during the lifetime of the producing reservoirs. Regarding geo-mechanical behavior, chalk material belongs to soft rocks and exhibits lots of deformation under high depletions. Another complexity specific to chalk formations is creep deformation and chalk weakening; Creep deformation refers to continuous material deformation under constant stress and chalk weakening refers to the fact that chalk is weaker when saturated with water compared with organic fluids such as crude oil or glycol. Despite water...
weakening which has a known effect on chalk [2], defining a general mechanical behavior when CO2 is injected into chalk is not straightforward [3-4].

At the onset of injecting CO2 in subsurface, effective stresses drop as pore pressure builds up. Thus, uplift of the reservoir top is often expected to occur as formation pressure rises back to the virgin value. However, the decades of depletion within most of the hydrocarbon fields in the North Sea have caused visco-plastic deformation of the rock that continues after shutting down the wells and the cessation of production. Visco-plastic strain accumulating in chalk reservoirs is non-negligible due to the weak mechanical properties of the rock, thereby resulting in significant subsidence of the reservoir top as observed in the Ekofisk field. Therefore, two contradictory processes acting simultaneously determines the geo-mechanical deformation of the rock during CO2 injection within a depleted chalk formation: 1) uplift caused by the reservoir pressure build-up and; 2) subsidence that results from the viscous properties of chalk. The safest injection scenario to avoid the risk of fault reactivation, induced seismicity, and potential loss in CO2 containment consists of minimizing the geo-mechanical deformation within the reservoir. This study aims at identifying the effect of different injecting scenarios on geo-mechanical deformation of highly depleted chalk reservoirs. A rate dependent constitutive model [5] is utilized to calculate visco-plastic deformation in 1D simulation during depletion and injection phases. The constitutive model is calibrated for pelagic chalk from the North Sea and takes into account the water weakening effect. The simulation focuses on information obtained from well log data along an observation well in Harald East field that experienced significant deformation during the depletion.

2. The Harald East field

The Harald East structure is a 5x3 km (Fig. 1), slightly north-south elongate, anticline structure formed by discontinuous phases of halokinesis (Zechstein salt) from Late Jurassic to Early Neogene. The top chalk horizon overlaying the reservoir ranges between ca. 8900ft and 9100 ft TVDSS from the crest to the flanks. The reservoir interval consists of the M1 unit that is the uppermost part of the Tor Fm. of Maastrichtian age and the overlaying Ekofisk fm. composed of the D4 to D1 units from base to top. Contrary to D1 and D3 units, the D2 and D4 units are characterised by poor reservoir properties.

The facilities in the Harald field consist of a combined wellhead and processing platform, Harald A, and an accommodation platform with a helideck, Harald B installed in a 64 m water depth. Two abandoned vertical wells, the exploration Lulu-1 and the Lulu-2 wells were drilled in 1980 and 1985/86, respectively. Hydrocarbon is produced from two horizontal production wells (HEA-6 drilled in 1997 and HEA-3E in late 2000) and sent via pipeline to Tyra East.

The main reservoir interval, the D1 unit, contains a significant fraction of reworked Tor occurring in the matrix and in intraclasts. The interval of reworked Maastrichtian represents 30% to 75% of the D1 unit in the Lulu-1 and Lulu-2, respectively. In the crest of the anticline, the chalk of the D1 unit displays a 32.7% mean density porosity (35.4% porosity from core data) and 2.2 mD air permeability. Porosity deterioration down to <28% density porosity is observed towards the flanks by comparing the Lulu 1 and Lulu 2 wells located respectively in the crest and flank of the reservoir as well as along the two horizontal wells that follow the top chalk surface down flank. The porosity reduction is primary controlled by water saturation. The role of water saturation has been demonstrated by compiling a large dataset from nearby wells that points out a porosity threshold of 28% below which water saturation of chalk is consistently above 70%. Deteriorating sharply toward the west to northwest of the field, the petrophysical properties decreases more progressively eastward to southeastward. This reservoir architecture is most likely the result of the eastward tilting of the gas-water contact present in the field.
3. Geo-mechanical model

The preset study uses the geo-mechanical model first developed by Tron Golder et al., (2010) [6], and later calibrated by Amour et al., (2020) [7] for Danian and Maastrichtian chalk. This model employ a strain-rate dependent relation proposed by de Waal (1986) [8] into the yield function first adopted by Papamichos et al., (1997) for chalk formations. The yield function, $F$, is a modified Mohr-Coulomb yield function to include the end cap as one enclosed function:

$$F(p_{m}'J_2) = \sqrt{J_2} \left( \cos \theta + \frac{\sin \varphi \sin \theta}{\sqrt{3}} \right) - (p_{m}' + p_t) \sin \varphi \left( \frac{\sigma_{hy} - p_{m}'}{\sigma_{hy} + p_t} \right)^m$$  \hspace{1cm} (1)

with:

- $\sigma_{hy}$: current hydrostatic pore collapse strength.
- $p_t$: tensile strength.
- $p_{m}'$: mean effective stress.
- $\varphi$: angle of internal friction at low confining stress.
- $m$: parameter determining the shape of end cap.
- $\theta$: Lode’s angle ($\theta = -30^\circ$ for stress path in standard triaxial tests)
- $J_2$: second invariant of the deviatoric stress, which is related to von-mises stress, i.e. $q = \sqrt{3J_2}$

Within Eq.1, $\sigma_{hy}$ is hydrostatic pore collapse strength at current volumetric plastic strain rate $\dot{\varepsilon}_{vol}^{pl}$ and water saturation $S_w$. 

![Map view of the Harald East field with the location of the wells Lulu 1 and Lulu 2.](https://ssrn.com/abstract=4284515)
$$\sigma_{hy}^* = \sigma_{hy}^0 \text{Exp} \left( -\frac{\varepsilon_{vol}^p}{\chi} \right)$$

Referring to Eq.2, hardening is also controlled by standard isotropic pore-collapse strength \(\sigma_{hy}^*\) for oil-saturated chalk, which depends on the volumetric plastic strain \(\varepsilon_{vol}^p\) as:

$$\sigma_{hy}^* = \sigma_{hy}^0 \text{Exp} \left( -\frac{\varepsilon_{vol}^p}{\chi} \right)$$

where pore collapse hardening coefficient \(\chi = \frac{\lambda - \kappa}{1 + e_0}\) with \(e_0\) the initial void ratio and \(\lambda\) and \(\kappa\) the compression and swelling indexes, respectively.

In Eq.2 \(K(S_w)\) is a function that considers the water weakening effect with the following relation:

$$K(S_w) = \hat{k} + (1 - \hat{k})(1 - S_w)^{20}$$

With \(\hat{k}\) being the ratio of \(\sigma_{hy}^0\) of fully-water saturated chalk to that of fully-oil saturated chalk. This term aims at estimating the water weakening effect on yield stress and derived from Hickman (2004) [11].

4. Methodology

In this study we used 1-D simulation to estimate the compaction in the reservoir at crest (Lulu 1) and flank (Lulu 2) within depletion and injection periods. The 1-D model framework in the main reservoir is composed of 1231 and 1352 cells respectively for Lulu 1 and Lulu 2 with about 15 cm-thick for each cell. Elastic properties are calculated according to two steps. Dynamic moduli are calculated from iso-frame [12] model taking into account the mineralogical effect of chalk. Then elastic moduli are obtained using a linear relation suggested by Wang & Nur (2000) [13] from dynamic moduli. This relation is calibrated so the elastic moduli match with values obtained from existing triaxial tests at different depths (Fig. 2).

For plastic properties, this study considers the data collected by Amour, et al. 2021 for Danish chalk fields. These data include the porosity dependent functions to estimate plastic properties including pore collapse, hardening coefficient, creep parameter and water weakening effect (Table 1).

Simulations are carried out under uniaxial compaction condition, i.e., zero lateral strains, in 2 phases. In the first phase axial stress increases according to the depletion plan that the reservoir has experienced within 20 years of production, then axial stress linearly returns to initial reservoir state in different scenarios of injections (Fig 3a). In this study we didn’t change water saturation in time and used just the initial saturation distribution during the whole simulation.

Initial stresses are calculated from well-log densities and reservoir pore pressure.
The simulation results of compaction in Lulu 1 and Lulu 2 are shown in Fig 3 (b) and (c) respectively. Compaction from production phase is in the order of 7 m in the crest (Well Lulu 1) and declines to 1.2 m in the flanks (Well Lulu 2) which is in good agreement with reported 4-D seismic data. Despite significant compaction in Lulu 1 during production phase, returning to initial reservoir pressure within 20 years of injection shows about 30 cm uplift with respect to the beginning of injection. That indicates the most part of the deformation in production phase occurs in plastic regime which is irreversible in injection phase.

Considering No injection scenario in Fig 3, It shows compaction can continue significantly due to viscous deformation experienced in production phase. In the crest, compaction continues to 42% of the experienced total deformation in production phase within 80 years of creep. In the flank, it even reaches up to 67%. Therefore, CO2 injection can be also considered as a good solution to stop compaction in highly depleted chalk reservoir.

In Fig 4, the normalized compactions within injection phase are plotted for Lulu 1 and Lulu 2. The vertical axis shows displacements that are normalized to compaction value during the production phase. The horizontal axis shows the time after injection normalized to the period of injection. As observed in this Figure, uplift starts after compaction ends at apex of the curves. The amount of the uplifts for the whole scenarios are equals but the amounts of compactions before the apex depends on the duration of the injection. Longer injection period with lower injection rate leads to

| Table 1. Porosity-dependent functions for plastic properties of chalk integrated into the constitutive model Eq.1 |
|---|---|---|
| \(\sigma_{N}^p\) [MPa] | Ekofisk Fm. | Tor Fm. |
| \(\kappa\) | \(4357.1 \exp(-13.2 \, n)\) | \(1180 \exp(-10.3 \, n)\) |
| \(\lambda - \kappa\) | \(0.26 \, (0 < S_w < 0.2)\) | \(0.15 \, (0 < S_w < 0.2)\) |
| \(0.29 \, (0.2 < S_w < 1)\) | \(0.19 \, (0.2 < S_w < 1)\) |
| \(m\) | \(0.64 \exp(106 \times 0.4) + 0.33 \exp(106 \, n)\) | \(\frac{\exp(106 \times 0.4) + \exp(106 \, n)}{\exp(106 \times 0.4) + \exp(106 \, n)}\) |
| \(b\) | \(-0.37 \, n + 0.21 \leq 0.1\) | |

5. Results

The simulation results of compaction in Lulu 1 and Lulu 2 are shown in Fig 3 (b) and (c) respectively. Compaction from production phase is in the order of 7 m in the crest (Well Lulu 1) and declines to 1.2 m in the flanks (Well Lulu 2) which is in good agreement with reported 4-D seismic data. Despite significant compaction in Lulu 1 during production phase, returning to initial reservoir pressure within 20 years of injection shows about 30 cm uplift with respect to the beginning of injection. That indicates the most part of the deformation in production phase occurs in plastic regime which is irreversible in injection phase.

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(a) Depletion plan
(b) Compaction in Lulu 1
(c) Compaction in Lulu 2

Fig 3. (a) Simulations are carried out under 2 phases, in production phase reservoir pressure declines 35 MPa within 20 years. Reservoir pressure returns to initial value in different scenarios of injection phase. The results of 1D-Simulation for (b) Lulu 1 (at crest) and (c) Lulu 2 (at flank) show the reservoir has experienced lots of visco-plastic deformation in production phase.

Fig 4. Normalized compaction within injection phase for (a) Lulu 1 (at crest) and (b) Lulu 2 (at flank). Normalized displacement indicates disp. within injection phase normalized to compaction value during the production phase. Normalized time indicates the time after injection normalized to period of injections.

more compaction. The apex of each curve in Fig 4 corresponds to a pressure build up when compaction ends in injection phase. These values are listed in Table 2. As observed in Table 2, compaction stops at different pressure depending on the rate of injection. In faster injection scenarios, compaction stops at lower pressure build up. Comparing the compaction in different scenarios of injections indicates that injection rate in depleted chalk reservoir can be optimized to limit the geo-mechanical deformation.

<table>
<thead>
<tr>
<th></th>
<th>Lulu 1</th>
<th>Lulu 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 yrs Injection</td>
<td>6.1</td>
<td>0.9</td>
</tr>
<tr>
<td>40 yrs Injection</td>
<td>8.4</td>
<td>3.5</td>
</tr>
<tr>
<td>60 yrs Injection</td>
<td>9.5</td>
<td>4.6</td>
</tr>
<tr>
<td>80 yrs Injection</td>
<td>10.1</td>
<td>5.4</td>
</tr>
</tbody>
</table>

Table 2. Pressure builds up [MPa] when compaction ends in injection phase, corresponding to apex of the curves in Fig 4.
6. Conclusions

This study investigated the effects of CO2 injection in depleted chalk reservoir for CCS project. With 1D simulation of two wells in Harald East field, the deformations were simulated in production and injection phase. The summary of the results is as follows:

- It was shown that without injection plan in Harald East fields, compaction can continue significantly within long-term due to creep effect, even after end of production.
- Despite significant compaction in Harald East field in production phase, it was shown that returning to initial reservoir pressure does not lead to such deformation since most part of the deformation in production phase occurs in plastic regime which is irreversible in injection phase.
- With starting injection in highly depleted chalk reservoir, compaction takes time to stop. The amount of compaction in this period depends on injection rate. Faster injection rate leads to less compaction. Compaction stops at different pressure depending on the rate of injection. The amount of the uplift after compaction does not depend on injection rate.
- Injection rate in depleted chalk reservoir can be optimized to limit the geo-mechanical deformation.

Acknowledgments

The authors gratefully acknowledge the Danish Underground Consortium (Total Energies E&P Denmark, Noreco and Nordsøfonden) for providing data and granting the permission to publish this work. The authors also are very thankful to Rasmus Lang, for his constructive discussions for this work.

7. References