GEOMECHANICS INITIATIVE

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Geomechanics Initiative Meeting – Agenda

Topics: (i) Geomechanics in CO_2/H_2 storage sites (including related thermal / geothermal operations)
(ii) Fault reactivation prediction

Date: Thursday 24th March and Friday 25th March 2022

Time: 10.00 – 15:35 (European time) Thursday 24th March
10.00 – 12:15 (European time) Friday 25th March

Location: Virtual

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Thursday, 24th March 2022			UK time	EUR time
1	Welcome and objectives for the meeting	OTM, Justin Weeks	09:00	10:00
2	Introductions	All	09:15	10:15
3	Geomechanics at ConocoPhillips Norway	ConocoPhillips, Edvard Omdal	09:30	10:30
4	Geomechanics for CCUS: workflows for thermal induced fractures and faults stability evaluations	Eni, Silvia Monaco and Marco Brignoli	09:45	10:45
5	OMVs considerations and first steps into geothermal and CCU/CCS projects including fault reactivation analyses.	OMV, Mira Persaud	10:30	11:30
Lunch			11:15	12:15
6	Summary Introduction to Geomechanics at Neptune	Neptune, David Ginger	12:15	13:15
7	CCUS and Geomechanics in Shell: Containment and other geomechanical challenges.	Shell, Sergio De Gennaro	12:45	13:45
Break			13:30	14:30
8	Geomechanical assessment of containment in TotalEnergies	TotalEnergies, Peter Shotton	13:45	14:45
9	Day 1 close	OTM, Justin Weeks	14:30	15:30
End of day 1			14:35	15:35

Friday 25th March 2022			UK time	EUR time
10	Welcome	OTM, Justin Weeks	09:00	10:00
11	Modelling fault re-activation at Valhall	Aker BP, Andreas Bauer	09:05	10:05
12	Seismic risk analysis in the Netherlands for the small onshore gas fields.	Shell, Rob van Eijs	09:50	10:50
Break			10:35	11:35
13	Meeting wrap up to include discussion on: - Member update - Future topics - Next meeting format/ timing - AOB	OTM, Justin Weeks	10:45	11:45
End of day 2			11:15	12:15

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1 Introduction

1.1 Geomechanics in CO2/H2 storage sites (including related thermal / geothermal operations)

A number of companies are transforming towards achieving a net-zero goal and CO_2 storage are studying CO_2/H_2 storage solutions.

Such solutions require geomechanical actions beyond those that are commonly used in oil and gas production/injection operations. Solutions for presentation and discussion include:

- Maximum pressure of injection
- Better characterization of the relationship between stress and fluid flow along faults and fractures
- Understanding of the physical mechanisms of creation and propagation of faults fractures under pressure cycles
- Thermal effect associated with injection
- Integrity of storage on long term (100 years)
- Prediction and quantification of induced seismicity
- Large scale multi-physics modelling
- Multi-scale coupling
- Modelling of fault instability
- Modelling of the sedimentary pile
- Uncertainties of mechanical properties of the storage rock and the sedimentary pile
- Impact of injected fluid on mechanical and flow properties
- Risk assessment of integrity loss
- Consistency and quality of geomechanical and geoscience input
- Tools and analysis to support acceptability of storage solution
- Geomechanical input translation into business drivers

1.2 Fault reactivation prediction

Fault reactivation is of interest to society in general. Fault reactivation is the main mechanism involved in earthquakes that can damage houses and create tsunamis. Earthquakes are generated from fault reactivation where the reactivation of the fault is a release mechanism for energy that is stored in the earth due to continental plate movements. These movements increase the shear stress on a fault until the fault slips. The fault-slip when the shear strength of the fault is exceeded. As the fault-slip it radiates stored-up elastic strain energy in the form of seismic waves which propagates through the earth and causes the ground surface to shake. Earthquake magnitudes are mostly quantified using the Richter scale which is logarithmic in terms of the induced ground motions. Events from 0 to 1 are not felt at the surface. From 5 to 6 damage at the surface begins, but fatalities are rare. From 7 to 8 severe damage is expected and many fatalities are possible. The largest recorded event is 8.9 offshore Chile in 1960.

Earthquakes are also induced due to oil and gas activities such as production, water and gas injection and injection during stimulation operations. The mechanism is that the injection is increasing the bulk volume of the rock mass and production is decreasing it. These bulk volume changes induce increased shear stresses on weak planes such as faults that can slip when the shear strength is exceeded. Most of these man-made events are on the negative side of the Richter scale indicating slip of a few millimeters involving some square meters of rock surface area. These so-called micro-seismic events have been monitored more often in the oil and gas industry in the last few decades, especially to optimize hydraulic fracturing operations.

Some larger events do also occur, including events that can be felt at surface, i.e., higher than 1 on the Richter scale. In 2001 out of zone injection in the subsiding Ekofisk field offshore Norway induced an earthquake close to 5 on the Richter scale. Another subsiding field, the Groningen field onshore Netherlands, has experienced earthquakes since 1986 with a 3.6 event reported in 2012. Plans are in place to shut-in the field in the future since future predictions indicate that events will increase to the 4 to

5 range on the Richter scale. Since 2009 man-induced earthquakes in Oklahoma, called the Oklahoma earthquake swarms, related to wastewater injection from the oil and gas industry, has increased earthquake frequency in the area. The largest events measured in Oklahoma have also occurred in this period with events reported in the 5.8 range on the Richter scale.

In addition, there are many observations of well deformations in wells that cross faults, some of these deformations are triggered by natural earthquakes while others are clearly induced by oil and gas activities with a high frequency in compacting and subsiding fields.

The questions to discuss in our workshop are:

- When should we perform fault reactivation predictions?
- How should we do it?
- Is the frequently used Mohr-Circle analysis useful at all?
- Are we accurate in our predictions?
- How accurate do we need to be?

2 Presentations

Each company is asked to prepare slides for approximately 30 minutes of presentation and 15 minutes for Q&A.

We politely request that presentations are sourced from each company's global resource pool and not only from the North Sea (unless of course your company only holds North Sea acreage). The meeting is a technical forum and these presentations are intended to provide a background to stimulate discussion.

Please ensure you include case studies; and come armed with company and other industry experiences, to bring the lessons learnt and best practices to life.

3 Organisation

Please advise OTM who will be attending if you have not done so already.

4 Abstracts

3. ConocoPhillips, Edvard Omdal

Title: Geomechanics at ConocoPhillips Norway

An introduction to Geomechanics at ConocoPhillips Norway.

4. Eni, Silvia Monaco and Marco Brignoli

Title: Geomechanics for CCUS: workflows for thermal induced fractures and faults stability evaluations

In CCUS projects, assuring the integrity of the subsurface complex is one of the main tasks to be accounted for. Cap rock seal, thermally induced fracturing (TIF) and faults stability are among the items to be considered in the storage complex integrity evaluation. We will show the workflows we have implemented for TIF and faults stability evaluations.

Thermally Induced Fracturing relates to the fracture creation due to the horizontal stress decrease because of cold fluid injection. For the assessment of the risk of TIF generation, we have implemented a workflow with COMSOL® Multiphysics. The activity considers the setup of simplified 2D models. A planar one is used to investigate the cooled region extension, the TIF onset in reservoir and the eventual temperature interference between wells. Next, a 2D near wellbore radial model is built to evaluate TIF in reservoir and at reservoir-caprock interface.

Fault stability investigation evaluates the stress changes associated to the CO2 injection that can induce a fault reactivation process, leading eventually to seismic events. The workflow couples the fluid dynamic model and the geomechanical model, built in Abaqus®. In this methodology, the geomechanical model does not implement an explicit faults representation – i.e. faults are not physically present in the model. Therefore, a post processing phase is required to determine if the fault is stabilizing or destabilizing; knowing the geometry and position of the faults in the 3D space, the stress in correspondence of the faults position can be projected onto 2D triangulations of the fault surfaces. Then, the Slip Tendency can be computed for each faults' element as the ratio between the tangential and normal stress on fault surface, to understand whether the fault is stabilizing or destabilizing under the simulated injection conditions.

5. OMV, Mira Persaud

Title: OMVs considerations and first steps into geothermal and CCU/CCS projects including fault reactivation analyses.

OMV is only at the beginning of some geothermal project, both for heating and heat storage as well as scouting for possible CCS locations. Therefore work in geomechanics has only just begun for these topics. In this talk, we will give you an overview of the status of geomechanical work and considerations for both geothermal and CCS. Since fault reactivation is part of both topics since one of the major risk we are facing is induced seismicity, we will also cover this topic in our talk and show you which methods we are using and where we are still lacking expertise.

6. Neptune, David Ginger

Title: Summary Introduction to Geomechanics at Neptune

An introduction to Geomechanics at Neptune.

7. Shell, Sergio De Gennaro

Title: CCUS and Geomechanics in Shell: Containment and other geomechanical challenges.

In the UK, Shell is part of a number of CCUS projects including the Acorn project, the Northern Endurance Partnership, and the South Wales Industrial Cluster. In addition, Shell is also helping to develop large scale CCUS projects in Australia, Canada, and Norway. Geomechanics has a crucial role to play in understanding the long-term containment of a storage complex. In this talk, I will focus on a number of geomechanical questions that have to be addresses to ensure long-term storage efficacy. Does the store have a caprock seal? How can I be sure that it is effective? How past production has affected containment? Is there evidence that containment has been compromised? Is there evidence to support that it has not been compromised? Are there likely to be faults that will move? Are there likely to be any thermal fracturing near wellbore or caprock seal? Any chemical disequilibria imposed by introducing CO2 into host rock? Are there legacy well bores penetrating the caprock seal and what is the status of isolation barriers in those wells?

8. TotalEnergies, Peter Shotton

Title: Geomechanical assessment of containment in TotalEnergies

For any CO2 underground storage project, geomechanics is critical in determining the containment of the injected CO2 and the risks associated with injection. The key geological routes migration of CO2 outside of the storage complex include fracturing the caprock and migration along reactivated faults/fractures within the storage complex. These mechanisms are controlled by the in situ stresses, pressures and temperatures in the reservoir and caprock as well as injection pressures at the wells, all of which vary over production/injection timescale.
To understand the geomechanics of seal integrity and caprock containment for CO2 injection projects, we need to understand whether tensile failure (hydraulic fracturing) and shear failure (shear fracturing or larger scale fault slip and /or reactivation) would occur as a result of stress alteration induced by pressure and temperature change within the reservoir and caprock during fluid withdrawal or injection.

A caprock integrity assessment was performed for the Aramis CO2 storage project in the Netherlands, specifically on the L4-A field. The workflow assessed the impact of the depletion in the field then simulated the injection of CO2 for 15 years. The impact of the pressure and temperature changes on both the reservoir and the caprock were assessed to understand the following key risks: risk of loss of containment due to caprock fracturing, risk of loss of containment due to reactivated fault permeability enhancement in the field, risk of induced seismicity with CO2 injection. The study also evaluated the ground deformation (compaction/subsidence). The performed work enabled to define the maximum injection pressure for L4-A CO2 injectors. Whilst the standard caprock integrity workflow is applicable, development of the uncertainty modelling for the fracture closure pressure and the inclusion of the thermal effects are critical to delivering a maximum injection pressure.
These points were studied considering the entire storage complex including the reservoir, intermediate caprock (Silverpit Formation) and the ultimate caprock of the system (Zechstein Group) using the available stress calibration data from the area. This calibration data includes the LOT/FIT data available from wells, Mini-Frac data from virgin and depleted reservoirs, log data, core data and thorough literature

review from the area. Whilst there is numerous data, it has been acquired with the aim of hydrocarbon extraction so it is challenging to have sufficient overburden data. The modelling was based on a new geomodel of the storage complex using surfaces, faults and properties such as porosity to populate the geomechanical model. A reservoir flow model of the reservoir, matching the historical production period, was used in order to generate historical pressure changes in the reservoir during production and expected pressure and temperature changes during the CO_2 injection period.

The maximum injection pressure has been defined based on the geomechanical analysis carried out on the various reservoir simulations. The stresses were assessed from the 1D geomechanical model and then updated with 3D geomechanical simulations accounting for the stress changes in the reservoir and caprock during depletion and injection. This enabled to derive a conservative minimum horizontal stress and maximum injection pressure. An additional safety margin was derived from a probabilistic uncertainty study. This study demonstrates that the set pressure limits enable to avoid any geomechanical damage to the structure. In addition, the simulation results indicate there are no significant stress changes to the Zechstein Group basal carbonates within the storage complex which add an additional stress barrier above the primary caprock formation.

No fault re-activation occurrence was simulated during the depletion of the field and there is no risk of fault re-activation with the planned injection in the L4-A field. The thermal effects have the greatest impact on the stresses around the faults, so it is important to model their impact in stress reduction. Even with the thermal front reaching the major bounding faults, no fault re-activation is expected. The low levels of plastic shear strain around the faults also suggests a low maximum magnitude event potentially triggered by the CO_2 injection.

The use of the 3D geomechanical model allows for the simulation of the depletion and injection to understand the risks/hazards of CO_2 injection. The key challenges identified in the study relate to the data quality in the caprock and overburden, in particular the lack of stress calibration. With the increase in CCS studies, caprock data acquisition should be considered early in the project. This study allows the project to conclude that the risk of loss containment through the caprock and faults is extremely remote.

11. Aker BP, Andreas Bauer

Title: Modelling fault re-activation at Valhall

The re-activation of faults or other weak planes such as bedding planes can be assessed by geomechanical modelling. However, due to high uncertainties of initial stresses acting of the faults, depletion-induced stress changes, and fault strength (cohesion, friction angle), accurate predictions of fault re-activation is difficult and requires proper calibration against field data. At Valhall, the large compaction of the chalk reservoir has resulted in re-activation of faults and beddings planes both in the reservoir and the overburden, which resulted in failure of several wells. Those well failure events, together with other field data including reservoir and seabed subsidence monitoring data, production/injection data, extended leak-off and minifrac test data, as well as seismic and 4D-seismic, have been used to calibrate the 3D geomechanical model for Valhall. Results of the geomechanical model are used for well planning: Areas in the overburden with an increased risk for fault or weak-plane re-activation over the well lifetime are avoided when planning trajectories of infill wells. This approach has been quite successful in the past but there is still room for improvements in particular with respect to more quantitative risk assessment.

12. Shell, Rob van Eijs

Title: Seismic risk analysis in the Netherlands for the small onshore gas fields

Gas is being produced in the Netherlands from around a hundred smaller gas fields. Induced earthquakes have been observed in 20% of these fields with a magnitude up to M=3.5. To manage the risk, the Dutch regulator provided a guideline which is imbedded as a mandate in the license and production application process. We will present in this talk the elements of the guideline and why it is not based on geomechanical fault reactivation calculations. Furthermore, a traffic light system, developed within NAM, will be presented.