# Geomechanical Modeling to Assess Caprock Integrity in Oil Sands

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## Summary

Ensuring caprock integrity is critical to successful thermal recovery processes in oil sands such as steam assisted gravity drainage (SAGD) and cyclic steam stimulation (CSS). Continuous steam injection triggers complex coupled thermal and hydraulic processes, which can dramatically change the state of in-situ stresses, reduce rock strength, induce new fractures or re-activate existing fractures posing continued risk of containment breach of caprock. This can ultimately lead to breach in well or reservoir integrity and providing pathways for bitumen or steam to flow to the shallower fresh aquifers or to the surface, both of which pose significant risk to the safety and the environment. In this paper, we present an integrated geomechanics modeling approach for evaluating caprock integrity specifically devised for assessing the risks involved in heavy oil production.

## Introduction

Ensuring caprock integrity is critical in any subsurface injection process such as SAGD and CSS. Continuous steam injection triggers complex coupled thermal and hydraulic processes which alter the formation pressure and temperature leading to various changes within the reservoir as well as surrounding rock (e.g. change in in-situ stresses, rock properties, porosity and permeability). High temperature and injection pressures can reduce rock strength, induce new fractures or activate existing fractures posing continued risk of containment breach of caprock or fault reactivation. This can ultimately lead to breach in well or reservoir integrity and providing pathways for bitumen or steam to flow to aquifers or surface, both of which pose significant risk to safety and the environment. Accurate estimation of these dynamic changes in stresses and rock properties requires coupled numerical modeling between reservoir simulation (thermal fluid flow) and geomechanical model (changes in stress, strain and dilation).

## Effect of Steam Injection on Stresses

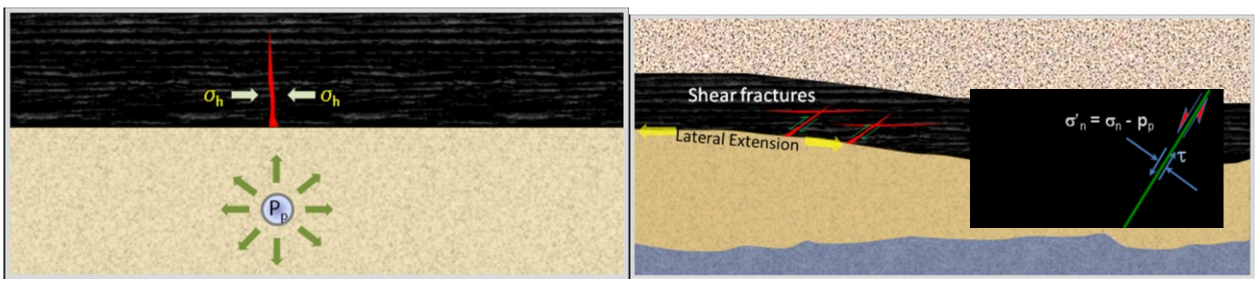
When steam is injected, pore pressure in the reservoir increases which has several effects on mechanical behaviour of rock:

- Increase in pore pressure can cause (i) dilation in the adjacent layers, (ii) transient increase in overburden stress, and (iii) deficiency in horizontal stresses among many other effects. These effects can lead to micro shear fractures in the adjacent layers, especially at the reservoir boundaries.
- Increase in formation pressure decreases the effective stresses which can reactive the existing fractures or faults.

- If effective stress decreases significantly, there is a possibility that it can become zero or negative leading to tensile fractures.
- At low confining pressures, shear strength of rock reduces significantly [Handing and Hager, 1957], making rock susceptible to fail in shear easily.
- A high-rate injection may lead to inadvertent hydraulic fracturing within the reservoir, with the potential for such fractures to grow upwards into and through the cap rock.

**Rock Failure Mechanism**

Rock can fail in tension, compression, shear or combination of these modes as shown in Figure 1. Predicting tensile failure is relatively easy because fracture pressure can be measured using mini-frac test which can be used as upper limit for injection to avoid hydraulic fracturing. However, prediction of shear failure or combination of other modes is not so easy; it involves a number of parameters and requires sophisticated numerical modeling of the reservoir and the surrounding rock. This requires coupling between changes in pressure and temperature, and changes in stresses, strain, rock properties, porosity permeability, dilation etc.




(a) tensile failure (hydraulic fractuting)    (b) shear failure or fault re-activation

Figure 1. Possible caprock failure mechanisms [after Khan et al., 2010].

**Caprock Integrity Analysis**

One of the key steps in caprock integrity analysis is to predict potential changes in stresses associated with the proposed injection plan, and the effect of these changes on caprock integrity. Maximum safe operating pressure that doesn't compromise the integrity of the caprock depends on several key factors such as rock mechanical properties, rock strength, in-situ stresses and changes in rock properties, and stresses due to steam injection. In order to estimate these parameters as accurately as possible, data from the following sources are essential:

- Sonic logs with anisotropic parameters;
- Image Logs (fracture identification);
- Mini-Frac test (closure stress);
- Formation pressure measurement; and
- Core test (rock mechanical properties and strength).

Data from these sources are integrated with coupled reservoir-geomechanics modeling to estimate induced stresses and changes in rock strength due to steam injection. These changes will be ultimately used to assess shear failure as well as tensile failure in the caprock.

Coupled reservoir-geomechanics modeling is conducted to quantify the changes in in-situ stresses caused by steam injection. For each injection scenario, changes in temperature ($\Delta T$) and changes in pressure ($\Delta p$) are computed in the reservoir simulation model, ECLIPSE. The corresponding changes in stresses ($\Delta\sigma$) and strains ($\Delta\varepsilon$), porosity ($\Delta\phi$), and permeability ($\Delta k$) are computed in VISAGE (a 3D finite element based geomechanics simulation software), iteratively. The values of $\Delta\phi$ and $\Delta k$ are fed back to ECLIPSE for computing new $\Delta p$ and $\Delta T$. Once the new state of in-situ stresses and the stress path are obtained, they are checked against various failure criteria to predict possible occurrence and location of mechanical failures in the primary caprock.

## Case Study

We investigated mechanical integrity of the caprock of a SAGD pad in the Athabasca oil sands area. The reservoir is located at around 450m depth with average porosity of 30% and reservoir datum pressure is about 35 bar. The average geomechanical properties within the reservoir and over and underlying formations are given Table 1. The reservoir grid including over and underlying layers consists of 80x10x58 cells as shown in Figure 2. This reservoir grid is embedded with few more layers on the boundaries of the reservoir model with a total grid size of 20x107x74. The embedded model is typically 2-3 times larger than the reservoir model to avoid boundary effects on the modeling results. The changes in stresses due to steam injection and failure scenarios in caprock obtained from coupled reservoir-geomechanical modeling are shown in Figure 3.

Table 1: Average geomechanical properties in the reservoir and over and underlying formations.

| **Rock Type** | **Young's Modulus (Mpa)** | **Poisson's Ratio** | **Friction Angle (Degree)** | **Tensile Stress cutoff (Mpa)** | **Cohesion (Mpa)** |
|---|---|---|---|---|---|
| Shale | 2230 | 0.38 | 20 | 5.0 | 10 |
| Shale Sand | 1210 | 0.33 | 25 | 2.5 | 5 |
| Unconsolidated Sand | 65 | 0.31 | 35 | 0.0 | 0 |
| Limestone (underburden) | 38560 | 0.20 | 40 | 20.0 | 30 |

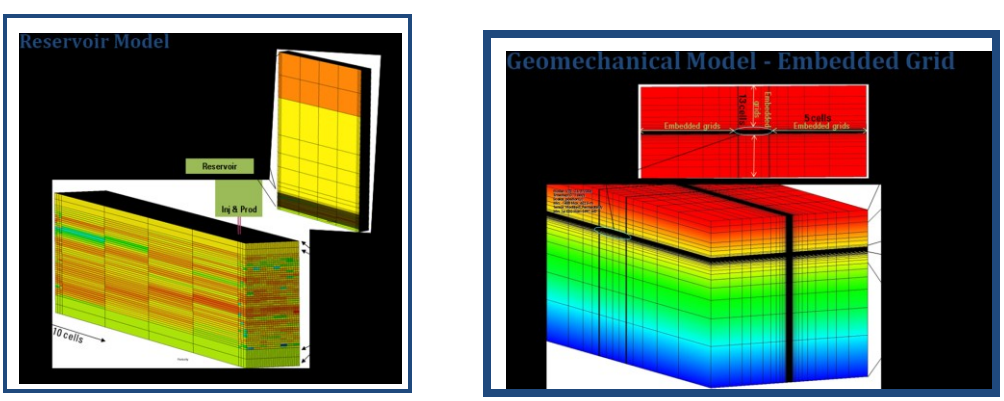



Figure 2: Reservoir model and embedded geomechanical model.

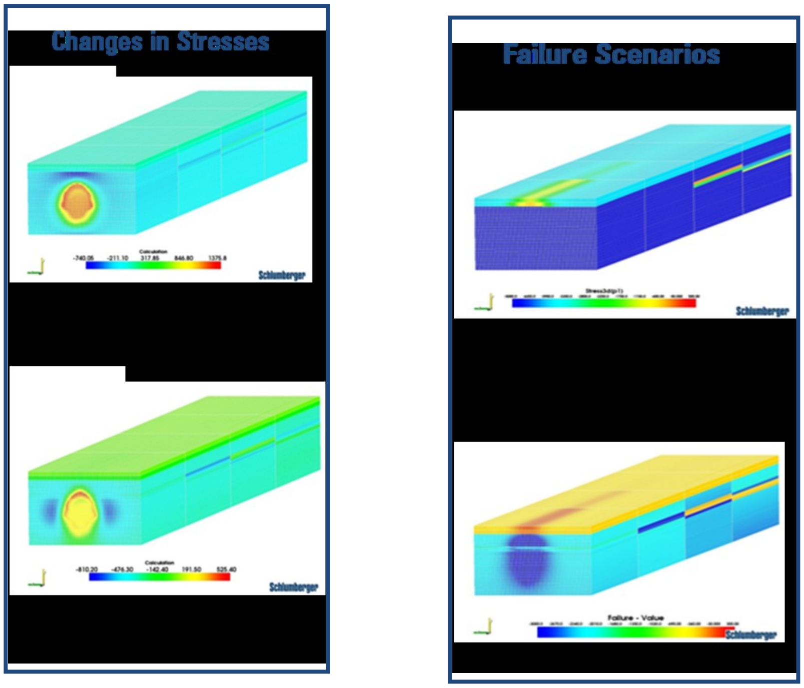



Figure 3: Changes in stresses due to steam injection and failure scenarios in caprock.

Coupled reservoir-geomechanical modeling results indicate that three years after the injection of steam, there is significant change in both horizontal and vertical stresses. Left side picture in Figure 3 shows variation in stresses, blue and red colors indicate decrease and increase respectively, in stresses. As can be seen, there is a substantial increase in stresses within the reservoir and decrease at the boundary of steam chamber. This variation creates considerable amount of stress contrast at the boundaries which can induce shearing stresses. Right side picture in Figure 3 shows failure scenarios. Proposed injection plan doesn't cause mechanical failure in the primary caprock layers. In order to determine the safe operating pressure, injection pressure is ramped to double the proposed initial injection pressure but still below the fracture pressure. After three years of continuous injection (double the proposed injection pressure), although, effective stress in the primary cap layer decreases significantly it doesn't become zero, meaning no tensile failure will occur. At the same time, shear failure will have already occurred in the cap layer as indicated in red color in bottom right picture in Figure 3.

This example clearly demonstrates that keeping the injection pressure lower than the fracture pressure (determined from mini-frac tests) is not necessarily safe. Not only the tensile failure but other failure modes should also be checked. To predict shear or other complex failure modes, coupled reservoir-geomechanical modeling is required. Therefore, integrating all the available data with geomechanical modeling can help operators proactively plan and take preventive measures to avoid any catastrophic events which can force to stop production or even abandoning of operations.

**References**

Handing, J. and Hager, R. V. Jr. [1957]. Experimental Deformation of Sedimentary Rocks Under Confining Pressure: Tests at Room Temperature on Dry Samples. Bulletin of the American Association of Petroleum Geologists, Volume 41, Number 1, 1957.

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