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Study of Fault Reactivation During CO2 Storage Using the Mohr-Coulomb Criterion and Flow-Geomechanical Coupling

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Introduction

In the context of climate change, the search for alternatives to reduce the environmental impacts associated with greenhouse gas emissions, such as CO_2, has become essential for contemporary society. Faced with this problem, scientific and technological initiatives have focused on mitigation strategies, such as geological carbon capture and storage (CCS). This technology involves capturing CO_2 from industrial processes and energy generation, followed by its compression, transportation and injection into deep geological formations, such as saline aquifers and depleted oil or gas reservoirs.

In this context, geomechanics has emerged as an essential tool for ensuring the safety and effectiveness of CCS operations. Studying the mechanical behavior of geological formations during CO_2 injection makes it possible to calculate maximum operating pressures, predict changes in the state of stress, and assess the integrity of cap rocks and geological faults. The integrity of these structures is crucial to avoid the risk of leaks and ensure the safe confinement of CO_2. Therefore, numerical modeling and geomechanical analysis, based on criteria such as Mohr-Coulomb, are widely used to predict and mitigate potential risks associated with these operations.

In a reservoir with faults, especially in the case of gas storage, the faults that occur in the planes are generally shear faults. This is because the principal stresses are often not equal. This creates a shear environment. The stress differential ends up generating shear and, consequently, failure (Zoback, 2007).

It is therefore essential to know the predominant failure regime and to analyze possible reactivations of existing failures, as well as trying to predict possible shear failures that may occur.

Method and/or Theory

Shear Failure

In this work, only failures caused by shear stresses were considered to cause failure reactivation, since the tensile strength limit is slightly higher than the shear strength limit.

The Mohr-Coulomb theory was used to study the reactivation of faults, which is a theory that describes the resistance to shear in rocks, mathematically representing the conditions under which the material will fail by shear. The Mohr-Coulomb criterion can be expressed mathematically as follows:

$$\tau = c + \sigma \tan(\phi)$$

Where: τ represents the shear stress, c the cohesion of the rock, σ is the normal stress on the rupture plane and ϕ is the internal friction angle of the material.

The Morh-Coulomb circle is a graphical tool that represents the shear failure conditions of a rock. In order to construct the Mohr-Coulomb circle, it is necessary to use the highest and lowest principal stresses. The Mohr-Coulomb envelope is represented by the point where the shear stress is zero, represented by Cohesion. This line has a certain slope, which is given by the tangent of the internal friction angle of the rock. The point where the Mohr-Coulomb circle meets the straight line is the point of rupture and reactivation of faults.

In order to visualize the fault reactivation scenario, it is necessary to assume a new fluid pressure inside the reservoir, since the reservoir will be subjected to fluid injection.

This fluid injection, in this case CO_2, will change the effective stress regime in the reservoir and consequently in the faults that are present in it.

By applying the Mohr-Coulomb criterion, we can estimate the maximum pressure at which the rock will resist the shear forces being applied by the change in the effective stress regime (Figure 1).

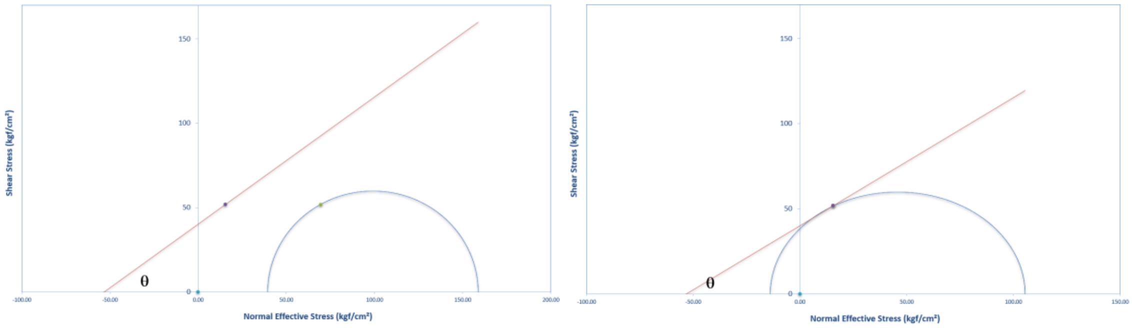

Figure 1: Mohr-Coulomb envelope in the initial conditions of the reservoir (left). Application of the Mohr-Coulomb criterion in the shear fault reactivation scenario (right).

In this way, the pore pressure calculated in this case will be the maximum shear strength pressure, i.e. the maximum pressure at which injection will be possible without reactivation of shear faults will be the maximum shear strength pressure of the rock.

The other parameters were kept the same, as their values do not vary greatly due to the change in the effective stress regime (Figure 2).

Depth	*1500 m*
Cohesion	*40 kgf/cm²*
Friction Angle	*37 °*
Biot	*0.82*
Overburden Stress	*384.27*
Minimum Horizontal Stress	*264.87*
Critical shear stress	*322.8 kgf/cm²*

Figure 2: Data used to apply the Mohr-Coulomb criterion for calculating the shear strength limit stress.

Model with geomechanical coupling

The simulation model (Figure 3) used was a heterogeneous model with faults and fractures, the cap rock being an inactive natural fracture. The reservoir contains 14 inactive faults (Figure 4), which limit the flow of fluid from one region to another. The integrity of the faults and the caprock was analyzed by incorporating the data calculated in the 1D Geomechanical Model, such as Young's Modulus, Poisson's Ratio, friction angle and cohesion. In addition, stresses were incorporated into the simulation model in the form of stress gradients, which run from the top of the extended model (Figure 3) to the bottom.

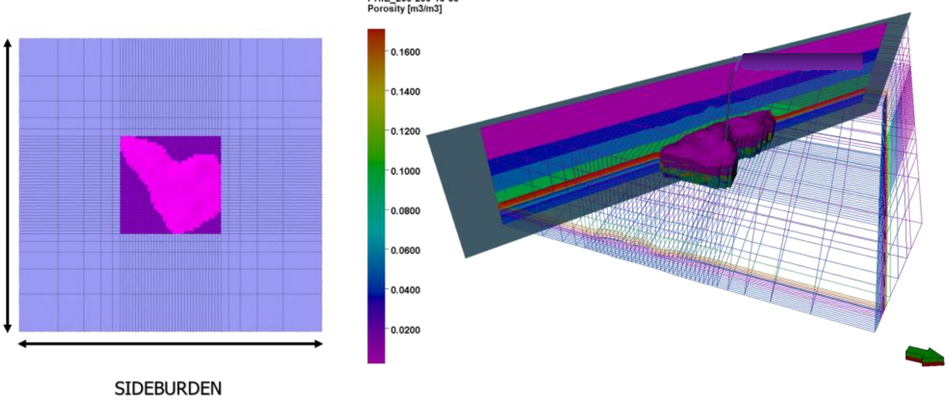

Figure 3 3D model constructed for coupled simulation.

Figure 4: Arrangement of faults that comprise the model can be observed. One of the main parameters to be analyzed in this study is fault reactivation.

The increase in pore pressure, the portion of pressure exerted by the fluids, tends to increase as CO_2 is injected. Increased pore pressure tends to decrease the shear strength of faults, inducing reactivation (Streit & Hillis, 2004). This can also be seen in the Mohr-Coulomb rupture criterion, which shows the relationship between maximum shear strength and effective stress, which is directly linked to pore pressure.

In addition, the injection of CO_2 will show a change in the stress state of the blocks, including the fault blocks (Nicol et al., 2005). The state of stress can be altered due to a change in the pressure exerted by the fluid, especially in contexts where there are pre-existing faults.

The fault reactivation criterion used in the GEM® geomechanical coupling simulator was the Mohr-Coulomb criterion, the same criterion used in the 1D fault reactivation analysis. In addition to the Mohr-Coulomb criterion, the Slip Tendency of a fault was used in the simulation.

Slip tendency is a geomechanical criterion used to study the propensity of a fault to slip when subjected to a critical state of stress (Morris et al., 1996). This parameter is crucial for numerically predicting the reactivation of faults, especially when a reservoir is subjected to the injection of large volumes of fluid, as is the case with CO_2 storage.

The fault reactivation pressure, calculated using the Mohr-Coulomb criterion, was 32,200 kPa.

In the study of fault reactivation, the slip tendency parameter (*ST*) is a ratio between the actual shear stress and the slip shear stress (Sanchez et al., 2016), as defined by Byerlee (1978) in the equation:

$$ST = \frac{\max(\tau_{t,}\ \tau_s)}{\tau_{slip}}\ , 0 \leq ST \geq 1$$

The fault will be considered reactivated, i.e. it will allow flow from one region to another if the *ST* value is 1. In this work, the critical slip tendency value (*ST*) was 0.8, as a safety measure.

Results

In the figure below (Figure 5) you can see several regions, in red, where the critical slip tendency value has been reached, when the fault reactivation pressure is reached. The areas highlighted in red indicate regions with a high slip tendency, suggesting that these faults are more susceptible to reactivation due to the increased ratio of shear stress to normal stress caused by the increased pressure exerted by the fluid.

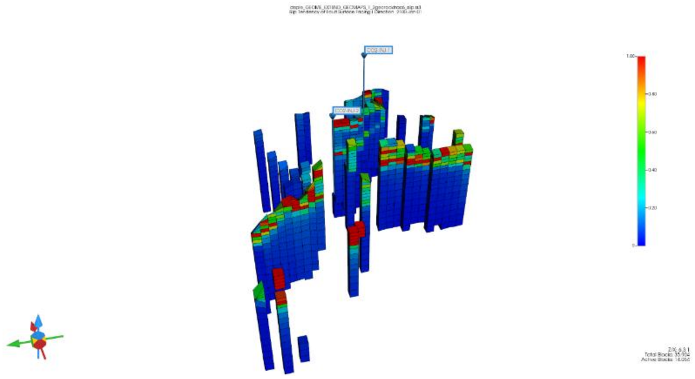

Figure 5: Red areas are critical zones that require more rigorous monitoring during CO_2 injection as they are more prone to failure and may result in leaks.

During depletion, the fluid pressure in the pores of the reservoir decreases. This causes a change in the balance of effective stresses, increasing the effective stress in the rock. As a result, the rock around the reservoir can experience compaction, and the normal stresses (perpendicular to the fault surface) increase (Sanchez et al., 2016).

Fluid injection increases the pore pressure in the reservoir and adjacent rocks. This increase reduces the effective normal stress in fractured faults and in all blocks of the reservoir matrix, making them more susceptible to slip if the shear stress is sufficient, since the tendency to slip is a ratio between the increase in shear stress as a function of normal stress (Byerlee, 1978).

In this study, an increase in the tendency to slip was observed during depletion. The figure below shows this increase as a function of the decrease in pore pressure. The decrease in pore pressure is a characteristic of depletion, since when fluid is removed from a reservoir, the fluid's share of pressure decreases.

When CO_2 storage begins, there is a decrease in the tendency to slip until this property begins to increase, until it reaches the critical limit of tendency to slip, which has been set at 0.8.

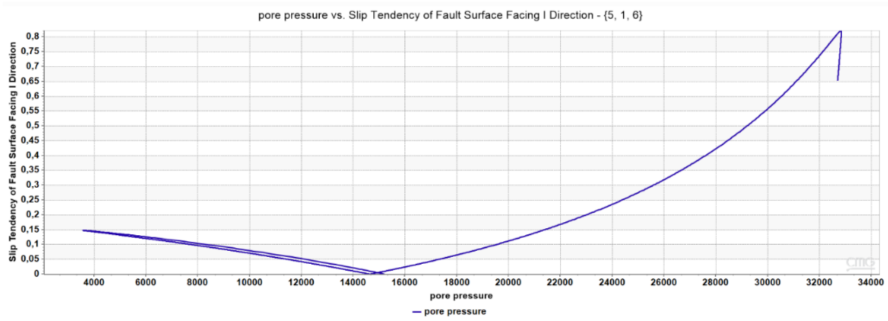

Figure 6: Until the critical slip tendency limit is reached, the curve goes through a phase of stability during the beginning of CO_2 storage (or reduction of tendency), followed by a progressive increase in the slip tendency as the pore pressure continues to rise. This behavior highlights the importance

of monitoring the pore pressure to prevent it from reaching levels that could induce fault reactivation.

Conclusions

CO_2 storage is one of the most efficient and practical climate change mitigation measures available today. However, its operation requires in-depth studies of the formation, including monitoring, geological modeling and numerical simulation to predict the various behaviors that both the reservoir and the cap rock and faults that make it up will have.

It is therefore essential to understand the behavior of the cap rock when subjected to high pressures, since it may fracture as a result. It is also important to understand the conditions of the faults present in the reservoir and the scenarios in which they may reactivate and allow CO_2 to flow from one region to another.

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