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Analysis of the Mechanical Behavior of the Salt during Field Production for the Brazilian Pre-Salt Reservoirs: An Example in the Santos Basin

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Summary

The pre-salt province of the Santos Basin, located offshore Brazil, has significantly driven exploration and production (E&P) activities due to its extensive hydrocarbon reserves. These carbonate reservoirs are typically overlain by a complex salt layer, with thicknesses varying from a few meters to over 3 kilometers. Above this salt layer lies a thick siliciclastic post-salt sequence. Over the past decades, various constitutive models relating stress and strain have been proposed to describe the mechanical behavior of rock salt, ensuring its integrity as a geological seal. This study outlines the fundamental requirements for selecting an appropriate constitutive model for the salt section, considering the field's production timeline.

Introduction

The analysis of the mechanical behavior considering the creep of the cap rock is essential to ensure safe injection and production operations throughout the productive life of petroleum reservoirs in the offshore Santos Basin (Amaral et al., 2017). Geomechanical models that capture these complexities require collaborative efforts within an integrated geoscience and engineering environment. In this context, high-resolution seismic data plays a crucial role in constructing the stratigraphic framework and estimating 3D mechanical properties (Meneguim et al., 2021). The salt cap rock lies above the carbonate reservoir and below a wedge of siliciclastic sediments in the post-salt sequence, as shown in Figure 1. A preliminary analysis of how the stress state in the salt layer will evolve during the reservoir's productive life is an excellent indicator of the requirements that the constitutive model must fulfill.

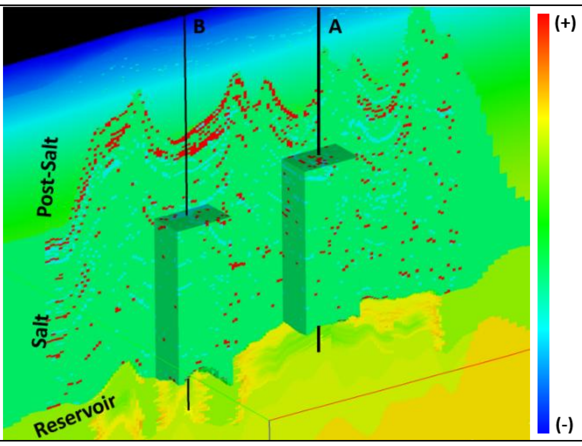

Figure 1: Density in an offshore section of the Santos Basin passing through two wells, A and B, illustrating the sequences: Reservoir, Salt, and Post-Salt. Rectangular regions within the salt around wells A and B are highlighted. Distance between wells A and B is 5 km.

Several constitutive models have been proposed over the years to simulate the creep behavior of rock salt in underground facilities (e.g., Munson, 1997; Labaune and Rouabhi, 2019; Reedlunn, 2022; Cirone and Vargas, 2023). The basic formulation of these models generally relies on the description of deformation mechanisms at the macro or micro scale. To address these challenges, stress tensor invariants in the salt layer adjacent to two wells, A and B, are analyzed for two distinct years: 2014 and 2037. Well A experiences a pressure drop in the reservoir associated with production, while Well B undergoes a pressure increase in the reservoir due to injection.

Method

The stress state at a point within the material is represented by a second-order symmetric tensor, denoted as $\boldsymbol{\sigma}$, which can be expressed as a matrix in cartesian coordinates:

$$\sigma_{ij} = \begin{bmatrix} \sigma_x & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \sigma_y & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \sigma_z \end{bmatrix}$$

$I_1 = \boldsymbol{tr}(\boldsymbol{\sigma})$ is the first invariant of the stress tensor, where $\boldsymbol{tr}$ represents the trace of a matrix.

The deviatoric part of the stress tensor, denoted as **s,** is defined as:

$$s_{ij} = \sigma_{ij} - \frac{I_1}{3}\delta_{ij} = \begin{bmatrix} \sigma_x - \frac{I_1}{3} & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \sigma_y - \frac{I_1}{3} & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \sigma_z - \frac{I_1}{3} \end{bmatrix}$$

where δ_{ij} is the Kronecker delta.

The second invariant of the deviatoric stress tensor $\boldsymbol{J_2}$, is given by $\boldsymbol{J_2}$= $\boldsymbol{tr}(s^2)$ and **q** is the equivalent Von Mises stress, given by **q** = $(3.\boldsymbol{J_2}/2)^{1/2}$.

The third invariant of the deviatoric stress tensor $\boldsymbol{J_3}$, is given by $\boldsymbol{J_3}$= $\boldsymbol{tr}(s^3)$ and $\boldsymbol{\theta_c} \in [0, \pi]$ the Lode angle, is a measure of the loading type, given by $\cos(\boldsymbol{\theta_c}) = \sqrt{6}.\boldsymbol{J_3}/(\boldsymbol{J_2})^{3/2}$.

Figure 2 illustrates the pore pressure variation within the reservoir from 2014 to 2037, according to the reservoir flow model forecast. Over these 23-year period, a pressure drop of 35 MPa is observed near well A, while a pressure increase of 15 MPa occurs near well B.

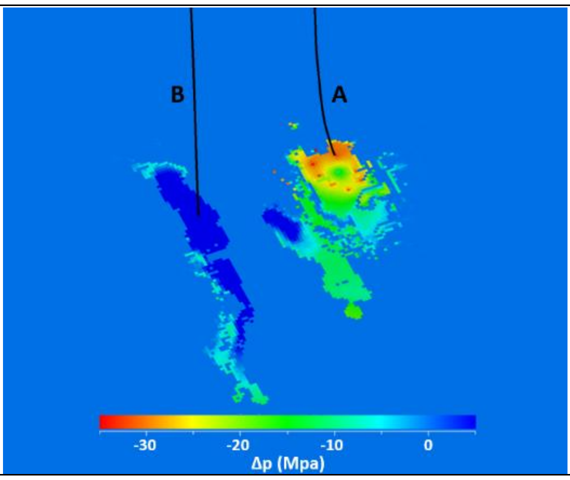

Figure 2: Pore pressure variation within the reservoir from 2014 to 2037

This set of stress tensor invariants (I_1, q, Θ_c) was estimated within the salt, in regions surrounding wells A and B, as shown in Figure 1, for a 3D numerical simulation over 23-year period.

A numerical simulation was conducted using the GeomecBR6 code (CENPES Petrobras, Rio de Janeiro, Brazil), a 3D finite element simulator. The model consisted of 41 million elements, with an aerial dimension of 35 km × 35 km and a vertical dimension of 10 km. The constitutive behavior of the salt layer was represented by an elastic, perfectly plastic Drucker-Prager model in the calculations; however, the details of this model are not provided here. While this constitutive relation for salt behavior may be overly simplified, it is adequate for a preliminary analysis.

Results

Figure 3 shows the invariant q, indicating deviatoric stress magnitude, in the salt around wells A and B for 2014 and 2037. The top panel illustrates salt near well A, where reservoir depletion increased q. The bottom panel depicts salt near well B, where reservoir pressurization slightly reduced q.

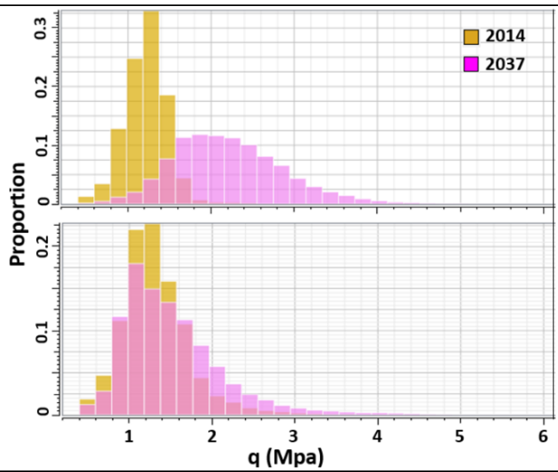

Figure 3: The top panel shows the invariant q for salt around well A, while the bottom panel shows it for salt around well B. Yellow represents 2014, and pink represents 2037.

The results for the lode angle Θ_c, which is an indicator of the loading type (compression or extension), in the salt regions surrounding wells A and B for the years 2014 and 2037 are shown in Figure 4. The top panel of Figure 4 shows salt near well A, where reservoir depletion shifted cos(Θ_c) from +1 (compression) in 2014 to -1 (extension) in 2037. The bottom panel shows salt near well B, where pressurization increased cos(Θ_c) toward +1 (compression) in 2037.

Figures 3 and 4 emphasize key requirements for a salt constitutive model, which must capture changes in q and Θ_c invariants. The invariant q increases near depleted regions and slightly decreases in pressurized, confined areas, showing isotropic hardening/softening consistent with models like Sandia's Multimechanism Deformation Model (Munson, 1997) and Lubby2. The invariant Θ_c demands stricter modeling as salt shifts to extension regime in depleted zones and compression regime in pressurized ones, exhibiting both kinematic and isotropic hardening/softening. These combined behaviors require more advanced constitutive models (e.g., Labaune and Rouabhi, 2019; Reedlunn, 2022; Cirone and Vargas, 2023).

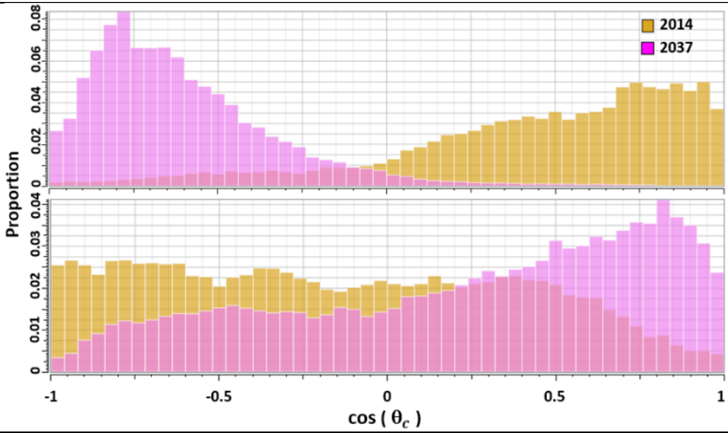

Figure 4: The top panel shows $\cos(\theta_c)$ for salt near well A, and the bottom for salt near well B. Yellow represents 2014 and pink represents 2037 indicate a 23-year shift: well A's salt moved to extension regime, while well B's salt shifted to compression regime.

Conclusions

The analysis of salt cap rock in Santos Basin pre-salt reservoirs highlights the need for advanced constitutive models addressing combined isotropic and kinematic hardening. Properly calibrated models (e.g., Labaune and Rouabhi, 2019; Reedlunn, 2022; Cirone and Vargas, 2023) meet the minimum requirements for accurate cap rock behavior prediction.

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