International Workshop on Multiscale and Multiphysics
Processes in Geomechanics
R.I. Borja, E.M. Dunham, E. Kuhl and J.A. White (Eds)
Stanford University Campus, June 23-25, 2010

GEOMECHANICS APPLIED TO THE WELL DESIGN THROUGH SALT LAYERS IN BRAZIL: A HISTORY OF SUCCESS

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Keywords: Salt, Geomechanics, Well, Drilling

Summary. The lessons learned on the geomechanical salt behavior and its application in subsalt wells design are described in this paper. In addition, it is presented the developed methodology validation, through comparison between computing modeling results with measurements carried out in experimental panels, in the potash mine, and with measurements obtained in an experimental well drilled for the purpose of calibrating and optimizing directional drilling in salt layers. These parameters and methodology have been used to support the design of the wells drilled in the Pre-Salt giant oil fields in Brazil with very successful results.

1 INTRODUCTION

A major challenge in drilling in the Pre-salt area, in Brazil, arises from the special structural salt behavior, when compared to other geomaterials, since it develops high creep strain rates under high levels of deviatoric stresses and temperatures. The salt or evaporitic rocks, formed by the sea water evaporation, have different chemical compositions. In the Pre-salt area the more important types are: halite, carnallite and tachyhydrite. The tachyhydrite, for the same state variables, deviatoric stress and temperature, develops creep strain rates up to one hundred times higher than halite. Many operational problems, such as stuck pipe and casing collapse, have been reported when intercalation of these rocks within a thick layer is found. The challenge of designing excavations near tachyhydrite, began with the development of an potash underground mine to extract sylvinite ore in Northeast Brazil. The research that began in the 70s, to enable the mining of this ore overlying tachyhydrite, triggered one of the largest R&D projects in rock mechanics, including computing modeling, laboratory and field tests. For the design of the pre-salt wells this previous experience was used and additional triaxial creep tests were performed using a new rock mechanics laboratory. Field tests and computer modeling improvement were used to overcome the challenge of the Pre-salt drilling.

2 CONSTITUTIVE EQUATION FOR SALT BEHAVIOR

Due to its crystalline structure, salt rocks exhibit time-dependent behavior when subjected to shear stress. The creep strain rate is influenced by the formation temperature, mineralogical composition, water content, presence of impurities, and the extent to which differential stresses are applied to the salt body. Early in the 1990´s, creep constitutive laws based on deformation mechanisms, have been recommended by the international technical literature, to represent the intrinsic behavior of the evaporates [1-2].

The law that incorporates the deformation mechanisms for the evaporite rocks was developed by Munson [1,2]. The constitutive equation based on Munson's creep law considers the following mechanisms: Dislocation Glide, Dislocation Climb and Undefined Mechanism. The largest contribution of either mechanism depends on the temperature conditions and differential stress to which the salt is submitted.

In this paper, the salt rock behavior is analyzed according to the elasto/visco-elastic behavior, adopting the Double Mechanism creep law, as shown in equation 1:

$$\varepsilon = \varepsilon_0 \cdot \left(\frac{\sigma_{ef}}{\sigma_0} \right)^n . e^{\left(\frac{Q}{RT_0} - \frac{Q}{RT} \right)} \tag{1}$$

where: ε is the strain rate due to creep at the steady state condition; ε_0 is the reference strain rate due to creep (in steady state); σ_{ef} is the creep effective stress; σ_0 is the reference effective stress; Q is the activation energy (kcal/mol), Q=12kcal/mol [4]; R is the Universal gas constant (kcal/mol.K), R=1.9858E-03; T_0 is the reference temperature (K); and T is the rock temperature (K).

3 VALIDATION OF THE CREEP PARAMETERS

As part of the rock mechanics studies used to enable the mining of the lower sylvinite layer in the potash mine, an experimental panel, [4] was designed and excavated in the lower sylvinite layer, overlying a layer of tachyhydrite 15m thick. An experimental room was excavated in this panel with length of 95m, divided in three sections, isolated from the effects of nearby excavations, with intensive use of field instrumentation, for back-analysis, allowing the calibration of the creep parameters. In each section, a slab protection was left with three different thicknesses (3m, 2m and 1m). The strategy is to evaluate the influence of the slab protection thickness of sylvinite in inhibiting the floor heave due to the creep of tachyhydrite.

Among the various instruments installed in the room, this paper shows the comparison between the vertical closure measurements with those obtained by the numerical simulation. The geology description in the area of the experimental panel and the finite element model used in the simulations are shown in Figure 1. The SIGMA [4] system is used for pre and post processing of the finite element model. The numerical simulations have been done through application of the finite element code ANVEC [4]. Figure 2 shows the comparison between the closure measured in the experimental gallery in different locations along its axis for a slab protection of syvinite of ~2.50m. The plot shows the closure predicted by numerical simulation with and without the initial deformation after excavation, which normally is lost in the field. In these numerical models, it is used the creep parameters obtained in the laboratory creep tests.

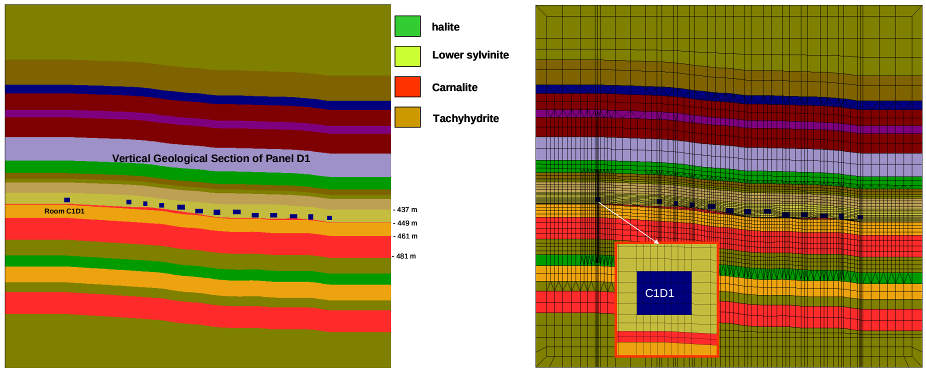

Figure 1: Geology description in the experimental panel and the plain strain model used in the simulations.

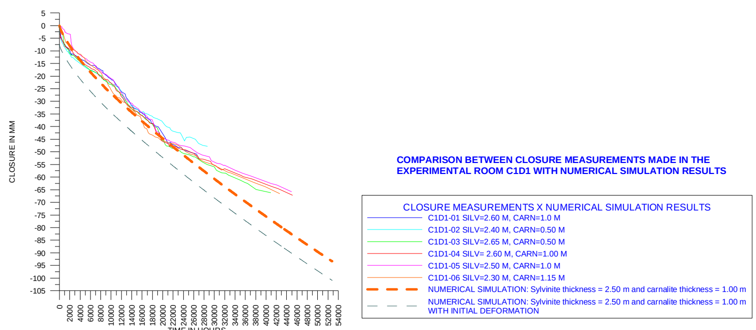

Figure 2: Comparison between closure measurements and numerical simulation, sylvinite slap protection 2.5m thick.

The results obtained by numerical simulation shows excellent fit to the closure measured in the experimental room C1D1 up to 16000 h. After this time the refrigeration process starts in the mine and reduces the rock temperature and the creep measurements. This process wasn't introduced in the numerical simulation.

4 FINITE ELEMENT MODEL OF WELL CLOSURE

With the creep parameters validation, it was applied the constitutive equation in the numerical simulation of the creep salt behavior to predict the evolution of well closure with time during drilling of thick layers of salt, for various mud weights. These results were used to define several technically feasible alternatives for the drilling strategy through the salts intervals. The prospect expected 2000m of different salt rocks, to be drilled at the interval of 2600 to 4600m, (WD = 1600m). This case study considered a tachyhydrite layer of 5m just 100m from the salt base. The temperature at the top of the salt interval is 40°C and at the base 60°C. The well will be drilled with a diameter of 17 ½" and a 14" casing will be used.

The axisymmetric model, according to the longitudinal axis of the well, comprises 2000 m of salt rocks and 200 m of thick hard rock, above and below the anhydrite layer to represent the boundary condition. 86418 quadratic isoparametric elements (with 8 nodes) and 264063 nodal points are employed in the finite element model. Figure 3 shows the finite element mesh used and the numerical results, for different mud weights.

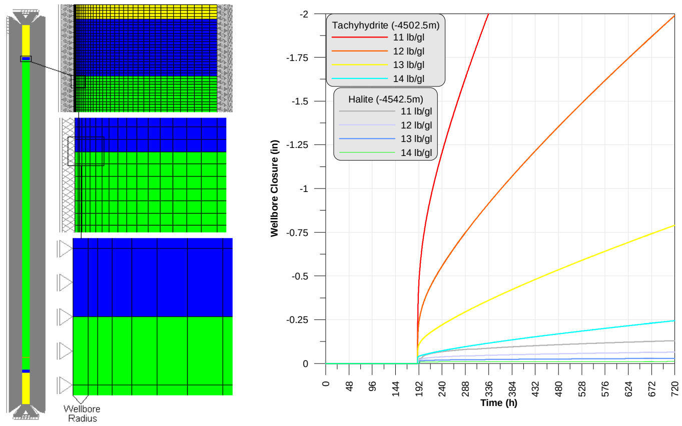

Figure 3: Finite element mesh and numerical results.

4.1 Numerical prediction of well closure: drilling fluid design

Figure 3 shows the evolution of the 17 ½” well closure with time, when it is adopted from 11 lb/gl to 14 lb/gl mud weight. As is expected, the tachyhydrite layer has a very high closure rate, and the halite layer, a low closure rate. Considering a minimum thickness of 0.75” for the cementation of the 14” casing, for a well 17 ½” in diameter, the acceptable closure will be 2”. The curves of well closure with time of each depth begin when the bit reaches the respective depth. In this case in order to have enough time to complete the drilling operation and set the casing, use a drilling fluid over 12lb/gl is recommended.

5 CONCLUSIONS

This work presents a methodology developed by PETROBRAS for the design of the subsalt reservoir wells for the exploration and production phase. The numerical simulations have been done through the application of an in-house developed computer code based on the finite element method. This methodology has been used to support the design of the wells drilled in the Pre-Salt giant oil fields in Brazil with very successful results.

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