# Modeling of creep closure of salt rocks drilled by directional wells

Carlos M. A. Tenorio[1], Catarina N. de A. Fernandes[1], Joao P. L. Santos[1], William W. M. Lira[1], Themisson S. Vasconcelos[1]

[1]*Laboratory of Scientific Computating and Visualization, Technology Center, Federal University of Alagoas LCCV/CTEC/UFAL*
*Campus A. C. Simões, 57072-970, Maceió/Alagoas, Brazil*
*carlos.tenorio@ctec.ufal.br, catarina@lccv.ufal.br, jpls@lccv.ufal.br, william@lccv.ufal.br, themisson.vasconcelos@lccv.ufal.br*

**Abstract.** This paper presents a strategy for three-dimensional modeling of directional wells penetrating salt rocks, aiming at predicting the closure of these rocks due to creep. One of the major challenges in oil production in the pre-salt region is drilling through thick layers of salt rocks. During drilling, these rocks deform in the direction of the wellbore closure due to creep. The accumulated deformation of the wellbore wall over a given time interval can lead to the restriction of the drilling string's passage and even its irretrievable entrapment. Directional wells in salt regions present an even greater complexity, as changes in inclination alter the stress distribution around the well, changing the configuration of the deviatoric stress, with no symmetry around the well's central axis (as in vertical wells). This paper discusses a strategy for modeling directional wells in salt regions using the commercial software *Abaqus* [1]. This software implements the Finite Element Method, including its three-dimensional formulation, and allows modeling of creep deformation of materials, enabling the implementation of constitutive models different from traditional ones through subroutines. The adopted constitutive equation is the most recurrent in the literature to describe the creep phenomenon in wells drilled through Brazilian salt rock. To verify the developed strategy, a vertical well is modelled, and the obtained results are compared with those presented by axisymmetric modeling, already consolidated in other works developed by the group. After verification, directional wells are modelled and studied, and their behavior is discussed regarding the observed displacement and stress fields, mainly along the region near the wellbore wall. This work contributes to the understanding of the creep behavior in salt rocks when drilled by directional wells, and discusses some strategies that can contribute to the stability of the rock formation, aiming at the safe and efficient construction of wells in salt regions.

**Keywords:** Salt rocks, Directional wells, Three-dimensional finite elements.

## 1 Introduction

The presence of evaporitic sections in oil or gas exploration areas increases the likelihood of success due to favorable conditions for hydrocarbon trapping. Nonetheless, the process of drilling in salt rocks is extremely complex due to creep effects [2]. This phenomenon is explained by the salt's deformation tendency over time under constant stress, which unavoidably leads to wellbore closure and, if severe, may result in string entrapment and other significant operational challenges [3]. Thus, deep knowledge about these properties is essential for the planning and execution of drilling operations in salt formations. In order to minimize the consequences caused by creep, three-dimensional modeling becomes an interesting tool. It allows the prediction of wellbore closures and the identification of high-risk areas, enabling the implementation of effective mitigation strategies. Usually, wellbore modeling on salt has focused on vertical configurations where the stress distribution around the wellbore is symmetric, which simplifies the analysis and prediction, and it was not usual to drill directional phases on salt. However, it is becoming increasingly common to drill inclined sections in salt regions, which raises questions about the creep behavior in these scenarios. Directional well drilling, which is often necessary to optimize reservoir extraction and avoid geological obstacles, presents additional complexity on numerical modeling since the problem is no longer axisymetric. The objective of this work is to develop a methodology for modeling directional wells in salt rocks, aiming to understand what changes in the behavior of these rocks when the drilled well is not vertical. The step-by-step process adopted for modeling directional wells in salt using the Abaqus tool is outlined, detailing the strategy employed for validating the adopted methodology, and presenting a study on the well's behavior in response to variations in its inclination.

## 2 Modeling Strategy

To simplify the interpretation of the results, well sections with a single inclination were modeled. The comercial software *Abaqus* [1] was used to model and study the problem, its macro routines in python were of great use to automate the generation process. Since a single inclination was adopted, it was possible to model the vertical well and then apply a rotation around a Cartesian axis.

To maintain consistency with axisymmetric modeling, a method with which the group has prior experience, the C3D20R element was selected due to its similarity in shape and integration with the CAX8R element. Regarding the geometry, an initial attempt was made to use a design similar to that presented by Poiate [4] (see Fig. 1(a)). However, the meshes generated by Abaqus exhibited poor conditioning, even after trying various different partitions within the model. To improve mesh quality, the geometry in Fig. 1(b) was considered, where the massif was modeled as a cylinder. While this improved the mesh quality, modeling larger inclinations using this geometry would require a significantly high number of elements, which was not ideal for this study's purpose of analyzing different inclinations. Consequently, the geometry shown in Fig. 1(c) was adopted for modeling in this work.

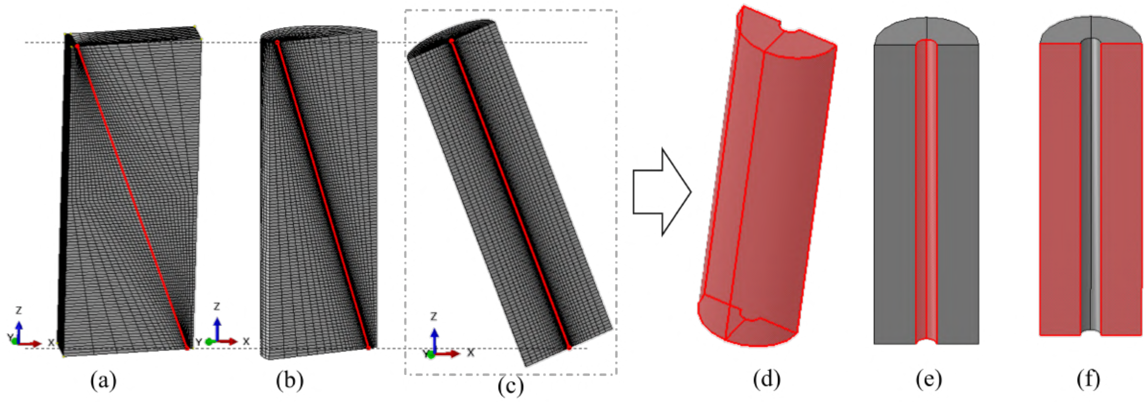


Figure 1. (a, b, c) Geometry attempts for modeling the massif; (d, e, f) Sets to define loads and boundary conditions.

After defining the geometry of the problem, the step-by-step modeling process is similar to what the group had already been doing in the study of the vertical problem, which will be further detailed in the following sections.

### 2.1 Geometry and Material Properties

The first step in modeling a problem in Abaqus is to create a "part", where the massif geometry is defined. The half-cylinder is a deformable 3D solid of type Extrusion, where a half-circle with external radius ($r0$) and centered at the origin is defined as the face to be extruded, and then the length of the model is defined. To add the well to the massif, a cut of the same shape (half a circle) was made on the symmetry face, also using the extrude tool, where the radius of the half-circle is the well radius ($rw$). To assure mesh quality a plane perpendicular to the x-axis at the origin divides the part into two cells. Next, the model is discretized. The vertical edges are divided into an equal number of parts, and the circular edges are partitioned similarly. The radial edges (at the top and base of the model) are divided considering a ratio (BIAS) between the size of the first element (closest to the wellbore) and the last element (farthest from the wellbore). The element type is selected: Twenty-node brick element with reduced integration (C3D20R), and the mesh controls technique is set to structured.

The material is created by defining its mechanical properties, Poisson ratio and Young Modulus for the elastic model, and the creep model adopted is the Double Power Law [1]. The double- mechanism of deformation model has proven effective in representing the viscoelastic creep behavior of salt rocks. According to Araújo [3], the primary advantage of this model is its ability to accurately predict the deformation rate under equilibrium conditions. Poiate Jr et al. [2] applied this model in experimental studies with Brazilian halite, obtaining a good correlation between numerical and experimental results. The model's equation was modified to account for the specific properties of the studied materials, further confirming its robustness for secondary creep analysis. However, implementing this creep law in Abaqus requires using subroutines, which slow down the simulation due to the necessity of linking with Fortran compilation software. Given that the objective of this work is to model and understand the impact of well inclination on salt rock behavior, the study remains valid using the Double Power Law. With the adjusted parameters, it produces results sufficiently close to the double-mechanism model, and the same law is applied to all models described and discussed here. The Double Power Law is described by:

$$\bar{\varepsilon}^{cr} = A_1 \exp\left(-\frac{B_1}{(\theta - \theta^Z)}\right)\left(\frac{\dot{q}}{\sigma_0}\right)^{C_1} + A_2 \exp\left(-\frac{B_2}{(\theta - \theta^Z)}\right)\left(\frac{\dot{q}}{\sigma_0}\right)^{C_2}, \tag{1}$$

Where, $\bar{\varepsilon}^{cr}$ is the equivalent uniaxial creep strain rate, $\dot{q}$ is the equivalent uniaxial deviatoric stress (von Mises), $\theta$ is the temperature, $\theta^Z$ is the user-defined value of absolute zero on the temperature scale used, $\sigma_0$ is the normal stress, and $A_1$, $A_2$, $B_1$, $B_2$, $C_1$, and $C_2$ are other material parameters.

Once the geometry and the materials are defined it is possible to add the part to the assembly, and at this moment, a rotation is applied to the entire part. The angle, in degrees, will determine the well's inclination relative to the vertical direction. After that, a translation on the z-axis is applied so the mesh coordinates will agree with the depth of the well.

### 2.2 Steps, loads and boundary conditions

With the geometry and model established, the next step is to define the simulation steps and the loads and boundary conditions. To establish the geostatic equilibrium, which is the state of the massif before drilling the well, a geostatic step is defined. Araújo [3] explains: due to the zero porosity of salt rocks, there is no pore pressure, causing the total stresses to equal the effective stresses. The geostatic stress state is defined by the weight of the overlying layers and the lateral earth pressure coefficient ($k_0$). The geostatic stress is established as a "Predefined field" acting throughout the entire problem domain, from the first step to the end of the simulation. The temperature is another "Predefined field" that remains constant from the first step to the last. It is defined, in Kelvin, by an "Analytical field" that establishes the temperature as a function of depth ($z$). The weight of the massif, which balances the variation in geostatic stress in the depth direction, is defined as a "Load" of the "Body force" type, remaining unchanged throughout all time steps.

Regarding the boundary conditions, displacements in all three coordinate directions are constrained on the top, bottom, and outer radial surfaces (Fig. 1(d)), during the entire simulation steps. The surface that defines the wellbore walls (Fig. 1(e)) also has restricted displacements in all three Cartesian directions during the geostatic time step, as the well is not yet considered at this stage, and the massif is assumed to be in equilibrium with no displacements. The symmetry surface (Fig. 1(f)) has a displacement symmetry condition along the y-axis, which is also maintained throughout all simulation steps.

Next, an elastic step is added to establish the initial conditions for the subsequent "Visco" step. This step, using a creep constitutive law, describes the creep behavior of the salt rock, taking into account the temperature and time dependence of the creep rate.

In these two steps, the loading and boundary conditions are identical. The only change from the geostatic step occurs on the wellbore wall surface (Fig. 1(e)), where the displacement constraints are deactivated, and a "Pressure" load is applied, representing the drilling fluid pressure used in well construction. The magnitude of this pressure is also defined using an analytical field as a function of depth ($Z$), since it corresponds to the static pressure of the fluid filling the well from the rotary table.

## 3 Case Study

Once the step-by-step modeling procedure is defined, a synthetic well in a scenario similar to those found in Brazilian pre-salt wells is adopted. Due to the high memory consumption and processing time, only a 100-meter section is considered. Based on the group's experience with axisymmetric problem modeling, as well as what is presented in the literature (e.g., Firme et al. [4]), simulating a 100-meter section is more than sufficient to eliminate edge effects, so that simulating the entire phase would lead to identical results. Table 1 describes the well data.

The Double Power Law was used as the constitutive model to describe the creep-induced deformation in this problem. Elastic parameters and those from the Double Mechanism of Deformation were presented by Poiate [5], they were used and adjusted by the research group to ensure that the results obtained were similar between the two creep models (see Table 1).

In addition to the 2D axisymmetric model, 3D wells were modeled with different inclinations: 0º, 20º, 40º, 60º, and 80º (see Fig. 2). In the two-dimensional axisymmetric model, a complete phase of 1024 meters was simulated, while in the three-dimensional models, only the deepest 100 meters were modeled, and discretized into

Table 1. Problem parameters

| Model parameters | | Halite constitutive parameters | | | |
|---|---|---|---|---|---|
| Parameters | Values | Global and DM (Poaite [5]) | | Double Power | |
| Well diameter ($2rw$) | 12.5” | R/Q [$10^{-4}$ 1/K] | 1.655 | $A_1$ [1/h] | 38.305 |
| External radius ($r0$) | 15 m | $\sigma_0$ [MPa] | 9.91 | $A_2$ [1/h] | 38.305 |
| Temperature (top/bottom) | 110ºC/115ºC | $\epsilon_0$ [$10^{-6}$ 1/h] | 1.888 | $B_1$ [K] | 6042.905 |
| Fluid weight | 10.5 ppg | $T_0$ [K] | 359.15 | $B_2$ [k] | 6042.905 |
| Fluid pressure at the top | 64.7 MPa | $n_1$ | 3.364 | $C_1$ | 3.364 |
| Geostatic stress at the top | 93.7 MPa | $n_2$ | 7.564 | $C_2$ | 7.564 |

100,000 brick elements. The observed and discussed results are from the well walls 50 meters above the bottom of the phase and during 100 hours of creep closure.

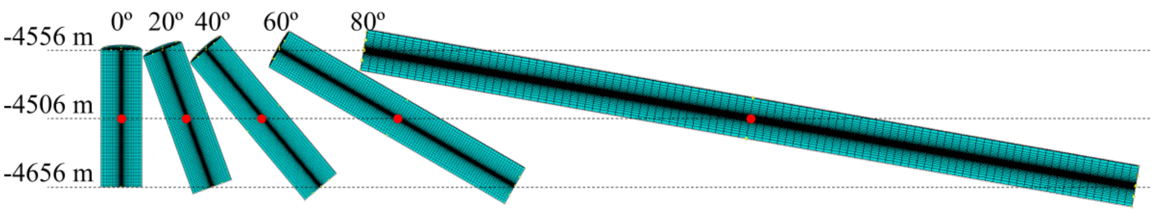


Figure 2. Modeled domains and its interest points and depths.

The Figure 3 shows the diametral displacement of the modeled wells over time. Diametral displacement is defined as the variation in the well's diameter, measured between two opposite walls. In vertical wells, both in the 2D axisymmetric vertical modeling and in the 3D vertical model, any position of the wall showed equal displacement due to the symmetry of the problem. Therefore, in these cases, the diametral displacement is given as twice the radial displacement. In the case of directional wells, points on opposite sides showed slightly different displacements due to the inclination of the well. Thus, it is necessary to sum the displacement of these points.

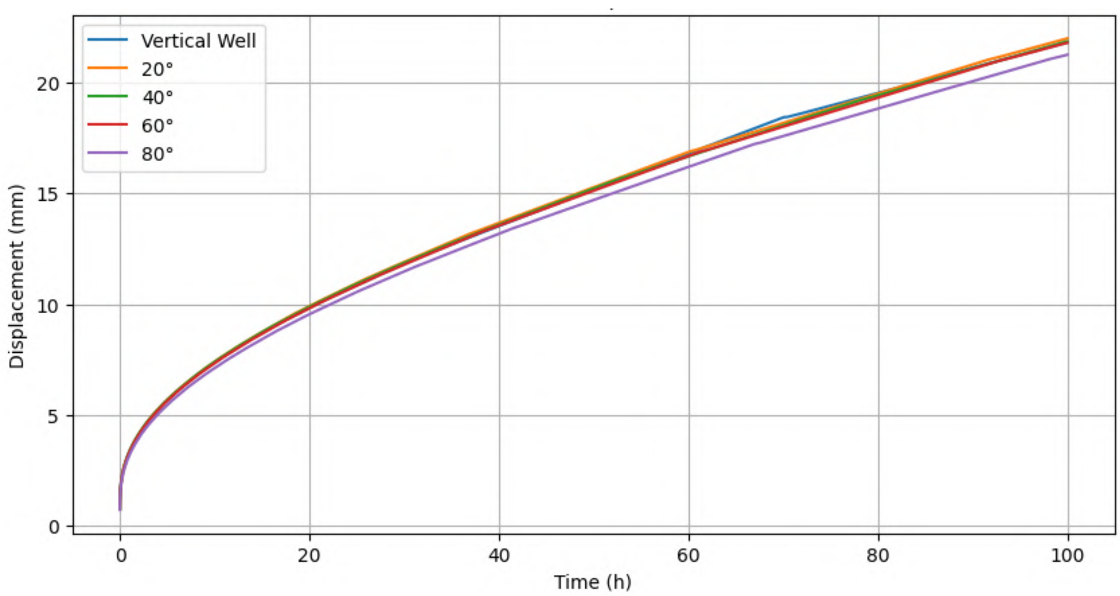


Figure 3. Obtained diametral displacement over time.

The closure in the study region provided by the axisymmetric model and the 3D vertical model showed a difference of less than 0.01%, leading to the conclusion that the 3D modeling approach is valid. The simulation results (Fig. 3) showed that well inclination impacts diametral displacements, even if minimally. It was expected that the greater the well inclination, the greater the displacement would be. However, the data obtained were slightly different from what was expected, resulting in a non-linear correlation. The greatest discrepancy was observed in the well with an 80-degree inclination, where the absolute diametral contraction was 2.61% less than that of the vertical model. This variation, though measurable, is relatively insignificant in terms of practical decisions.

Another relevant point about the modeling and simulations is the significant processing power required to execute them, especially in terms of memory. Using medium-performance personal computers was not sufficient for running the simulations. It was necessary to use high-performance machines dedicated exclusively to these types of tasks, including a machine equipped with an AMD Ryzen 7 5700G processor and 64 GB of RAM. Additionally, the simulation was accelerated by outputting results only for the variables and nodes of interest, reducing computational costs.

## 4 Conclusions

Based on the results obtained, it is evident that the strategy proposed in this paper is valid and efficient for the three-dimensional modeling of directional wells. However, this is a task that requires significant computational power. Thus, for future studies, it is advisable to consider even smaller sections of the well (for example, Poiate Junior [5] considered an 18-meter section) and explore the possibility of using a smaller external radius, as well as other mesh refinements. Furthermore, it can be inferred that displacement shows slight variations depending on the well inclination. For smaller inclinations, the displacement is slightly greater than in vertical wells. As the well inclination increases, the displacement shows lower values compared to the vertical well.

Moreover, the observed non-linear relationship between well inclination and diametral displacement should be further explored. Initially, experimenting with different mesh refinements would be beneficial. Future studies should aim to delve deeper into these phenomena, considering the impact of varying material properties across different salt formations. Studies on lateral earth pressure values different from 1 should yield interesting results, as it is known that salt mobility, especially in domes formations, can alter geostatic stress distribution.

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