Comparative Analysis of Wellbore Closure in Salt Rock Formations Considering Primary Creep

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Abstract. This study presents a comparative analysis of vertical wells wellbore closure behaviour considering constitutive models with and without the incorporation of primary creep in salt rocks. In the context of drilling wells in the pre-salt region, one aspect that can jeopardise the operation is the phenomenon of creep, as time-dependent deformations accumulate and can lead to irreversible drilling column entrapment due to wellbore wall closure. Because of the complexity of drilling in salt formations, vertical trajectories are usually adopted in this region. During the design stage, well closure simulations are necessary to predict undesirable scenarios and thus assist in the appropriate selection of drilling fluids and the planning of reaming operations. Therefore, it is crucial to employ constitutive models capable of adequately representing the behaviour of salt rocks in these simulations. The constitutive model traditionally adopted for Brazilian rocks is the so-called Double-Mechanism of deformation. This model describes only the secondary creep stage, which is dominant over longer periods of time. This study focuses on comparing the differences between the results of well closure simulations considering the Double-Mechanism and the EDMT model (Enhanced Double-Mechanism using a Transient Function), which incorporates primary creep into the Double-Mechanism of deformation, thus being able to better represent short-term deformations. To achieve this objective, a case study is employed with the modeling of a synthetic well, using data consistent with real pre-salt wells. Elastic and viscoelastic parameters of saline rocks are obtained from the literature. The numerical simulation is performed using the finite element method. The well closure profiles of a well section obtained over time are compared. In comparative analysis, the importance of primary creep in the well wall closure is further discussed by comparing different temperature gradients and critical time windows for restricting the passage of driling equipment.

Keywords: Creep Stages; Salt Rocks; Finite Element Method.

1 Introduction

Drilling through thick layers of salt rocks, as found in Brazil's pre-salt reserves, presents significant challenges for the planning, design, and execution of oil wells. One of the main difficulties arises from the mechanical behavior of this type of rock. The properties of salt rock, along with temperature and stress conditions in the well, are factors that influence the phenomenon of creep. This mechanical behavior can be concerning for drilling operations, as it increases the deformation of the wellbore wall, reducing the effective diameter and potentially causing the drill string to get stuck. In more critical cases, this phenomenon can lead to wellbore collapse [5] [7].

As mentioned in Poiate [7], creep can be defined as the slow and progressive deformation over a period of time, subject to a state of constant stress and temperature, characterizing a viscous behavior of the solid. The creep of salt rock can be divided into three stages: primary, or transient, creep, which occurs right after elastic deformation and exhibits initially high deformation rates that progressively decrease until the secondary phase, which presents a constant deformation rate, and finally, the tertiary phase, where an accelerated deformation rate occurs, which is associated with the rupture of the solid body.

Simulating the behavior of salt rocks is essential before well execution. Due to the complexity of this problem, such simulations are carried out using physically non-linear modeling with the Finite Element Method (FEM), employing appropriate constitutive laws [2]. The accuracy of the results requires that the constitutive models adequately characterize the viscous behavior and, therefore, be calibrated for the various types of salt rocks. In the context of wellbore closure analysis, simulations are performed considering long periods of time, and therefore, constitutive models that adequately capture only the secondary phase are commonly considered appropriate, such as the Double-Mechanism (DM) of deformation law. Considering more challenging drilling scenarios with increasingly deeper wells subjected to high temperature and high pressure, disregarding primary creep should be done with caution, as mentioned by Melo and Fontoura [5]. According to Firme et al. [3], primary creep is influenced by temperature, deviatoric stresses, impurities, and the mineralogical composition of the rock, and they propose the Enhanced Double-Mechanism using a Transient Function (EDMT) law to model the primary creep phase.

This study aims to simulate creep for a synthetic case of a vertical well, using the previously mentioned constitutive models, EDMT and DM, and using FEM. The purpose of this work is to examine the impact of considering or not considering primary creep over the simulation time, across different temperature levels and depths, which are factors that directly influence creep behavior. It is expected that this study will aid in estimating the magnitude of primary creep for the simulation of salt rocks.

2 Constitutive Models for Salt Rocks

Constitutive models describe the behavior of materials based on their properties. Two types of constitutive models are commonly applied to simulate salt rock behavior: empirical and classical rheological models. These models are constantly improved by incorporating micromechanical and macromechanical characteristics of materials into their formulation. Other models try to describe the main micromechanical behavior more thoroughly, such as the Multi-Mechanism Deformation model (MD) proposed by Munson et al. [6], however, calibrating this model for different types of rock becomes more difficult due to the large number of parameters, restricting its practical use because of the large amount of triaxial tests required for calibration. Therefore, in this work, two constitutive models will be used: the Double-Mechanism (DM), which describes the secondary creep stage, and the Enhanced Double-Mechanism using a Transient Function (EDMT), which is an improved version of the DM model, incorporating primary creep into its expressions. Both DM and EDMT were calibrated for halite, which is the most important and prevalent salt rock in Brazil's pre-salt.

2.1 Double-Mechanism Creep Law

The DM model is a simplified version of the MD model and accounts for the presence of two mechanisms that govern grain movement within the microstructure of the rock, primarily controlled by temperature and deviatoric stress (dislocation creep and steady-state cracking) [3]. This model is considered effective for capturing the secondary creep stage in the context of well geomechanics, and has been thoroughly calibrated for Brazilian salt rocks [7]. Equation 1 presents the formulation.

$$\dot{\varepsilon}_{ss} = \dot{\varepsilon}_0 \left(\frac{\sigma_{ef}}{\sigma_0}\right)^n e^{\left(\frac{Q}{RT_0} - \frac{Q}{RT}\right)}; \qquad n = \begin{cases} n_1, & \sigma_{ef} \le \sigma_0 \\ n_2, & \sigma_{ef} > \sigma_0 \end{cases} \tag{1}$$

Where σ_0, $\dot{\varepsilon}_0$, T_0 are the deviatoric stress, strain rate and temperature of reference. σ_{ef} is the effective stress, T is the temperature of the simulated well. Q is the thermal activation energy, R is the universal gas constant. The stress power n indicates the activated mechanism (n_1 for dislocation creep and n_2 for steady-state cracking). Both σ_0, $\dot{\varepsilon}_0$, T_0, n_1 and n_2 are calibrated using experimental data.

2.2 Enhanced Double-Mechanism using a Transient Function

The EDMT uses a transient function from the MD model. This allows for capturing the behavior of the primary creep stage. The main expression is provided in Eq. 2, while Eq. 3 presents the transient function F.

$$\dot{\varepsilon} = F \dot{\varepsilon}_{ss} \tag{2}$$

$$F = \begin{cases} \exp\left[\Delta\left(1-\dfrac{\zeta}{\varepsilon_t^*}\right)^2\right], & \zeta \leq \varepsilon_t^* \\ \exp\left[-\delta\left(1-\dfrac{\zeta}{\varepsilon_t^*}\right)^2\right], & \zeta > \varepsilon_t^* \end{cases} \tag{3}$$

In Eq. 2, $\dot{\varepsilon}_{ss}$ is the steady-state creep rate of the DM model. In Eq. 3, δ is a softening parameter, and Δ, ζ and ε_t^* are described in Eq. 4, 5 and 6.

$$\Delta = \alpha_h + \beta_h \cdot log\left(\frac{\sigma_d}{G}\right) \tag{4}$$

$$\varepsilon_t^* = K_0 \cdot e^{c \cdot T} \cdot \left(\frac{\sigma_d}{G}\right)^l \tag{5}$$

$$\dot{\zeta} = (F-1)\dot{\varepsilon}_{ss} \tag{6}$$

Where G is the shear modulus, Δ is the hardening equation, α_h and β_h are both fitting parameters. ε_t^* is an empirical expression obtained from creep curves. In Eq. 5 K_0 is a transient parameter, c is the theoretical constant, l is the integer power. $\dot{\zeta}$ is an internal variable of isotropic hardening subjected to an evolution law, and ζ can be obtained from Euler's forward scheme [3].

3 Study Case

3.1 Computational Simulation and Studied Scenario

An in-house simulator developed at the Laboratory of Scientific Computing and Visualization (LCCV/UFAL) is used, according to the formulation presented in Araújo [1] and Gonçalves [4]. This simulator implements the finite element method, eight-node axysimmetric quadratic element are considered with reduced integration. The domain of the problem is the evaporite rock phase, and the simulation time is the period it is supposed to be exposed until the cementation operation is finalized and the cement is rigid. Both creep laws are implemented on the simulator, being possible to model the problem considering the exact same conditions, changing only the creep law considered. Python routines are used to automatically generate the input models description, run the models and compare the obtained results, facilitating the process, and assuring its consistency.

The vertical well analyzed is a synthetic model, its stress, temperature, and geometry data are consistent with the data from wells drilled in the Brazilian pre-salt region. The modeled phase goes through 1020 m of halite rock layer, from the vertical depth of -3630.00 m to -4650.00 m. The drilled diameter is 12.25 inches, and the water depth considered is 643.00 m. Halita's Young's Modulus was 25.37 GPa, and Poisson's ratio 0.36, the viscous parameters are detailed in Tab. 1, as provided by Firme et al.[3].

Table 1. Halite Rock DM and EDMT Parameters

DM model			EDMT model		
Thermal activation energy	$Q\ (J/mol)$	50160	Transient parameter	K_0	$7.750 \cdot 10^4$
Universal gas constant	$R\ (J/mol \cdot K)$	8.314	Theoretical constant	$c\,(K^{-1})$	$9.198 \cdot 10^{-3}$
Threshold creep stress	$\dot{\varepsilon}_0\ (h^{-1})$	$1.888 \cdot 10^{-6}$	Theoretical power	l	3.0
Threshold deviatoric stress	$\sigma_0\ (MPa)$	9.91	Fitting parameter	α_h	-17.37
Threshold temperature	$T_0\ (K)$	359.15	Fitting parameter	β_h	-7.738
Dislocation creep power	n_1	3.36	Softening parameter	δ	0.58
Steaty-state cracking power	n_2	7.55			

Three different values were considered for the temperature at the top of the phase: 100°C, 110°C, and 120°C, the thermal gradient assumed was of 15°C/km. Subsequently, the obtained results were compared at an average depth of 4140.00 m and a maximum depth of 4650 m. The simulation times observed were 5h, 20h, 100h, and 280h. It was considered a fluid weight of 12.2 lb/gal (leading to a pressure of 51.7 MPa at the top of the phase) and the geostatic stress ate the top of the phase was 74.1 MPa (equivalent stress equal to 17.2 lb/gal).

3.2 Results and Discussions

The Fig. 1 presents the wellbore closure profiles of the analyzed synthetic well and the comparison of radial displacements obtained at a depth of 4650 m (Base of the well). The simulation results using the DM and EDMT models are presented for the different temperature gradients analyzed.

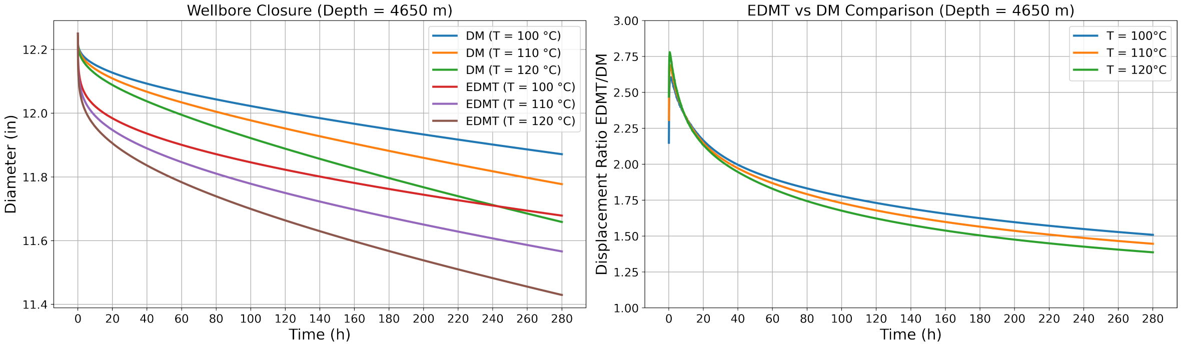

Figure 1. Graph of the wellbore closure and displacement ratios of the studied models, respectively.

It is evident that as the simulation time increases, the radial diameter of the well tends to decrease from 12.25 in to a minimum value of 11.40 in with the EDMT model at a temperature of 120°C. This occurs because the closure increases with the EDMT models, as it adds a transient function to the DM model, inducing large displacements at short periods of time. Additionally, it was observed that the increase in temperature is a significant influencing factor, as it considerably reduces the wellbore diameter.

Analyzing the first 10 hours of simulation, it was observed that the EDMT models produce radial displacements 2.5 times greater than those obtained with the DM model, with this ratio decreasing but remaining above 1.0 as the simulation time increases. It is important to note that, for a better characterization of an asymptotic value, simulation times longer than those used here would be necessary. This pattern is repeated for higher temperature values, where the maximum displacement with EDMT relative to DM reaches 2.75 times and similarly decreases over time. Given these results, the significant importance of considering primary creep in the initial hours of simulations is emphasized, demanding attention when using DM model to simulate wellbore closure in short periods of time. The Tab. 2 and 3 present the radial displacements for simulation times of 5 hours, 20 hours, 100 hours, and 280 hours at depths of 4140 m and 4650 m, respectively, along with the indication of the relative error between DM and EDMT.

Table 2. Radial displacements and relative error of DM and EDMT for different simulation times at 4140 m

	Radial Displacement (in) at 4140 m											
Temperature (°C)	Time (5 h)			Time (20 h)			Time (100 h)			Time (280 h)		
	DM	EDMT	ϵ (%)	DM	EDMT	ϵ (%)	DM	EDMT	ϵ (%)	DM	EDMT	ϵ (%)
100	0.0264	0.0646	59,13	0.0386	0.0847	54.43	0.0665	0.1217	45.36	0.1049	0.164	36.04
110	0.0293	0.0724	59.53	0.0437	0.0957	54.34	0.0786	0.1403	43.98	0.1293	0.1935	33.18
120	0.0325	0.0812	59.98	0.0495	0.1079	54.12	0.0935	0.1618	42.21	0.1601	0.2289	30.06

It can be observed that the absolute radial displacements are larger at greater depths and higher temperature levels. The relative errors indicate that simulations of salt rock behavior during the first few hours, using a model that omits primary creep, result in errors of significant magnitude. Consequently, during the initial 5 hours, the radial displacements calculated with the DM model show a reduction of nearly 60% compared to the EDMT model results. This outcome highlights the magnitude of the error when simulating wellbore closure without accounting for primary creep. This error decreases to around 30% after 280 hours.

Table 3. Radial displacements and relative error of DM and EDMT for different simulation times at 4650 m

	Radial Displacement (in) at 4650 m											
Temperature (°C)	Time (5 h)			Time (20 h)			Time (100 h)			Time (280 h)		
	DM	EDMT	ϵ (%)	DM	EDMT	ϵ (%)	DM	EDMT	ϵ (%)	DM	EDMT	ϵ (%)
100	0.0371	0.0909	59.19	0.0563	0.1216	53.7	0.1024	0.1818	43.67	0.1681	0.2528	33.5
110	0.0415	0.1022	59.39	0.0643	0.1381	53.44	0.1222	0.2109	42.06	0.2086	0.3001	30.49
120	0.0463	0.115	59.74	0.0734	0.1565	53.1	0.1467	0.2447	40.05	0.2594	0.3571	27.36

4 Conclusion

Thus, based on the results found and the analyses conducted, it can be verified that primary creep in vertical wells in salt rock formations cannot be disregarded, as the difference between the radial displacement values of the Enhanced Double-Mechanism using a Transient Function is greater compared to the Double Standard Mechanism model. This highlights the wellbore closure that can lead to various issues during its execution, such as material wastage, longer execution time, and new budgets for replacing lost equipment. This scenario can be exacerbated, particularly in deep pre-salt wells, as increased depth and temperature intensify the primary creep process. Additionally, more mobile rocks such as carnallite and tachyhydrite are commonly found in Brazilian pre-salt fields. It is important to also calibrate and study the primary creep for these rocks.

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