Drilling Geomechanics Salt Creep Monitoring: How to Optimize Mud Weight in Real Time and Get a Safe Time Window While Drilling, Tripping, Running and Cementing Casing in Salt Formations*

Joao Paulo Castagnoli[1], Cyrille Montesinos[2], and Diego Muñoz[2]

Search and Discovery Article #41954 (2016)**
Posted December 5, 2016

*Adapted from extended abstract prepared in conjunction with oral presentation given at AAPG 2016 International Conference and Exhibition, Cancun, Mexico, September 6-9, 2016. AAPG © 2016

[1] Schlumberger, Ciudad del Carmen, Mexico (jcastagnoli@slb.com)
[2] Schlumberger, Ciudad del Carmen, Mexico

Abstract

Drilling in, and through salt was for a long period avoided due to the challenges that was present when drilling these formations. However, large oil and gas reservoirs are associated with salt structures. In the Gulf of Mexico (GoM) some important oil and gas reservoirs are located below salt bodies. To reach the hydrocarbons section is necessary to drill thick layers of salt with different characteristics. The salt can reach considerable deformation when exposed to the drilling fluid. This deformation is function of the magnitude of in-situ stresses, mud density, exposure time, temperature, and the mineralogical composition. This behavior is known as salt creep.

The real time salt creep analysis can describe the wellbore diameter in function of drilling time. The higher mobility will faster to reduce the wellbore diameter. One example was a well in the Campos Basin in Brazil where the closure velocity was obtained in the order of 0.05 inches per hour in Halite. This rate of deformation depends on the conditions under which the rock is submitted. High mobility can generate non-productive times such as: back reaming, stuck pipe, well deviation, and a catastrophic lost hole.

This paper presents a new monitoring methodology that compute the wellbore diameter in function of exposure time while drilling, using an analytical model, calibrated with offset wells data. The specialist updated a geomechanical model, considering the lithology and mineralogical composition of the salt section using the LWD data and drilling parameters. Profiles of hole diameters and forecast from the actual time to the end of section are available in real time. The information allow the drilling engineers adjust the planned mud weight to reduce risks of stuck pipe and ensure a successful casing running and cementing operations.

Summary

Large economic viable oil and gas plays are associated with salt structures, however drilling through salt has been avoided in the past because of the associated great challenges. In the Gulf of Mexico (GoM), salt is primarily a massive halite deposit averaging 96% purity, with some occasional trapped sediment inclusions. The impurities are classified into three categories: anhydrite, other evaporates (sylvite, gypsum, and carnalite), and other impurities (quartz, dolomite, feldspar, and clay), Fredrich et al. (2007). All these inclusion will be affected by creep mechanism, inclusions surrounded by highly mobile salt tend to be more unstable or can contain overpressure. Salt deposits are typically non-radioactive, non-porous, low density, high velocity, electrically nonconductive, and soluble (Tixier and Alger, 1970). In the GoM some potentially important oil and gas plays are located below salt bodies. To reach the hydrocarbon section it is necessary to drill thick salt layers, up to 20,000 ft have been reported (Wilson and Fredrich, 2005). The salt can exhibit considerable deformation when drilled. This deformation is a function of the magnitude of in-situ stresses, mud density, exposure time, temperature, and the mineralogical composition. The process causing the deformation is known as salt creep.

Real time salt creep analysis calculates the hole diameter of the wellbore as a function of exposure time. A higher salt mobility will faster reduce the wellbore diameter. One example was a well in the Campos Basin in Brazil attained closure velocity in the order of 0.05 inches per hour in halite (Poiate et al., 2006). Salt creep can result in non-productive time from unplanned reaming, stuck pipe, well deviation issues, and ultimately catastrophic lost hole.

This paper presents a new monitoring methodology that computes the wellbore diameter as a function of time exposure, using two analytical models (Barker and Liu equations); the initial model is calibrated with offset wells data. Deliverables of the model are estimates of borehole diameter reductions, which are available in real time. This information allows the drilling engineers to adjust the planned mud weight and evaluate the calculated wellbore diameter to reduce risks of stuck pipe and ensure a successful casing run and cement job.

Introduction

Salt creep effect causes major problems that are typically associated with well construction in salt formations: excessive torque and pack offs, stuck pipe, casing running blockage, and poor cementing job. In addition, the salt exit may have a rubble zone characterized by mud losses and wellbore instability.

Both salt creeping and salt exit related challenges are controlled by mud weight and mud properties. Common industry practice is that drillers utilize pre-established tables with recommended mud weights to drill salt sections. In case salt creeping is underestimated on actual well conditions, results can end up in non-productive time and expensive additional rig time to correct for the inadequate salt creep estimation.

The drilling Geomechanics salt creep modeling presented in this paper integrates time and depth variables into one single platform. The workflow delivers a time forecast which is updated on regular depth intervals and provides wellbore diameter profiles in real time, including a look ahead for any stage of well construction process until the hole is cased and cemented. Two different theoretical salt creep models are discussed in this paper; the Barker (1994) model and the Von Mises elasto-viscoplastic model (Liu et al., 2011). The salt creep model is updated taking into account the lithology, updated overburden, actual mud weight, mineralogical composition of the salt section, and the temperature gradient using LWD logging. The workflow compares both creep modeling results with the drilling and tripping parameters, allowing the model to be recalibrated if needed.

The objective of this work is to show a methodology to estimate a wellbore diameter profiles in salt rocks, on time scale, together with mud weight schedule recommendations, to the driller and stakeholders, on regular basis while drilling and tripping, as part of the Drilling Geomechanics Salt Creep Monitoring deliverable.

Salt Creep Modeling

Salt rocks, also called evaporites, exhibit a creeping behavior due to the crystalline structure of the salt; the creep is defined as time-dependent permanent deformation when subjected to any level of shear stress. Several constitutive models are described in the literature to simulate the time-dependent deformation under a constant deviatoric stress (Maia et al., 2005). This creep behavior is influenced by the salt layer thickness, formation temperature, mineralogical composition, water content, presence of impurities, and the extent to which differential stresses are applied to the salt body. For mud weight determination and casing design, Mackay et al. (2008) and Maia et al. (2005) respectively simulated borehole creep using a finite element model that modeled the process while the borehole was excavated in stages. Mackay et al. (2008) used a power-law creep model that included a time hardening component. The simulations revealed that during salt movement, the radial and tangential stresses near the borehole decreased with time; however, the tangential stress far away from the borehole wall (at the radial distance of 10 to 20 borehole radii) increased with time (Liu et al., 2011).

By presupposing that the stress distribution around the wellbore is elastic, Barker et al. (1994) developed an analytical equation to allow engineering calculation at different stress, temperature, and closure-rate combinations. This equation is based on steady-state creep of salt formations and can be applied at any stress and temperature combination. This analytical equation express the radius of the well as a function of time:

$$\mathrm{R} = R_0 exp\left(-\frac{\left(\sqrt{3}\right)^{(n+1)}}{4n-2} A e^{-\frac{B}{T}} (p_0 - p_w)^n \Delta t\right) \tag{1}$$

where A is the salt constant, B is the temperature exponent of salt, T is the formation temperature, n is the stress exponent of salt, p_0 is the horizontal in-situ stress, p_w is the wellbore pressure, R is the radius after creep, R_0 is the original wellbore radius and Δt is the creep time or exposure time. This solution has been widely used when designing mud weights, cement, and casing to control salt creep (Liu et al., 2011). However, using finite element simulations, Wilson et al. (2003) determined that Barker's solution overestimates the rate of borehole closure. Field experience has also suggested that Barker's solution produces pessimistic wellbore closure forecasts. Liu et al. (2011) applied the Perzyna's viscoplastic theory (Perzyna, 1966) to derive a new analytical solution for borehole stresses and creep rates consistent with the Norton power-law model. The total strain rate is the sum of elastic and viscoplastic strain rate. The elastic strain rate is given by the Hooke’s law, and the viscoplastic creep strain rate can be calculated as a function of the fluidity parameter (γ), viscoplastic potential function (Q), and failure yield function (F). The viscoplastic strain model is shown in equation 2:

$$\dot{\varepsilon}_{ij}^{c} = \gamma \langle \Phi(F) \rangle \frac{\partial Q}{\partial \sigma_{ij}} \tag{2}$$

Considering the associated viscoplastic flow rule (*Q*=*F*) used for salt material, the Von Mises elastic viscoplastic model assumes the failure yield function and the viscoplastic potential are a function of the equivalent stress ($\bar{\sigma}$) and yield strength of material (σ_s):

$$F = Q = \bar{\sigma} - \sigma_s \qquad (3)$$

To consider the effect of temperature on salt creep behavior, Liu el al. (2011) assume by correlation with Barker's methodology that the fluidity parameter γ is given by

$$\gamma = Ae^{-\frac{B}{T}} \qquad (4)$$

After some steps, which are described in Liu et al. (2011), the new equation to determine the radius borehole closure for Von Mises elasto-viscoplastic model (denominated in this work as Liu`s equation) as a function of time is given by:

$$\mathrm{R} = R_0 exp\left(-\frac{(\sqrt{3})^{(n+1)}}{2n^n} Ae^{-\frac{B}{T}} (p_0 - p_w)^n \Delta t\right) \qquad (5)$$

The parameters are the same as in equation 1 (Barker's equation). The first step to simulate the salt creep is to build the creep model and determine the input parameters using a predrill model from offset well or laboratory data associated with finite element analysis, as described in Maia et al. (2016). The real-time workflow allows a comparison between the expected creep and real data to evaluate the real closure rate and define the appropriate model plus the parameters to fit the real behavior of the salt.

Real Time Creep Modeling Workflow

The most relevant variables that define salt creeping are related to deviatoric stresses, temperature, mineralogical composition, and time exposure. During real-time monitoring, it is important to have control over these variables to provide accurate input for creep calculation. Overburden is updated with a measured or synthetic density log derived from offset wells based on the sonic log, formation temperature is estimated with geothermal gradient from offset wells (preferably those with salt sections that have a temperature measurement with WL tools), mineralogical composition is inferred from LWD logging tools and surface sample description, and time is clocked from the time of drilling each meter and estimating the time until casing is run and cemented.

In the GoM, some of the salt impurities can be related to sediment inclusions with higher density compared to pure salt. Velocity increases slightly with depth, and the density of rock salt does not show a clear relationship with velocity, it is not possible to apply direct correlations such as Gardner to define salt density. To have a better estimate of density in salt sediments, it is necessary to review well logs in correlation wells and then define the best density estimate for salt bodies. Zong et al. (2015) gave an empirical relationship for velocity versus depth in the GoM from the log data analysis. The best way to obtain the density log data is to use the appropriate LWD or WL tools.

Salt formation are usually assumed to have in-situ stresses equal in all directions and those stresses are equal to overburden (isotropic stress state considered). When salt sections are drilled with mud weight equivalent less than salt stresses, the salt will creep. In this work, the input data were obtained from Barker et al. (1994).

This workflow requires building a time-of-exposure log for every meter drilled in salt, from the beginning of the drilling operation to the estimated casing time that is set during planning. If a reaming operation is applied, the time count is restarted at the specific depth interval (Figure 1a). The drilling time calculation is related to the estimated rate of penetration (ROP) based on correlation wells with similar conditions and updated with the real data. Figure 1a shows the expected exposure time of each meter drilled in salt on the two well sections indicated in Figure 1b. The time relation is one input for salt creep estimation (Figure 1c). Figure 1c shows the radial closure estimation as a function of time correction exposure, meaning that the behavior of salt creep will be modeled as a function of real drilling progress. The prognosis will be estimated using the updated model, and new drilling time estimations (as a function of real ROP and drilling operations).

Considering the Barker equation and a homogenous with 100% of halite, the Figure 1a shows exposure time for two sections drilled in salt. On the vertical axis drilled depth is shown, while the horizontal axis displays the number of hours that elapsed from drilling to setting casing. The green line shows exposure time for the first section drilled into salt. Because uncertainty in salt creeping velocity, one trip was done to ream drilled interval. After reaming that interval, initial borehole diameter is considered to be same as bit size and exposure time computation is restarted (blue line). The orange line shows exposure time for another section drilled in salt after previous casing was set. This graph provides estimated time of exposure for salt sections which is an input parameter to calculate salt creep. Figure 1c shows the change in borehole radius at given time for four different depths. The dark blue line represents borehole radius closure at 3344 m TVD, the model shows that borehole closure is the lowest compared to other intervals (This is caused by lower overburden and lower temperature at shallower depth). The light blue line shows that borehole radius closure at 3904 m TVD happens at higher rates compared to shallower intervals.

Before and during the salt drilling interval, a borehole diameter is estimated based on the real and planned mud weight. Figure 2 shows six depths of the salt interval, for both creep methodologies described in this paper, considering the same input parameters. Borehole diameter is calculated as a function of expected exposure time in a 100% halite interval. As shown in Liu et al. (2011), the Barker equation has more salt movement than is seen in the Von Mises elasto-viscoplastic model with the same input data.

Although less common, it is also possible to drill some salt types other than halite in the GoM. In this case, the same simulations under same conditions discussed above are calculated assuming carnalite inclusions are present. In Figure 3, it is evident that carnalite creep behavior using both methodologies is much more aggressive compared to halite. This would be the worst-case scenario for drilling operations, but the effect will depend on the depth at which carnalite inclusions are found and the mud weight being used. The need for this information is the driver for real-time salt creeping monitoring in which all inputs can be updated to account for real drilling conditions. Depending on the salt creep estimation in the worst scenario, some actions can be applied, such as increasing mud weight to decrease the deviatoric stress and monitoring the time of exposure. Having the real-time information enables the drilling operator to have a better knowledge of salt creeping effects under different scenarios and to account for a worst-case scenario.

Figure 4 shows the creep velocity profile expected in all salt sections. The creep velocity is independent of time exposure and can be interpreted as a salt property that is a function of the depth. Both creep models assume that the creep velocity is constant with time. Figure 4 allows us to confirm the effect of deviatory stresses and temperature since it is calculated with the same mud weight. As the drilling depth increases, the deviatory stress rises as a function of overburden and the temperature increases as a function of geothermal gradient. The graph shows that creep velocity is higher for intervals which are deeper (caused by higher overburden, higher temperature). The creep velocity is different when comparing the Barker and Liu equations. The Barker equation shows higher salt creep velocity than the Von Mises approach.

Discussion

Drilling parameters monitoring is part of the workflow to calibrate the creep model. A high closure velocity of a hole can cause sticking around a bit or stabilizers, increasing the friction and making it difficult to transfer weight to the bit. As a consequence of salt movement, torsional vibration can be produced and torque off bottom can increase, causing to decrease the rate of penetration (ROP). Stuck pipe events can also be frequent. The torque behavior together with the presence of stick-slip, shocks, and vibrations can be used as salt creep indicators during drilling operations. In case high mud weight are required to maintain a stable wellbore, the risk of stuck pipe due to differential sticking in interbedded permeable zones such as sands needs to be considered.

There is always a potential for losses when drilling through massive salt bodies, especially when using high mud weight to control the creep. In general, the losses can be in fractures/salt weld or permeable inclusions in the salt. In a salt formation, open fractures can be associated with a section of low creep velocity. A salt creep model can identify zones with high risk of losses when offset well information is available. The correlation between mud loss events, salt creep model, and seismic/geologic interpretation could help identifying the mechanism of losses.

Salt creep monitoring can be applied in massive salt or in a thin salt layer. A thin layer of salt may prove to be more problematic than a massive salt body for drilling operations, because, a thin layer might indicate that the salt is highly mobile.

Temperature is a crucial variables in the accuracy of the creep model. The temperature profile will depend on the shape of the salt body and the regional heat flow. A salt sheet will have a different profile from one with a bulbous or canopy shape. The profile will also depend on where the well will penetrate the salt. The temperature profile is commonly estimated through the propagation of the thermal gradient from offset wells. The uncertainty of this methodology is proportional to the number of offset wells and the geological correlation. The salt has higher thermal conductivity than shales and sandstones; this thermal property can generate a cooling effect at the base of the salt and a heating effect at the top, influencing the thermal gradient of the adjacent formations. The second methodology to determine the temperature profile is a numerical scheme. If there are no measurements available in the area, and the shape of the salt is known, a numerical scheme is probably the best way to model the temperature distribution in and around the salt, considering a steady-state regime.

When information about salt properties and offset well data is limited, some events related to salt creep can occur. If necessary, the model can be recalibrated with this events and a new prognosis is provided to the drillers considering actual ROP. The updated temperature, overburden, mineralogy interpretation, and salt creep parameters are checked for consistency and the model is updated. Updated model can help to explain drilling events and help discriminating mechanical events from actual salt creeping events.

Conclusions

In this work, a methodology to monitor the salt creep in exploratory and development wells in real time is presented.

Drilling a salt section has a lot of uncertainty regarding the pore pressure contained in the inclusions, presents risks of mud losses, rubble zones, and tight hole. A real-time geomechanics creep model provides tools that can be a significant help to drillers in properly defining mud weights to be used and, consequently, reducing the risk of costly events such as stuck pipe.

The workflow presented starts from predrill stage, with a theoretical approach of the input data. Continues into the planning phase to help drilling engineers in proper mud weight selection in order to minimize salt creep and other associated risks in salt. While drilling, the model is updated with real time data including the generation of look ahead wellbore diameter profiles. When caliper logs are available, a comparison between predicted wellbore diameter and measured diameter is delivered.

Different models to simulate the salt movement exist, and the magnitude of the velocity of strain could be overestimated without a real caliper acquisition and an accurate model update. Post mortem analysis is used as input data for future analysis and model calibration.

References Cited

Barker, J.W., K.W. Feland, and Y.H. Tsao, 1994, Drilling Long Salt Sections along the US Gulf Coast: SPE Drilling and Completion, v. 9/3, p. 185-188.

Fredrich, J.T., A.F. Fossum, and R.J. Hickman, 2007, Mineralogy of Deepwater Gulf of Mexico Salt Formations and Implications for Constitutive Behavior: Journal of Petroleum Science and Engineering, v. 57, p. 354-374.

Liu, X., R. Birchwood, and P.J. Hooyman, 2011, A New Analytical Solution for Wellbore Creep in Soft Sediments and Salt: Presented at the 45th US Rock Mechanics/Geomechanics Symposium, ARMA 11-383.

Maia, A., E. Poiate Jr, J.L. Falcao, and L.F.M. Coelho, 2005. Triaxial Creep Tests in Salt Applied in Drilling Through Thick Salt Layers in Campos Basin Brazil: SPE-92629-MS, 9 p.

Mackay, F., N. Inoue, S.A.B. Fontoura, and F. Botelho, 2008, Geomechanical Effects of a 3D Vertical Salt Well Drilling by FEA: ARMA 08-041.

Perzyna, P., 1966, Fundamental Problems in Viscoplasticity: Advances in Applied Mechanics, v. 9, p. 243-377.

Poiate, E. Jr., A. Maia, and J.L. Falcao, 2006, Well Design for Drilling Through Thick Evaporite Layers in Santos Basin – Brazil: SPE-99161-MS.

Tixier, M., and R. Alger, 1970, Log Evaluation of Nonmetallic Mineral Deposits: Geophysics, v. 35, p. 124-142.

Willson, S.M., A.F. Fossum, and J.T. Fredrich, 2003, Assessment of Salt Loading on Well Casings: SPE Drilling and Completion, v. 18/1, p. 13-21.

Willson, S.M., and J.T. Fredrich, 2005, Geomechanics Considerations for Trough- and Near-Salt Well Design: SPE 95621, 17 p.

Zong, J., R.R. Stewart, N. Dyaur, and M.T Myers, 2015, Elastic Properties of Rock Salt: Lab Measurements and Well Log Analysis in the Gulf of Mexico: SEG Technical Program Expanded Abstracts 2015, p. 3095-3099.

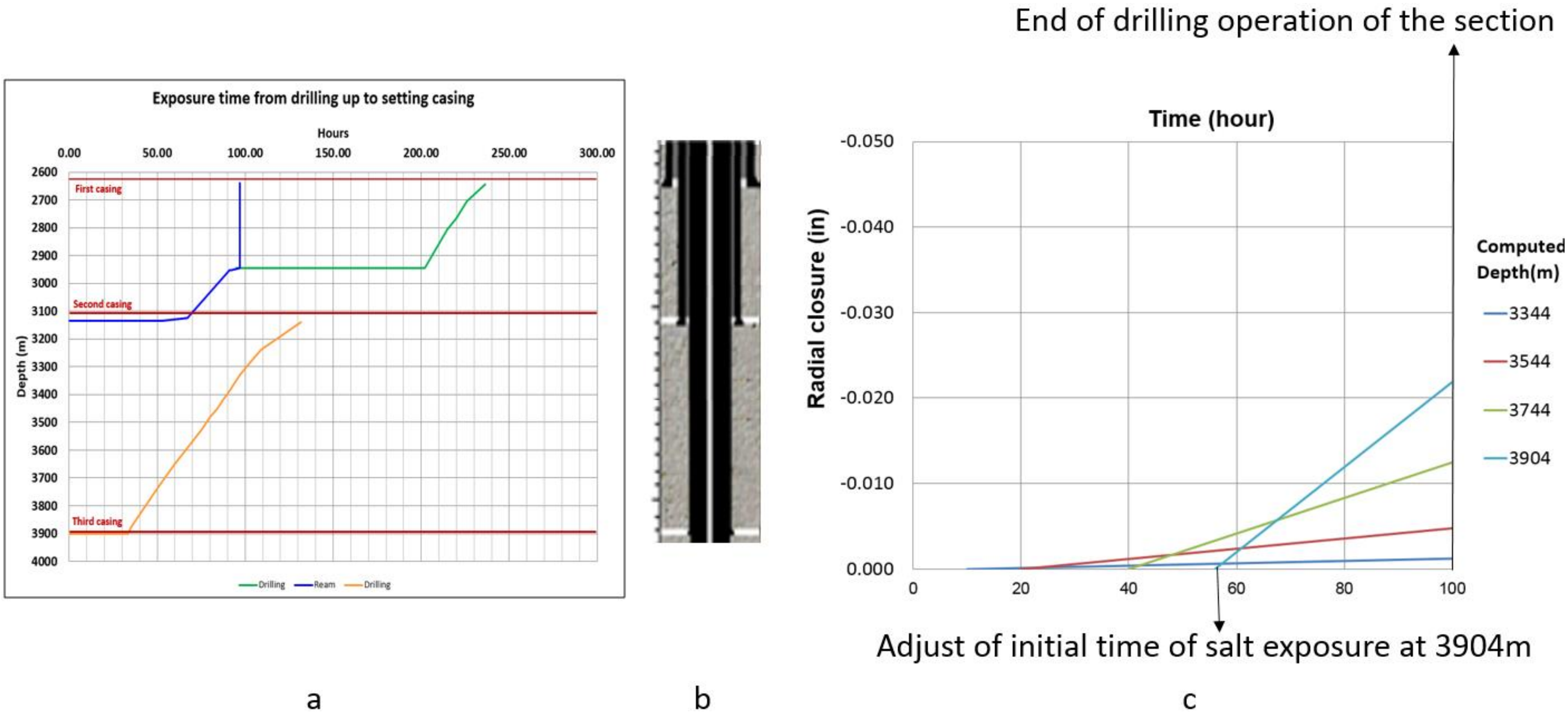


Figure 1. Time-of-exposure log for every meter drilled where salt is present and radial closure model.

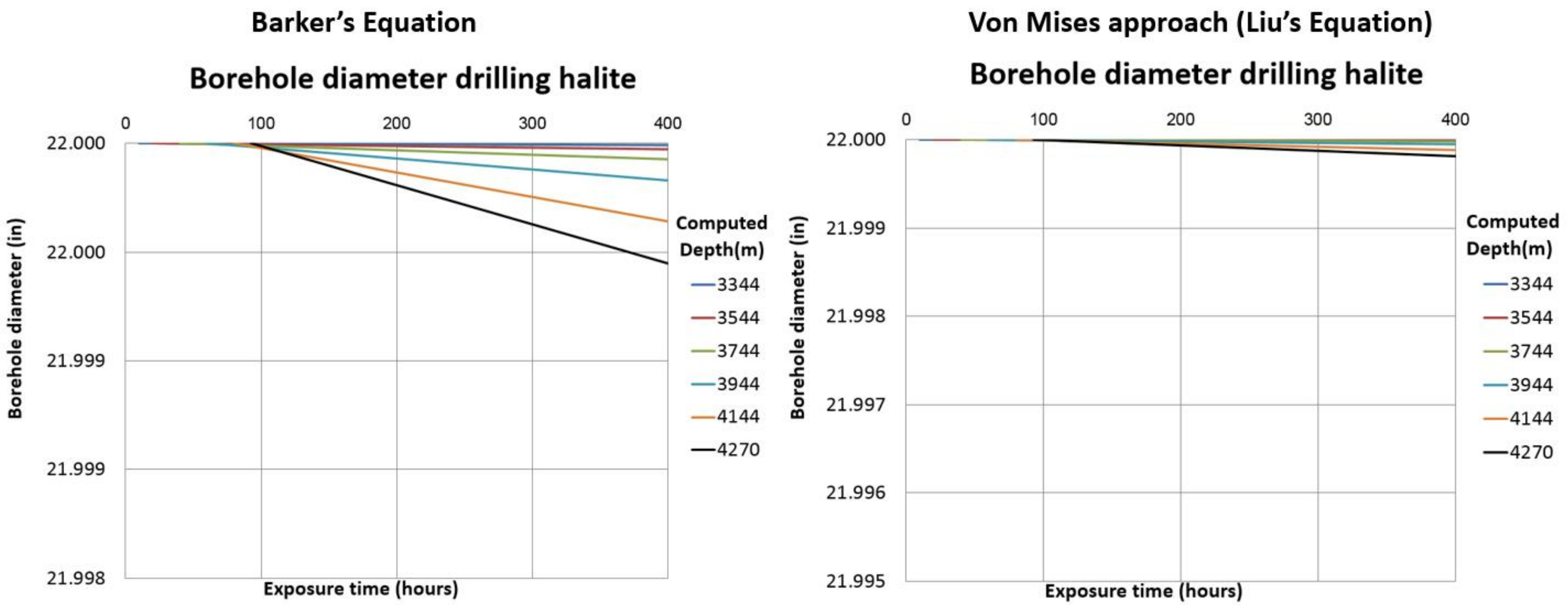


Figure 2. Borehole diameter curve with Barker and Von Mises elasto-viscoplastic models considering the same input and 100% halite, *n* = 4.5.

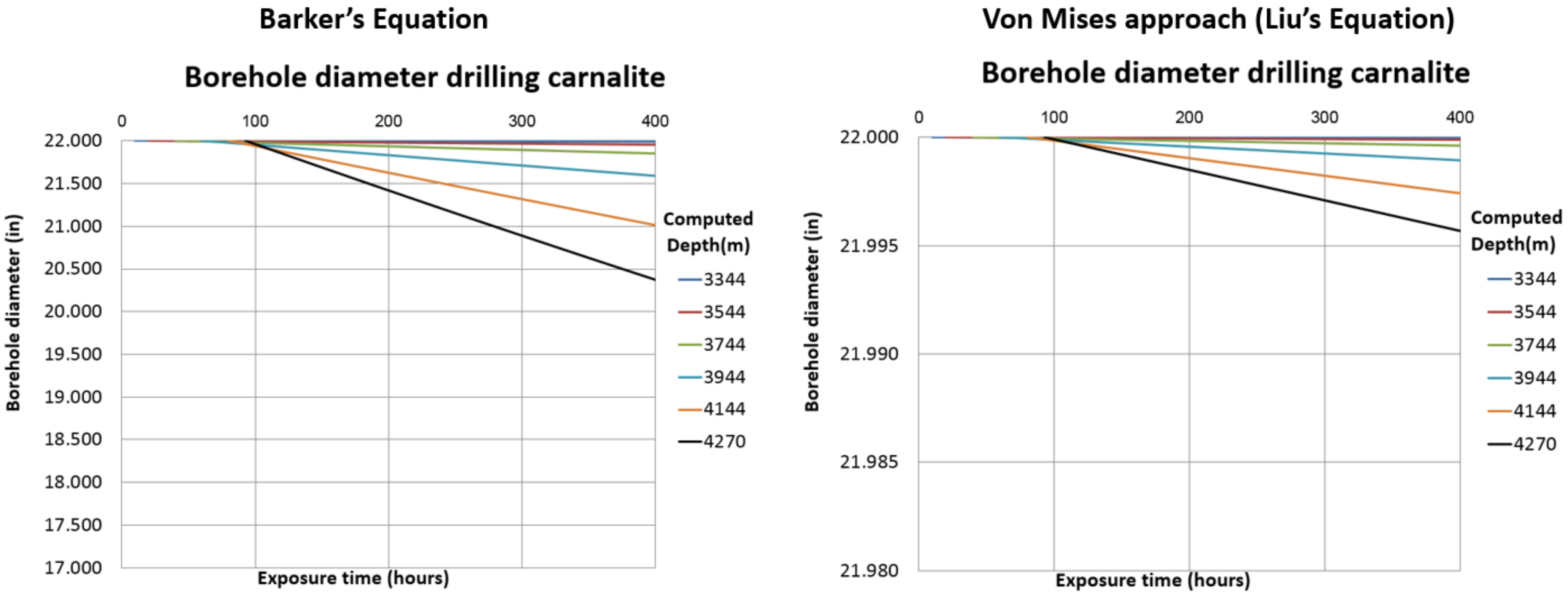
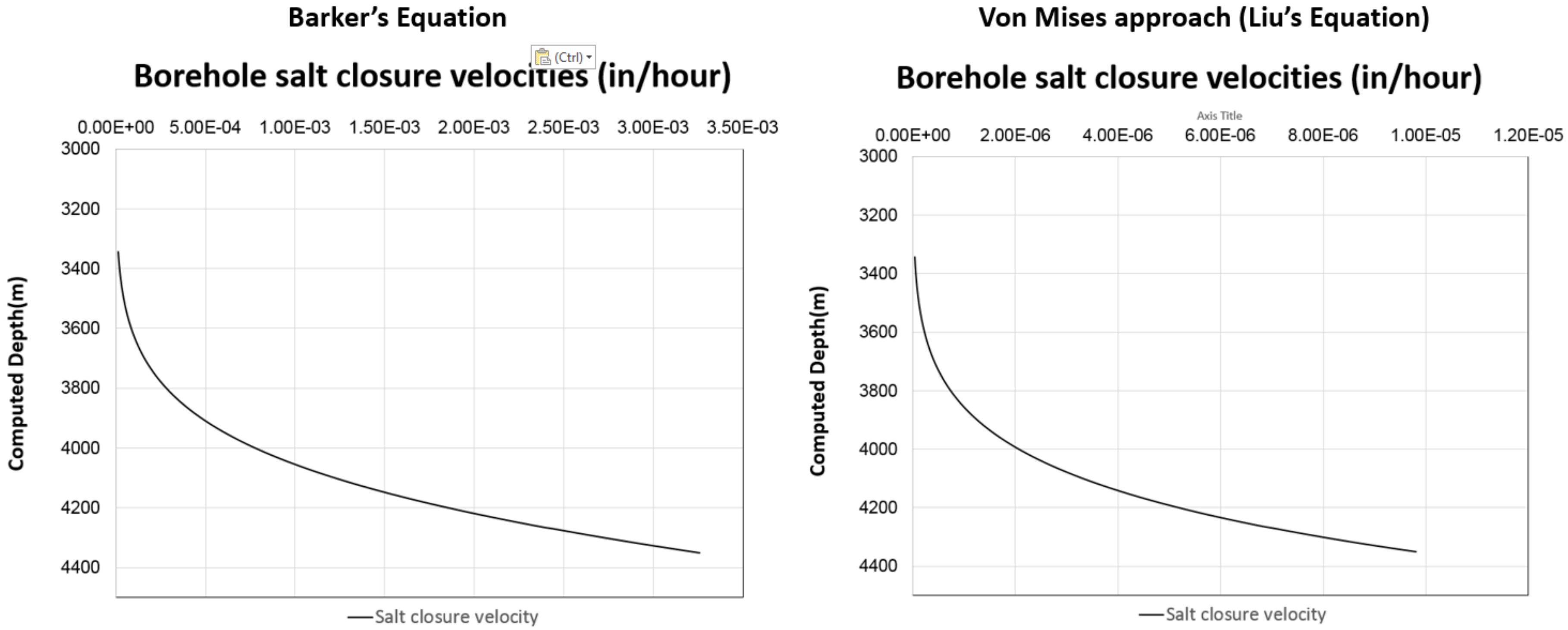


Figure 3. Borehole diameter curve with Barker and Von Mises elasto-viscoplastic models considering the same input and 100% carnalite, $n = 5.05$.



Barker’s Equation

Von Mises approach (Liu’s Equation)

Figure 4. Borehole salt closure velocities with different salt creep models considering the same well condition.