

Modeling and Analysis of Salt Creep Deformations in Drilling Applications

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Abstract: Drilling through salt has created increasing challenges for the oil and gas industry. In many cases, deepwater exploration around the world requires drilling through salt layers above oil and/or gas reservoirs. Borehole closure and instability due to salt creep are two major concerns in designing completions for production wells drilled through salt layers. Similar issues also occur where gas storage caverns are built in salt formations. Pressure changes that occur in the salt cavern during operation can cause cavern closure and instability. As such, predicting salt creep deformations is essential for designing completions for wells drilled through salt and for storage caverns built in salt formations. This paper presents a literature review of material models describing the behavior of salt creep. Using an established material creep model, a finite element analysis (FEA) methodology using Abaqus is then presented for analyzing salt creep deformations. Application examples are included to demonstrate the use of this methodology.

Keywords: Casing, Cavern Storage, Collapse, Constitutive Models, Drilling and Completions, FEA, Geomechanics, Salt Creep, Stability.

1. Introduction

Drilling through salt formations has created increasing challenges for the oil and gas industry. In many cases, High Pressure and High Temperature (HPHT) deepwater exploration around the world requires drilling through salt layers above oil and/or gas reservoirs. Borehole closure and instability due to salt creep are two major concerns in drilling and completions of production wells that penetrate salt layers. Salt creep deformations can also introduce several loading mechanisms on well casing, such as external pressure, potentially causing casing collapse, and tensile and shear loading, potentially leading to casing failure in tensile rupture. Several researchers have performed experimental and numerical simulations of salt creep and its impact on casing designs. Poiate et al (2006) showed that Petrobras performed numerical simulations leading to a two-stage drilling strategy for drilling through thick salt sections in the Santos basin off Brazil. Lao et al (2012) modeled and analyzed salt creep and casing damage in HPHT environments. Fossum and Fredrich (2002) studied salt mechanics primer for near-salt and sub-salt in deepwater Gulf of Mexico field development.

Another example of drilling through salt is for gas storage caverns built in salt formations. Pressure changes that occur in the salt cavern during operation can cause cavern closure and instability. In addition, storage pressure can induce microcracks and fracturing, resulting in gas migration through the salt into surrounding formations. The structural stability of a solution-mined salt cavern is often one of the principle concerns related to the long-term operation and risks associated with cavern storage. Geological and rock mechanical assessments typically form major

parts of any study investigating the design and development of a solution-mined salt cavern for gas storage. Hilbert and Saraf (2008) studied the salt mechanics and casing deformation in solution-mined gas storage cavern operations. The axial stress and strain distributions along the well casing during cavern operation were obtained, and the critical location with maximum stress and strain in casing was identified from Hilbert and Saraf (2008)'s study.

Predicting salt creep deformations is essential for designing completions for wells drilled through salt layers, and for storage caverns built in salt formations. This paper presents a literature review of material models describing the behavior of salt creep. Using an established material creep model, a finite element analysis (FEA) methodology using Abaqus is then presented for analyzing salt creep deformations. Two application examples, with casing collapse analysis under salt creep loading and salt cavern stability analysis, are included to demonstrate the use of this methodology.

2. Salt mechanical creep model

One of the frequently used salt creep constitutive models is the Multi-mechanism Deformation (M-D) creep model developed by Munson and Dawson (1982, 1984) for undamaged salt. The model was based on three dominant mechanisms defined through a deformation mechanism map (Munson, 1979), and used the techniques and data from conventional creep tests to obtain values for the various parameters in the model (Munson, 1989). Chan et al. (1996) advanced the work of Munson and Dawson to develop the Multi-mechanism Deformation Coupled Fracture (MDCF) model by taking into account the effects of fracture-induced damage, fracture growth and healing within the salt.

The work on solution-mined gas storage by Hilbert and Saraf (2008) was performed using the original M-D creep models, while the HPHT well salt creep analysis by Lao et al (2012) was based on a viscoplastic model considering the effect of creep, volumetric dilation and material failure following the Drucker-Prager criterion. Although the coupled salt creep and fracture model can provide the most rigorous representation of the salt behaviour, implementing such a model typically requires a significant effort in order to apply the complex constitutive equations in a non-linear finite element analysis program. Furthermore, according to Fossum and Fredrich (2002), the coupled creep and fracture model may not be necessary in the structural analysis for the conditions expected in deepwater/deep salt formations with very high mean stresses since fracturing is generally suppressed under such conditions. Due to these considerations, the M-D creep model developed by Munson and Dawson is presented and used in this paper.

Following Munson (1999), the M-D constitutive model was based on the creep strain rate defined by three mechanisms: (1) a dislocation climb controlled creep mechanism at high temperature and low stresses, (2) an empirically specified but undefined mechanism at low temperature and low stress, and (3) a dislocation slip controlled mechanism at high stress. The respective steady state creep rates for these three individual mechanisms are given by:

$$\dot{\varepsilon}_{s_1} = A_1 \exp\left(\frac{-Q_1}{RT}\right) \times \left(\frac{\sigma_{eff}}{\mu}\right)^{n_1} \quad (1)$$

$$\dot{\varepsilon}_{S_2} = A_2 \exp\left(\frac{-Q_2}{RT}\right) \times \left(\frac{\sigma_{eff}}{\mu}\right)^{n_2} \quad (2)$$

$$\dot{\varepsilon}_{S_3} = |H(\sigma_{eff} - \sigma_0)| \left\{ B_1 \exp\left(\frac{-Q_1}{RT}\right) + B_2 \exp\left(\frac{-Q_2}{RT}\right) \right\} \sinh\left[\frac{q(\sigma_{eff} - \sigma_0)}{\mu}\right] \quad (3)$$

where the coefficients A_i and B_i are constants, Q_1 and Q_2 are activation energies, T is the absolute temperature, R is the universal gas constant, μ is the shear modulus, σ_{eff} is the effective stress, n_1 and n_2 are the stress exponents, q is the stress constant, and σ_0 is the stress limit of the dislocation slip mechanism. $|H|$ is the Heaviside step function.

The generalized form of the creep strain rate (transient creep) can be derived from the steady-state creep strain rates:

$$\dot{\varepsilon}^{cr} = F \dot{\varepsilon}_s = F \sum_{i=1}^3 \dot{\varepsilon}_{si} \quad (4)$$

where $\dot{\varepsilon}_s$ is the steady-state creep strain rate, and F is a transient function which is shown in the following.

$$F = \begin{cases} \exp\left[\Delta\left(1 - \frac{\zeta}{\varepsilon_t^*}\right)^2\right] & ; \zeta < \varepsilon_t^* \\ 1 & ; \zeta = \varepsilon_t^* \\ \exp\left[-\delta\left(1 - \frac{\zeta}{\varepsilon_t^*}\right)^2\right] & ; \zeta > \varepsilon_t^* \end{cases} \quad (6)$$

Where Δ and δ are the work-hardening and recovery parameters, respectively; ζ is the hardening variable; and ε_t^* is the transient strain limit. These parameters are defined as follows:

$$\Delta = \alpha_w + \beta_w \ln\left(\frac{\sigma_{eff}}{\mu}\right) \quad (7)$$

$$\delta = \alpha_r + \beta_r \ln\left(\frac{\sigma_{eff}}{\mu}\right) \quad (8)$$

where α_w , β_w , α_r and β_r are constants defined from lab test results.

$$\varepsilon_t^* = K_0 \exp(cT) \times \left(\frac{\sigma_{eff}}{\mu} \right)^m \quad (9)$$

where K_0 , c , and m are constants defined from lab test results on salt samples.

The evolution rate of the hardening variable ζ is given by:

$$\dot{\zeta} = (F - 1) \dot{\varepsilon}_s \quad (10)$$

Fossum and Fredrich (2002) summarized the M-D constitutive model parameters for the WIPP clean salt and eight domal salts in the Gulf of Mexico region. Table 1 presents the model parameters for the WIPP clean salt which was considered as the median case in the data presented by Fossum and Fredrich (2002). In addition, Fossum and Fredrich (2002) proposed the Young's modulus of 31 GPa, and the shear modulus of 12.4 GPa for the WIPP clean salt.

Table 1. Parameters of the M-D salt material model (Fossum and Fredrich, 2002).

Property/constant	WIPP Clean Salt
A_1	$8.386 \times 10^{22} \text{ s}^{-1}$
A_2	$9.672 \times 10^{12} \text{ s}^{-1}$
B_1	$6.086 \times 10^6 \text{ s}^{-1}$
B_2	$3.034 \times 10^{-2} \text{ s}^{-1}$
Q_1	$1.045 \times 10^5 \text{ J/mol}$
Q_2	$4.18 \times 10^4 \text{ J/mol}$
n_1	5.5
n_2	5.0
σ_0	20.57 MPa
Q	5.335×10^3
R	8.3143 J/mol K
M	3.0
K_0	6.275×10^5
C	0.009198 K^{-1}
α	-17.37
β	-7.738
δ	0.58

For the work presented in this paper, the M-D creep behavior described above was encoded in a User Subroutine in Abaqus. The model parameters shown in Table 1 were used for analyzing the examples presented in the following section. Note Munson (1999) used Tresca stress as the effective stress in the M-D creep model. However, the work presented here used von Mises stress as the effective stress for the modeling.

Since the M-D model is not coupled with any material damage criteria, it may be necessary to perform a subsequent assessment on the strength of the borehole or cavern, to identify the possibility that failure modes such as micro-fracturing or dilation of the salt could occur if shear

stresses are high enough. The common procedure for checking for these failure modes is to use a stress-based dilatancy criterion which typically takes the following form:

$$\sqrt{J_2} = k I_1 \quad [11]$$

where J_2 is the second invariant of the deviatoric stress tensor, I_1 is the first invariant of the stress tensor, and k is a constant.

Ratigan et al. (1991) proposed that k should have a value of 0.27 based on salt from WIPP near Carlsbad, New Mexico. DeVries et. al (2005) proposed a conservative criteria by using a k value of 0.18, and Nieland et. al (2001) suggested a less conservative criteria with a k value of 0.45. In addition, more comprehensive forms of the failure criteria were proposed by Lee et al. (2004), Hunsche (1993) and DeVries et al. (2005).

3. Analysis examples

Two example cases are presented here. The first shows deep well casing ovalization deformation due to salt creep deformation, and the second considers a storage cavern subjected to pressure loading cycles during operation.

3.1 Analysis Example 1 - salt creep effects on deep well integrity

This example studied the borehole closure due to salt creep and its impact on the integrity of deep well casing. The assessment was performed at a depth of 5,500 m in a massive salt layer. The well was assumed to be completed with an un-cemented 273 mm, 126.8 kg/m L80 production casing. The casing internal pressure was assumed to be 80 MPa, with a wellbore annulus pressure of 75 MPa. The temperature of salt formation and casing was assumed to be 90°C.

As shown in Figure 1, the model considered an initial ellipticity of 10% for the borehole, with the salt formation and casing in contact at Location A, and with the largest gap between the casing and salt formation at Location B. Both the casing and formation were modeled using generalized plane-strain elements. Overburden weight was modeled by a global force acting on the salt model. The far-field radial displacement of the formation was constrained. The L80 casing material was modeled using an elastic-plastic constitutive relationship with a yield strength of 552 MPa (i.e. 80 ksi). The salt formation was modeled using the M-D creep model with the model parameters defined in Table 1.

Contact elements were used to model the contact interaction between the casing and formation. The primary casing design consideration was to evaluate how the external pressure loading resulting from the borehole closure due to salt creep might cause casing ovalization or collapse.

The analysis was performed in two steps. First, the initial stress conditions in the casing and formation were imposed on the model to simulate the initial conditions. In the second load step, salt creep analysis was performed to determine the contact pressure on the casing resulting from the creep deformation of the salt.

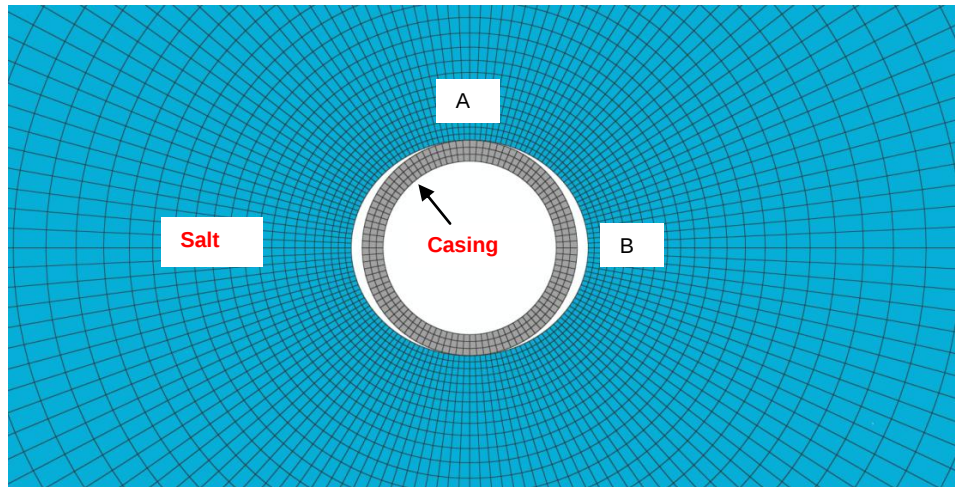


Figure 1. FEA model of casing and salt formation.

Figure 2 presents the analysis results of contact pressures at Location A and Location B as functions of time. It can be seen that the contact pressure at Location A was generated immediately, and reached the peak value of 28 MPa after 200 days. For Location B, the contact pressure was developed only after 100 days and remained significantly less than the contact pressure observed at Location A. The non-uniform distribution of contact pressure led to the development of casing ovality as also shown in Figure 2. The casing ovality increased very rapidly in the early stage and reached the peak value of approximately 4.5% after 40 days as the salt formation was in contact with the partial circumference of the casing. However, the casing ovality then decreased gradually with time as the borehole completed its closure with the contact around the entire circumference of casing, suppressing the radial expansion of the casing at Location B. The casing ovality is one of the key analysis results as it would indicate whether casing experiences collapse failure or the serviceability limit for well access is reached. For this example, the maximum ovality of 4.5% was considered tolerable for casing design.

Figure 3 presents the contour plots of effective stress in the salt around the wellbore at 0, 5, 40, and 200 days since the salt began to contact the casing. As noted in Section 2, the creep strain rate was defined as a function of the effective stress in the M-D creep model. At the start of analysis, high effective stress was present around the wellbore due to the difference between the formation stress and borehole hydrostatic pressure. The initial effective stress at Location B was slightly higher than that at Location A due to the effect of the borehole ellipticity. For the first 40 days, Location B continued showing higher effective stress, but the magnitude decreased from the initial value. After 40 days, the effective stress became insignificant around the borehole, and the potential for further creep strain decreased in the salt. One would expect that, with time, the minimum and maximum contact pressures converge as the salt gradually approaches its equilibrium isotropic stress state. However, as shown in Figure 2, due to the non-uniform vertical stress around borehole resulting from the initial borehole ellipticity, the contact stress at Location B would remain significantly lower than that at Location A.

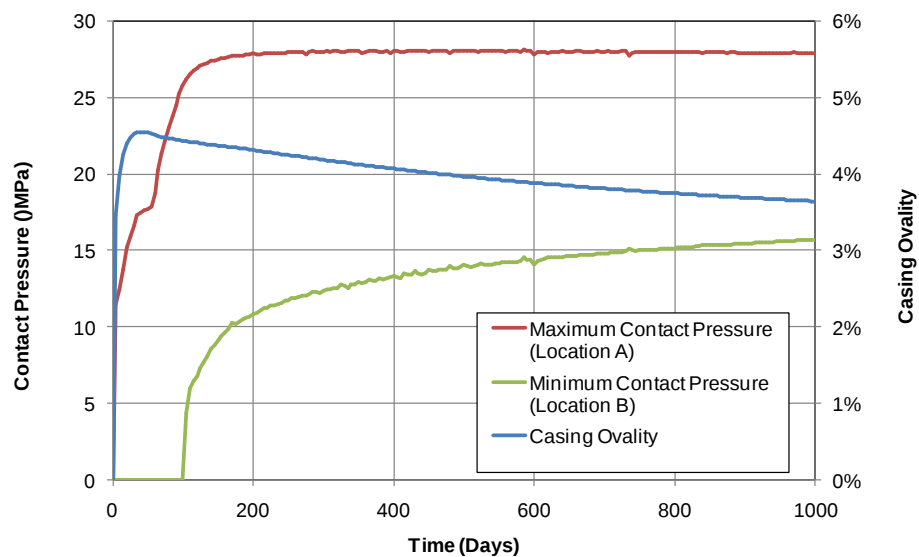
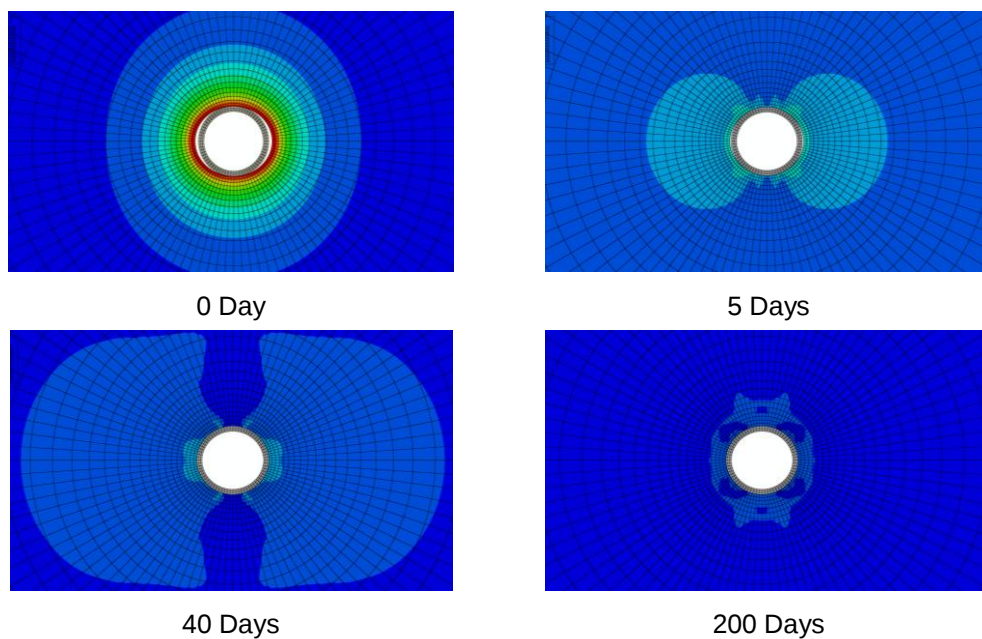


Figure 2. Contact pressures on casing and casing ovality.



(Red represents high effective stress and blue represents low effective stress)

Figure 3. Effective stress around wellbore with time.

3.2 Analysis Example 2 - salt cavern

Design of gas storage caverns must ensure that the cavern can be operated in a safe manner for many years. The primary focus for assessing cavern safety is determining the minimum internal cavern pressure necessary to limit creep displacement of the cavern walls, roof and floor. The maximum possible internal cavern pressure is usually considered to be the hydraulic fracture pressure of the salt formation at the top of the cavern. The creep displacement behavior also governs the design for the cavern diameter and cavern height.

Finite element analysis is often used to assess the stress surrounding a cavern due to the in situ stress and cavern operating pressure. This stress state changes with time due to variations in the cavern pressure during gas storage operations and due to stress redistribution caused by salt creep. Figure 4 shows the FEA model for the example storage cavern. The example case considers a salt cavern built at a depth of 1000 m from surface. The cavern was assumed to be 150 m in height, with a radius of 75 m at the top, and 25 m at the bottom. For the model, the far-field radial displacement of the salt formation was constrained.

The model included several layers from the surface to the cavern to represent the overburden materials. The analysis started with assuming a geostatic stress state in the model. The vertical geostatic stress gradient was assumed to be 0.022 MPa/m, and the two horizontal stresses in the salt layer were assumed to be the same as the vertical stress. A geothermal gradient of 0.0275°C/m was assumed for this analysis. The cavern was also assumed to be filled with brine with a density of 1200 kg/m³, and subjected to an initial wellhead pressure of 0.2 MPa. The FEA model simulated the effect of the brine in the wellbore by applying the hydrostatic fluid pressure on the inner surface of the cavern. Note that it was assumed that the brine was displaced from the cavern by gas at the initial pressure of 12 MPa prior to the start of the first pressure cycle.

The analysis simulated a series of gas injection and production cycles to represent typical cavern operating procedures. Each operation cycle was assumed to include a production phase of 30 days, an injection phase of 90 days, and a storage phase of 60 days. Figure 5 shows the gas pressure variation inside the cavern for two operating cycles. The maximum operating pressure was assumed to be 12 MPa, and the minimum pressure 4 MPa. The temperature change associated with gas injection and production was not considered in this example case.

The creep deformation analysis was activated immediately following the geostatic analysis, and the analysis simulated a pre-operation period consisting of 25 days of initial creep deformation in the salt, prior to the start of the pressure cycles.

Figure 6 presents the analysis results, showing the pressure-induced vertical displacement of the top of the cavern as a function of time. It can be seen that the pre-operation phase generated a vertical displacement of approximately 0.04 m downwards. The production phase in the first cycle of the operation period caused a significant increase in the vertical displacement to approximately 0.15 m. However, in the remaining operation period, the vertical displacement only fluctuated slightly. The maximum vertical displacement of the top of the cavern was approximately 0.178 m in the first cycle, and 0.203 m in the second cycle. These vertical displacements are considered insufficient to cause cavern stability concerns. However, the impact of this movement on the wellbore where it penetrates the top of the cavern should be studied further to ensure that significant deformations are not imposed on the well casing.

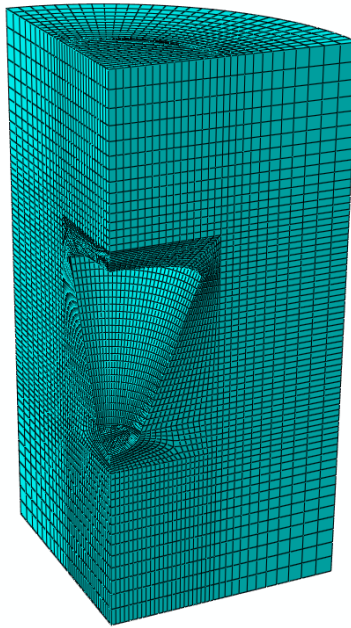


Figure 4. Finite element mesh representing the salt cavern.

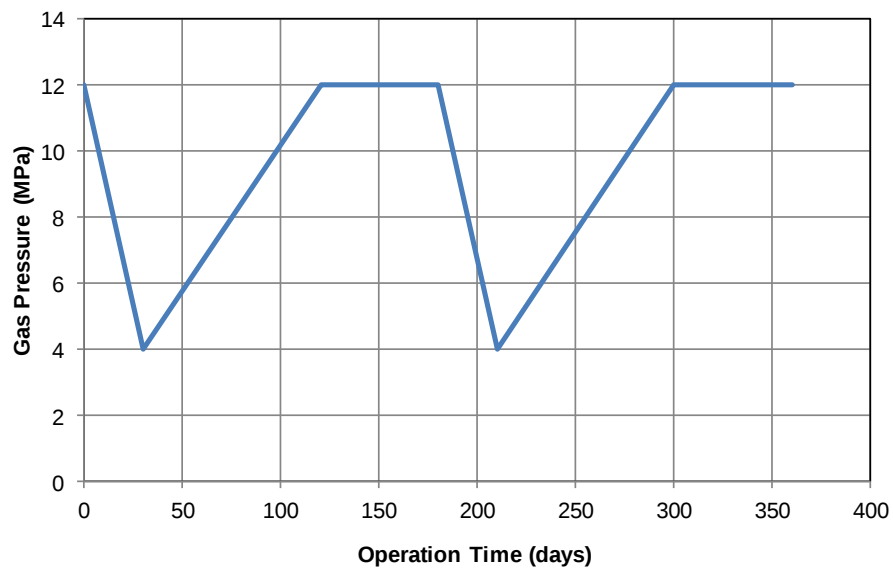


Figure 5. Gas pressure cycle inside the storage cavern.

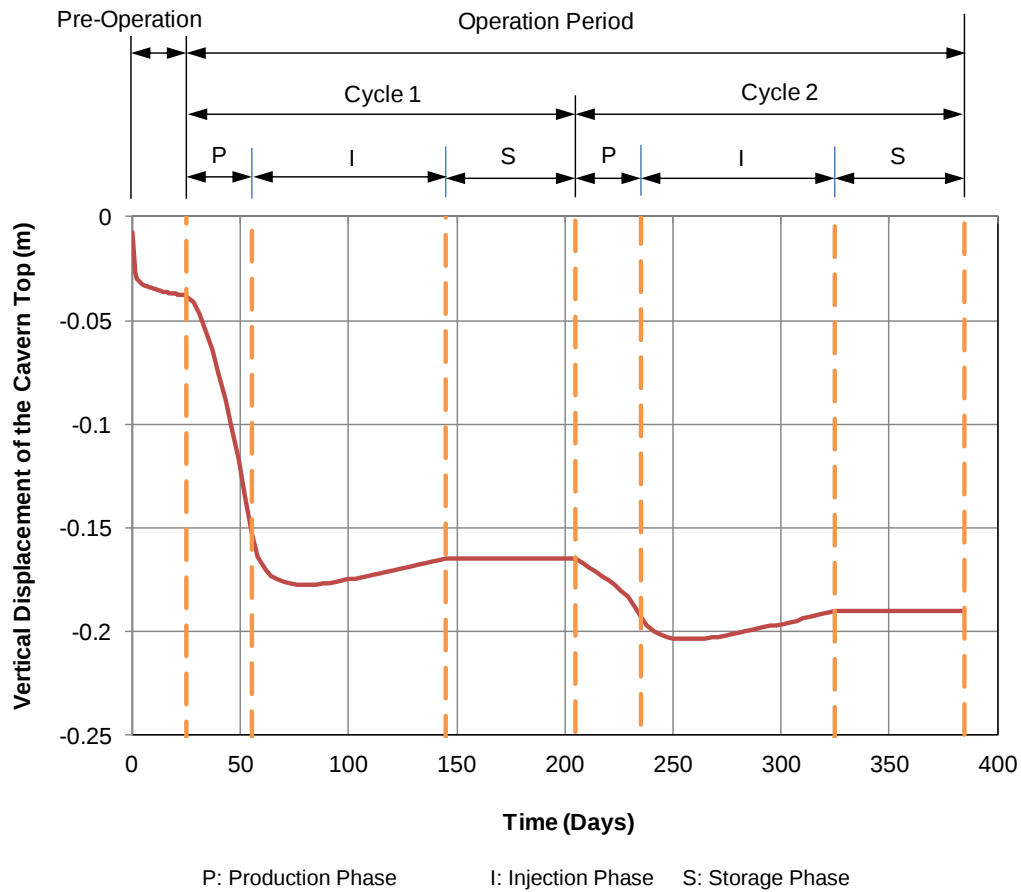


Figure 6. Vertical displacement of the top of the storage cavern.

4. Summary

This paper presents a finite element analysis methodology for modeling and analyzing salt creep deformations for drilling applications. The FEA approach was based on the established M-D creep model coded as a subroutine in Abaqus. The model was used to analyze a deepwater well casing deformation resulting from formation creep in the salt layer. A second example considered the modeling of the creep displacement of the top of a gas storage cavern due to the cyclic variations in cavern operating pressure. Both examples demonstrated that the proposed approach using Abaqus is a useful tool for solving salt creep deformation problems for drilling applications.

5. References

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