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Analysis of Salt Creep and Well Casing Damage in High Pressure and High Temperature Environments

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Abstract

Drilling and completing wells through deep thick salt formations is technically challenging and costly. Salt material flows over time whenever a stress difference, or shear stress, is induced. The rate of deformation primarily depends on the stress difference, and on the temperature. Both of these factors increase with increasing depth, often leading to severe loading and deformation of wells, and sometimes severe damage and loss of functionality. Geomechanical analysis can be applied to estimate such loading, to estimate damage risks, and to optimize well designs for these challenging conditions. We describe herein a process to evaluate salt creep and casing damage risk for high pressure and high temperature conditions typically encountered in deep salt formations. Because well costs often exceed 50 million dollars each, appropriate well design and risk analysis, supported by geomechanical modeling of salt and casing behavior, is critical to project economics.

To simulate the visco-elasto-plastic behavior of salt, we apply the time-dependent constitutive framework available in FLAC3D. The available formulation is modified by Terralog to account for damage accumulation during primary loading, associated strength degradation, compaction-dilation transition based on the Drucker-Prager yield criterion, and loading-unloading response.

We provide an illustrative example for a deepwater Gulf of Mexico field, in which a multi-string casing-in-casing design was considered to resist long-term creep. Laboratory creep data was used to calibrate the constitutive model, which was then applied to a near wellbore scale geomechanical model that included the casing strings, cement, mud pressure, and 10ft of surrounding salt. The simulation results indicate that the for the design configurations considered, the minimum time for salt to contact the outer casing was on the order of 2 years for the most severe scenarios (lowest annulus pressure), and more than 20 years for the strongest configurations. Geomechanical analysis of this type provides a relatively low cost approach to quantify casing damage risks and to optimize casing designs for completions in high stress and high temperature environments.

Introduction

Increasing exploration and production from deep regions around the world require drilling through and completing wells in thick salt formations, leading to very high well costs. Appropriate designs are required to withstand creep induced loads during drilling and after completion. The introduction of a wellbore in a salt formation changes the existing local stress field, inducing a stress difference between the borehole and surrounding salt, and resulting time-dependent (creep) loading on well casings. Production of hot fluids from subsalt formations adds additional thermal strains to the wellbore and thermally induced creep acceleration.

Both stress and temperature increase with depth. At greater depths, therefore, the stress and temperature changes induced in the near wellbore area become increasingly severe, leading to more rapid and larger salt deformation. Completion design of the wells drilled through high pressure-high temperature (HPHT)

salt formations often requires a detailed Geomechanical analysis to assess loading, damage risk, and optimum design configurations.

Casing damage caused by salt creep has long been observed and reported by many authors [1-8]. In more recent publications (i.e [9, 10]) numerical methods have been used to simulate the visco plastic behavior of the rock and the damage it may cause to the casings, sometimes by applying constitutive equations for salt proposed by Munson [11], or modifications thereof [12, 13].

In this study we apply modified forms of constitutive equations first proposed by Herrmann et al. [14] to model salt deformation at the Waste Isolation Pilot Plant (WIPP). This is an empirical creep law developed to simulate the time dependent (creep) behavior of salt rocks at nuclear waste isolation facilities. The available formulation is modified by Terralog to account for damage accumulation during primary loading, associated strength degradation, compaction-dilation transition based on the Drucker-Prager yield criterion, and loading-unloading response. This formulation is then calibrated against available laboratory data for salt creep under varying differential stress conditions.

Salt Material Behavior

Salt is a viscous, slowly flowing material encountered in many drilling operations around the world in forms of massive beds, salt domes and salt lenses. It is an impermeable rock, and this characteristic has made salt intervals ideal for liquid and gas storage. From geomechanical point of view, the time-dependent behavior property (intracrystalline flow behavior) commonly referred to as "creep" is the most important characteristic of salt materials. Temperature, stress, time (rate), history, moisture content, and fabric anisotropy (crystal imbrication or elongation) influence the mechanical behavior of salt.

The creep rate in salts can be defined by two components: one is known as the primary creep rate $\dot{\varepsilon}_p$; the second as the secondary creep rate $\dot{\varepsilon}_s$. The additive decomposition is given by:

$$\dot{\varepsilon} = \dot{\varepsilon}_p + \dot{\varepsilon}_s \tag{1}$$

It is worth noting that the primary creep rate $\dot{\varepsilon}_p$ depends on the secondary creep rate through equation:

$$\dot{\varepsilon}_p = \begin{cases} (A - B\,\varepsilon_p)\dot{\varepsilon}_s & \text{if} \quad \dot{\varepsilon}_s \geq \dot{\varepsilon}_{ss}^* \\ \left(A - B\left(\dfrac{\dot{\varepsilon}_{ss}^*}{\dot{\varepsilon}_s}\right)\varepsilon_p\right)\dot{\varepsilon}_s & \text{if} \quad \dot{\varepsilon}_s < \dot{\varepsilon}_{ss}^* \end{cases}. \tag{2}$$

The constants A, B and $\dot{\varepsilon}_{ss}^*$ in equation (2) are material constants to be determined from experimental data. The secondary creep rate $\dot{\varepsilon}_s$ is given by

$$\dot{\varepsilon}_s = D\,\overline{\sigma}^n\, e^{\left(-\frac{Q}{RT}\right)}, \tag{3}$$

Where Q is the activation energy, R is the universal gas constant, T is the temperature in degrees Kelvin, D is the salt constant and $\overline{\sigma}$ is the deviatoric stress. As indicated by equation (3), the long-term deformation rate in salts is primarily controlled by the stress difference and by the temperature.

Higher temperature decreases the salt-casing contact time and accelerates the creep rate significantly. It has been shown that, for relatively pure salt, thermal expansion and elastic deformation parameters do not vary significantly from site to site [15]. However, inelastic deformation, failure behavior, and creep properties have been shown to vary dramatically between sites [15, 16]

Wellbore wall deformation, creep, and casing damage risk increase with depth (due to both increasing stress and temperature) and with larger differences between the internal casing pressure and the external in-situ stress at salt formations. Moreover, because salt creeps and deforms differently than other rock materials in heterogeneous layers, the salt may flow significantly while other non-salt layers will not, thereby setting up shear stresses and potential bedding plane slip at salt-non-salt interfaces.

Salt response is characterized by three important types of behavior that need to be implemented in any numerical code. These are the initial elastic response followed by accumulation of damage and dilation and

eventual failure, the transient creep and the steady-state creep rate. **Figure 1** shows an example of creep behavior under a constant confining pressure of 2175 psi and a differential stress of 725 psi on a salt sample from the Gulf of Mexico. The strain versus time plot initiates with a transient behavior for about 3 days, and then continues with steady state behavior with a relatively constant strain rate.
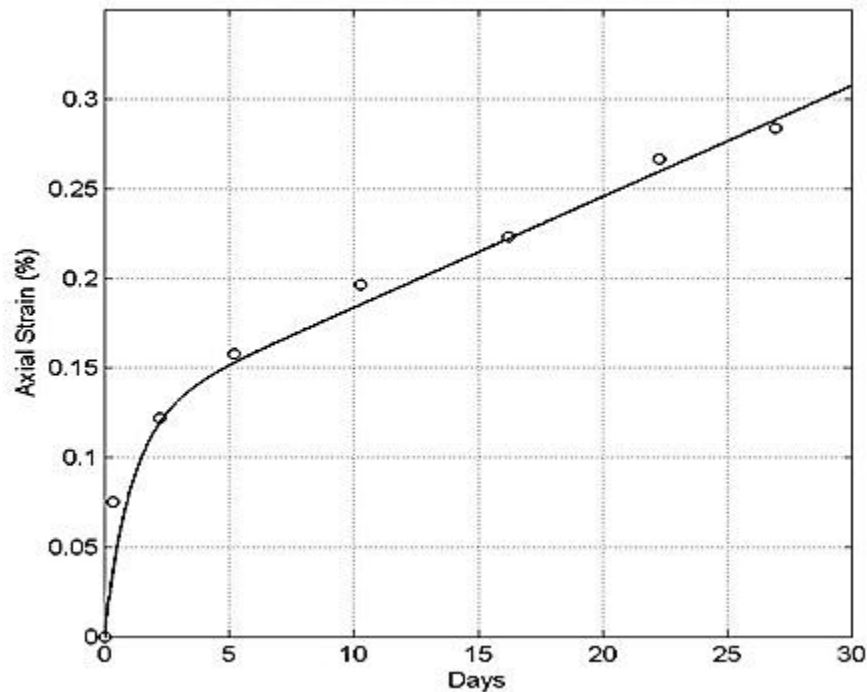

Figure 1. The axial strain vs. time plot for a salt rock sample, Gulf of Mexico

For our studies, we apply a form of the WIPP model combined with a Drucker-Prager plasticity criterion, implemented as PWIPP-Creep Viscoplastic Model in FLAC3D. The principal modifications to the WIPP constitutive model are:

- Initial elastic followed by the accumulation of damage during primary loading;
- Volumetric dilation and eventual material failure based on a Drucker-Prager failure criteria;
- Loading-unloading response based on stiffness properties of an undamaged material.

Material softening and dilation during primary loading is achieved through a work-hardening yield surface. After the initial elastic response, during which the material compacts, the volumetric response changes to dilation. Once the maximum strength criterion is satisfied, the material fails and the material strength returns to zero.

Geomechanical Analysis of Well Deformation in Salt

In this study 2D and 3D geomechanical models are developed and applied at the near wellbore scale, including detailed well completion components, and cement or mud pressure between casing strings or between outer casing and the salt, and 10 to 12 feet of surrounding salt formation. We provide an example of geomechanical simulation of salt creep and casing system deformation from the deepwater region of the Gulf of Mexico, where drilling through salt and well completions to depths exceeding 20,000 ft. result in high temperature and high pressure time-dependent loads. Due to high costs of well completion operations in regions where drilling through thick salt formations are necessary, geomechanical modeling of salt and casing behavior is critical for optimum casing system design, risk assessment, and project economics. Appropriate geomechanical analysis of deformations in salt and associated well casing damage risk in high pressure and high temperature environments often includes:

- The use of available laboratory data to develop and validate appropriate constitutive models;

- Detailed near-wellbore modeling to investigate salt-cement-casing interaction; and,

- Reservoir scale modeling to consider the range of loads likely to be imposed on the near wellbore-system when considering sections of the well exiting salt near producing intervals.
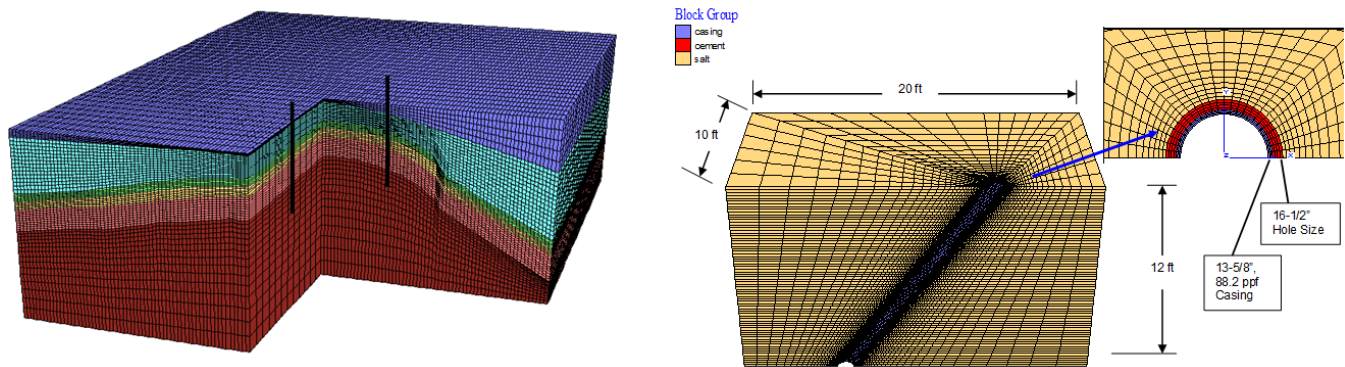

Figure 2. 2D and 3D examples of reservoir scale models and near-wellbore scale models to evaluate casing damage risks and optimum well trajectories

Figure 2 Typical 2D and 3D geomechanical models applied to study the salt creep and well casing damage.

We make use of the time-dependent constitutive framework available in FLAC3D to simulate the visco-elastic-plastic behavior of salt. Available material models are modified to take into account damage accumulation during primary loading, strength degradation in the rock, compaction-dilation transition based on the Drucker-Prager yield criterion and loading-unloading response using initial stiffness properties. Available laboratory data for salt creep under varying differential stress conditions are used to calibrate the constitutive model (through simulation of triaxial core tests), which is then applied within the larger near-wellbore scale geomechanical model.

As an illustrative example, we consider seven casing design configurations at selected through-salt depths from about 10,000 ft to 20,000 ft for a field in the Deepwater Gulf of Mexico, as presented in **Table 1** and **Table 2** below. Multiple concentric casing strings are evaluated to provide strength and resistance to long-term salt creep. Some configurations include 10-1/8" production casing inside 13-5/8" intermediate casing in a 17-1/2" borehole. Others include 13-7/8" intermediate casing and 16" surface casing in a 19" borehole. We assume10% wellbore ovality for all design cases. Variations of cementation (full or un-cemented) are considered between the casings annuli.

Different fluid pressure scenarios are considered in the annulus to mimic drilling mud weight during initial drilling and subsequent production. The inner annulus pressure are set equal to original drilling conditions for all models (Case 1a-7a) during 20-yrs of life cycle of the wells, while the outer annulus pressure (between outer casing and salt) is assumed to change to 10 ppg after 1 year of production in some instances (Cases 1a-2, 2a-2, 4a-2, 5a-2, & 7a-2).

Laboratory testing of the salt material indicate some variations in the value of the creep for different intervals and core samples. The steady-state creep rate varies by about 20% to 40% for different core samples of seemingly similar minearology. Such variations are not uncommon. For these simulations, we apply the "fast creep" values to provide more conservative (worst-case) loading conditions. The temperature of the salt is assumed to reach a maximum temperature of 260 F for most cases, and 160 F for one case. In-situ vertical and horizontal stresses are applied consistent with field measurements of minimum stress and estimates of maximum stress. A summary of casing configurations, temperature, in-situ stresses, and annulus pressure used for each geomechanical models is provided in **Table 2**.

Table 1. Casing designs simulation for damage studies due to salt loading for cases 1 to 7.

Casing Design	TVD	Production Casing	Annulus B Cementation	Intermediate Casing	Annulus C Cementation	Surface Casing	Annulus D Cementation	Min Hole Diam	Max Hole Diam
1	10150 ft Just below 18" shoe	10-1/8" 79.75#, SM-125S+	No-Cem	13-7/8" 106#, Q-125HP	Cement	16" 109#, HCQ-125	No-Cem	19"	20.9"
2	18400 ft Just above TOC in Ann-D	10-1/8" 79.75#, SM-125S+	No-Cem	13-7/8" 106#, Q-125HP	No-Cem	16" 109#, HCQ-125	No-Cem	19"	20.9"
3	18900 ft Just below 13-5/8 TOL	10-1/8" 79.75#, SM-125S+	No-Cem	13-7/8" 106#, Q-125HP	No-Cem	16" 109#, HCQ-125	Cement	19"	20.9"
4	18900 ft Just below 13-5/8 TOL	10-1/8" 79.75#, SM-125S+	No-Cem	13-7/8" 106#, Q-125HP	No-Cem	16" 109#, HCQ-125	No-Cem	19"	20.9"
5	20500 ft Just below 16" Shoe	10-1/8" 79.75#, SM-125S+	No-Cem	13-5/8" 88.2 #, Q-125	No-Cem			17-1/2"	19-1/4"
6	20500 ft Just below 16" Shoe	10-1/8" 79.75#, SM-125S+	No-Cem	13-5/8" 88.2 #, Q-125	Cement			17-1/2"	19-1/4"
7	20500 ft Just below 16" Shoe	10-1/8" 79.75#, SM-125S+	Cement	13-5/8" 88.2 #, Q-125	No-Cem			17-1/2"	19-1/4"

Table 2. Model parameters for casing damage studies due to salt loading for cases 1 to 7. Letters (a or a-2) indicate a different annulus pressure scenario on each case.

Case No.	Salt Constitute Model	Temp	Overburden Stress	Annulus A Press (Prod Casing Internal Press)	Annulus B Press (Prod Casing Outer Annulus Press)	Annulus C Press (Int Casing Outer Annulus Press)	Annulus D Press (Surf Casing Outer Annulus Press)
1a	"Fast Creep"	Tmin (160 F)	7,732 psi (14.65 ppg)	7495 psi (14.2 ppg)	7495 psi (14.2 ppg)	N/A	7389 psi (14 ppg)
1a-2							5278 psi (10 ppg)
2a	"Fast Creep"	Tmax (260 F)	14,735 psi (15.4 ppg)	13587 psi (14.2 ppg)	13587 psi (14.2 ppg)	14256 psi (14.9 ppg)	13395 psi (14 ppg)
2a-2							9568 psi (10 ppg)
3a	"Fast Creep"	Tmax (260 F)	15,233 psi (15.5 ppg)	13956 psi (14.2 ppg)	13956 psi (14.2 ppg)	14644 psi (14.9 ppg)	N/A
4a	"Fast Creep"	Tmax (260 F)	15,233 psi (15.5 ppg)	13956 psi (14.2 ppg)	13956 psi (14.2 ppg)	14644 psi (14.9 ppg)	13759 psi (14 ppg)
4a-2							9828 psi (10 ppg)
5a	"Fast Creep"	Tmax (260 F)	16,683 psi (15.65 ppg)	15137 psi (14.2 ppg)	15137 psi (14.2 ppg)	15883 psi (14.9 ppg)	N/A
5a-2						10660 psi (10 ppg)	
6a	"Fast Creep"	Tmax (260 F)	16,683 psi (15.65 ppg)	15137 psi (14.2 ppg)	15137 psi (14.2 ppg)	N/A	N/A
7a	"Fast Creep"	Tmax (260 F)	16,683 psi (15.65 ppg)	15137 psi (14.2 ppg)	N/A	15883 psi (14.9 ppg)	N/A
7a-2						10660 psi (10 ppg)	

Cross-section models are shown in **Figure 3**. A series of 12 simulations are run and used to predict time for salt to contact casing, casing yield and expected maximum casing strains.
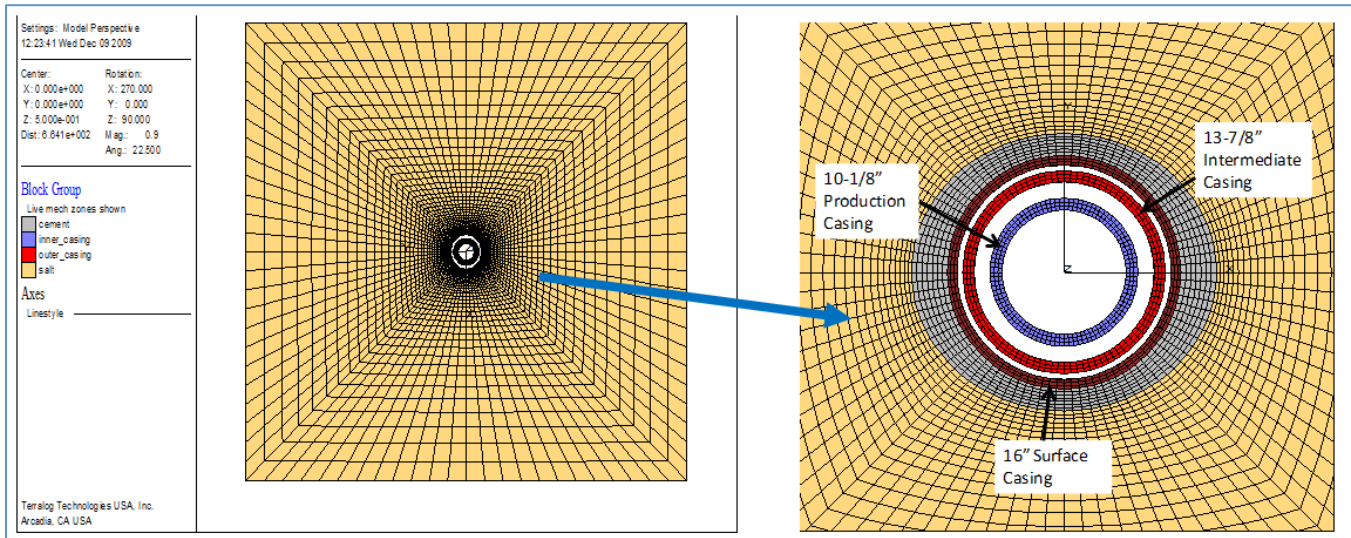

Figure 3. (Left) Sample 2D (plane strain) geomechanical model to evaluate time duration for salt to contact casing and subsequent casing deformation. (Right) Close-up view of a particular casing design.

During initial loading, the mechanical response of the material is defined by the shear modulus G and the bulk modulus K, both defined in the small strain region. For deformations above a critical strain, we assume that these values change to account for material degradation associated with micro-cracking. The Drucker-Prager yield criterion, which is part of the PWIPP model formulation, has been modified by Terralog to account for material failure. The initial location of the yield surface in the principal stress space is defined by the values of the parameters representing cohesion, internal friction and dilation, which are given as the last three entries in Table 3. The failure criterion assumes that the cohesion and internal friction are both dependent on the plastic strain accumulated during loading. With increasing plastic strain the value of these parameters reduce to zero at which point the deviatoric strength of the material vanishes. A summary of PWIPP material input parameters used for the "fast creep" constitutive model is presented in **Table 3**.

Table 3. PWIPP material parameters used for "fast creep" GoM through-salt model.

Values	Units	Model Parameter
2.4		WIPP-model constant, A
240		WIPP-model constant, B
1.15e-13	psi^-n day^-1	WIPP-model constant, D
4.9		WIPP-model exponent, n
10000	Cal/mol	Activation energy, Q
6.25e-4	1/day	Critical steady-state creep rate
1.987	cal/mol*K	Gas constant, R
1.798e6	Psi	Elastic shear modulus, G
2.997e6	Psi	Elastic bulk modulus, K
159	Psi	Hydrostatic tension limit, σ^t
160	Fahrenheit	Zone temperature, T
1305	Psi	Material parameter, k_ϕ
0.50		Material parameter, q_ϕ
0.50		Material parameter, q_k

The axial strain as a function of time, as measured in laboratory creep experiments, is used to calibrate the constitutive model. This is done by simulating the laboratory creep test, and adjusting material properties to provide a reasonable match between simulation results and laboratory measurements. For example, **Figure 4** compares simulation and laboratory results for the "fast creep" time dependent response and the corresponding changes in strain rate. The applied confinement is 20 MPa, the constant deviatoric stress differences are 10 MPa and 13 MPa, and the temperature is set at 160 F. As indicated below, there is a good agreement between modeled and measured laboratory results.
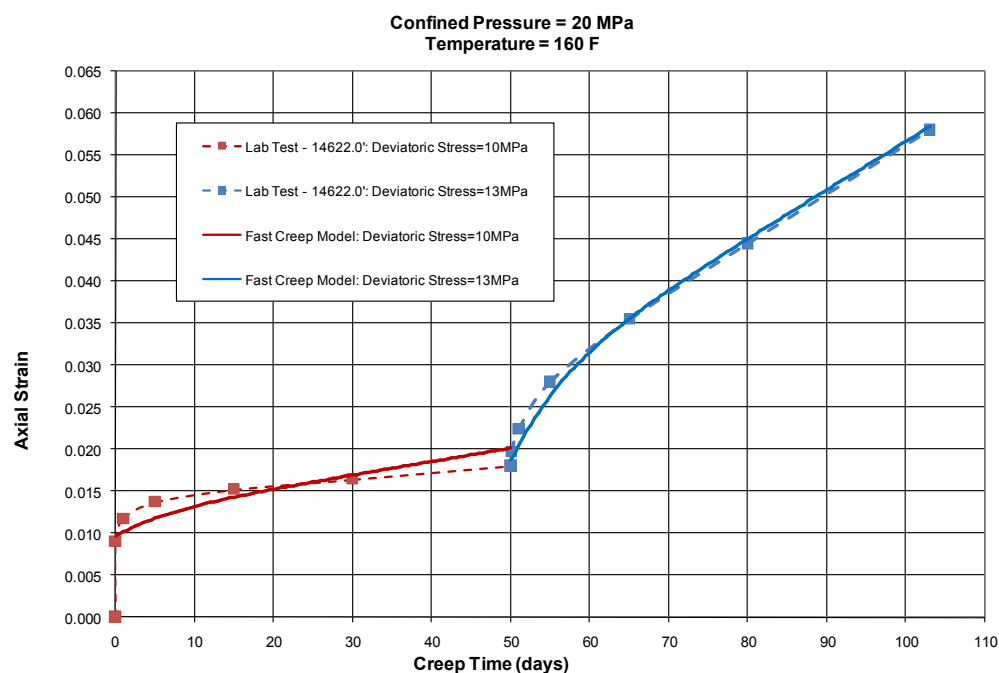
Confined Pressure = 20 MPa
Temperature = 160 F

Legend:
- – ■ – Lab Test - 14622.0': Deviatoric Stress=10MPa
- – ■ – Lab Test - 14622.0': Deviatoric Stress=13MPa
- —— Fast Creep Model: Deviatoric Stress=10MPa
- —— Fast Creep Model: Deviatoric Stress=13MPa

(Y-axis: Axial Strain; X-axis: Creep Time (days))

Figure 4. Example of time dependent response for "fast creep" salts. Dashed lines show the creep behavior of lab data and solid lines represent the salt behavior using the modified PWIPP model developed by Terralog.

A summary of simulations results for the design cases using 'fast creep' salt constitutive model are presented in **Table 4**.

The analyses provide estimates of the time for the salt to contact the casing, casing yield, and casing induced strains due to salt contact. For example, for case (2a-2) with stress conditions shown in **Table 2**, the results of geomechanical analysis indicate that the salt rock contacts the casing after 12 years. Also for this case, after 20 years, the salt creep causes maximum strain of 0.4% but no casing yield. As would be expected, the time for salt to contact the casing is most rapid, and the subsequent casing strain most severe, for those scenarios in which there is lower annulus pressure and one less casing string.

Sample contour plots of resulting principle stress and displacement magnitude at the end of simulations (20-year) for casing design # 4 are presented in **Figure 5** and **Figure 6**. We note that the salt moved slowly inward toward the casing and increased in salt creep once the annulus pressure is reduced and contact occurs at the minimum axes first. The contact casing moved inward with the salt and outward perpendicular to it (where contact has not occurs), causing casing ovalization as shown in the contour plots in figures below.

Table 4. Simulation results for varying casing designs.

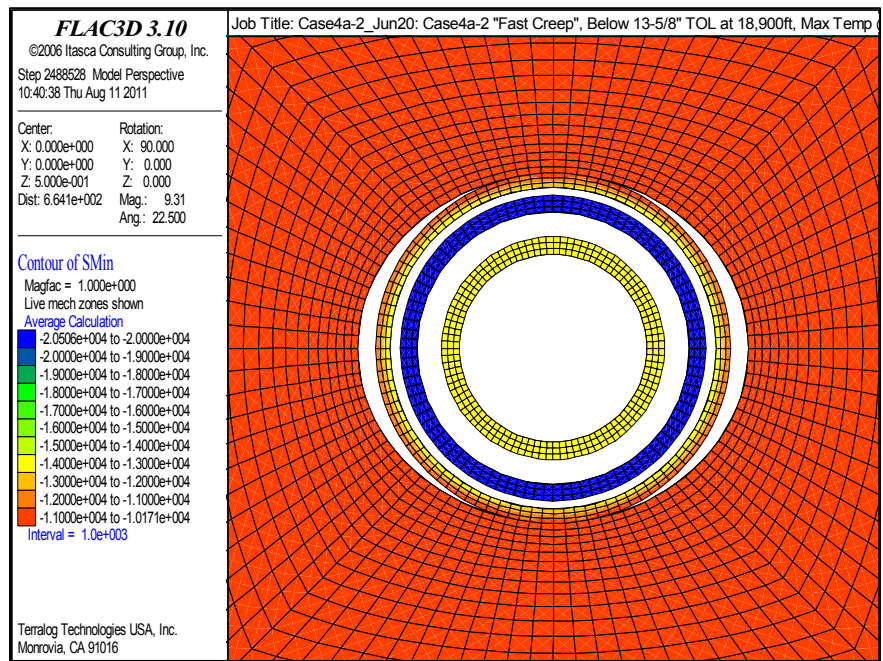| Case No.	Salt Constitute Model	Annulus Pressure (between Casing and Salt)	Time to Contact (yr)	Casing Yield	Max. Casing Strains at 20-yr (%)
1a	"Fast Creep"	7389 psi (14 ppg)	> 20	N/A	0
1a-2		5278 psi (10 ppg)	> 20	N/A	0
2a	"Fast Creep"	13395 psi (14 ppg)	> 20	N/A	0
2a-2		9568 psi (10 ppg)	~ 12	no yield	0.4
3a	"Fast Creep"	N/A (Cemented)	N/A	no yield	< 0.01
4a	"Fast Creep"	13759 psi (14 ppg)	> 20	N/A	0
4a-2		9828 psi (10 ppg)	~ 5	no yield	0.8
5a	"Fast Creep"	15883 psi (14.9 ppg)	> 20	N/A	0
5a-2		10660 psi (10 ppg)	~ 2	no yield	0.2
6a	"Fast Creep"	N/A (Cemented)	N/A	no yield	< 0.01
7a	"Fast Creep"	15883 psi (14.9 ppg)	> 20	N/A	0
7a-2		10660 psi (10 ppg)	~ 2	no yield	0.2

Figure 5. Plot contour of principle stress after 20 years for casing design # 4 with 'fast creep' salt constitutive model due to salt loading. Annulus pressures are reduced to mud weight of 10 ppg after year-1.
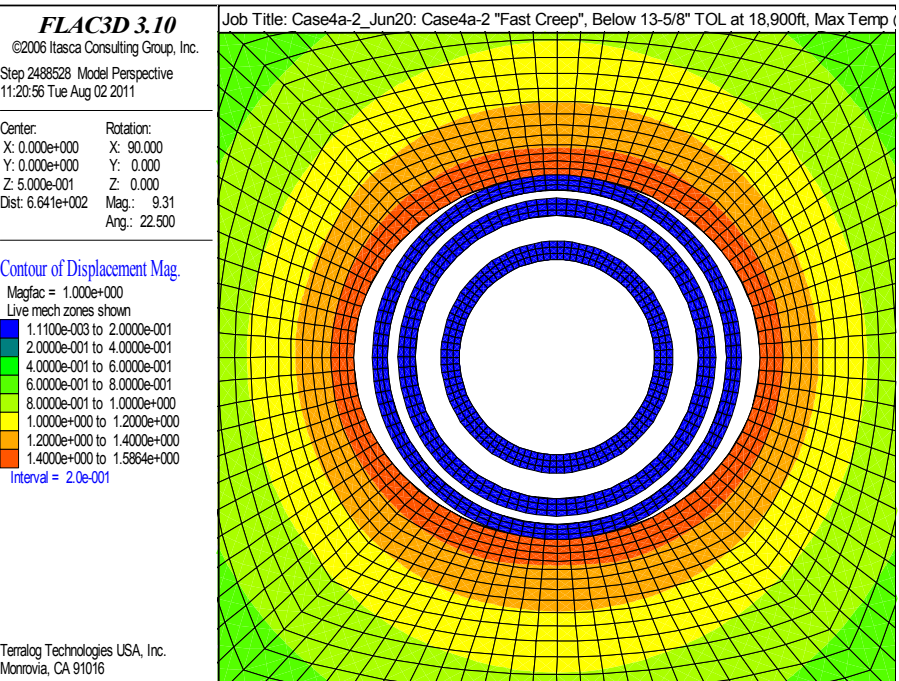

Figure 6. Plot contour of the displacements after 20 years for casing design #4 with "fast creep" constitutive model.

Corresponding plot histories of salt radial displacements and casing ovalizations for the same casing design are presented in **Figure 7**. From the figures below, it is observed that the salt contacts the casing at about year-5 and subsequent induced strain of less than 1% are observed for 20-year life cycle. The salt never fully enveloped the casing, and no yield has developed in the contact casing.
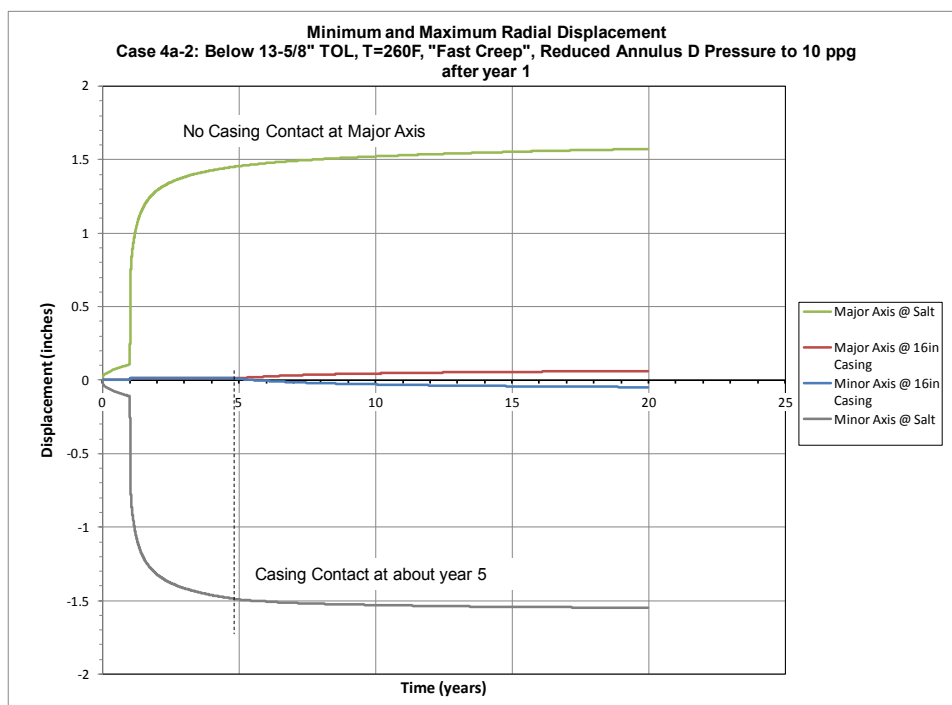
Figure 7: Predicted salt radial displacement and casing ovalization for casing design # 4 with 'fast creep' salt constitutive model. Annulus pressures are reduced to mud weight of 10 ppg after year-1.
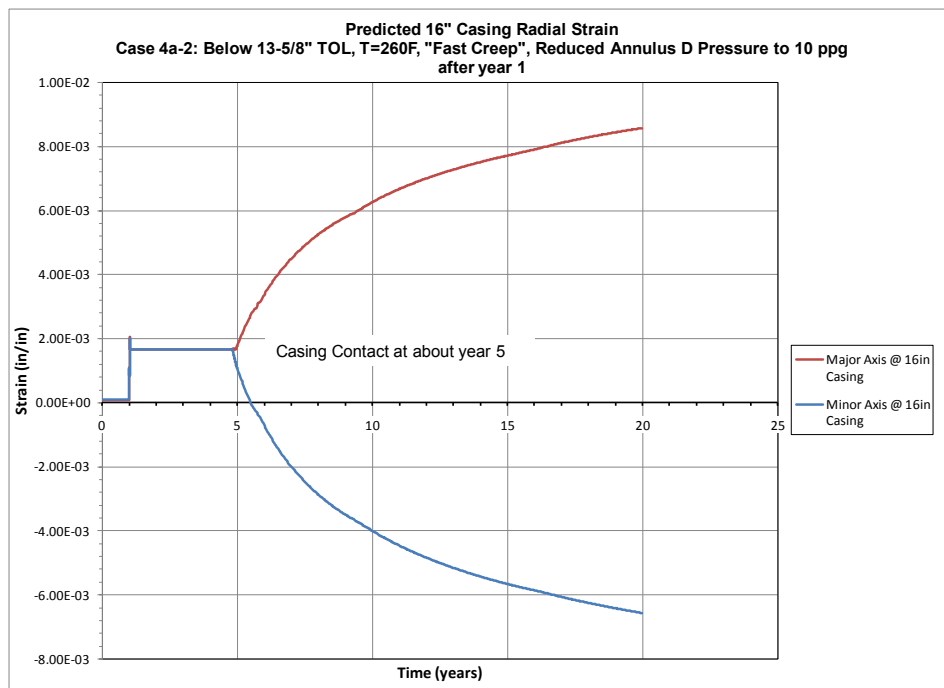

Figure 8. Resulting induced strain for casing design # 4 with 'fast creep' salt constitutive model. Annulus pressures are reduced to mud weight of 10 ppg after year-1.

Discussion and Conclusions

We describe herein a process to evaluate salt creep and casing damage risk for high pressure and high temperature conditions typically encountered in deep salt formations.   Geomechanical modeling can be effectively applied to consider casing damage risk, and to evaluate alternative completion designs to mitigate such damage.   We provide an illustrative example for a deepwater Gulf of Mexico field, in which a multi-string casing-in-casing design was considered to resist long-term creep.   Laboratory data was used to calibrate the constitutive model, which was then applied to a near wellbore scale geomechanical model that included the casing strings, cement, mud pressure, and 10ft of surrounding salt.   The simulation results indicate that the for the design configurations considered, the minimum time for salt to contact the outer casing was on the order of 2 years for the most severe scenarios (lowest annulus pressure), and more than 20 years for the strongest configurations.   Geomechanical analysis of this type provides a relatively low cost approach to quantify casing damage risks and to optimize casing designs for completions in high stress and high temperature environments.

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