Salt Creeping: A Major Challenge for Oilfields, A Review

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Abstract: Background: Salt creeping is a slow and progressive deformation of salt formations under stress over time. It poses a significant challenge to oil and gas production in salt formations, causing stuck pipe, casing failures, and ground subsidence. A comprehensive overview of salt creep, including its rock mechanics fundamentals, salt properties, salt formation behavior, geomechanical aspects, and determination methods of salt creeping were addressed and explained clearly. Salt creeping affected by many parameters such as temperature, time, quality of cement, casing type, casing ovality and eccentricity and loading uniformity. This paper provides a valuable resource for researchers, engineers, and industry professionals who are seeking to understand, manage, and mitigate the challenges associated with the mentioned phenomenon in oil and gas fields.

Keywords: salt creeping, stuck pipe, casing failure, rock mechanics, salt formations, casing ovality.

1. Introduction

The occurrence known as salt creeping, which involves the gradual and inevitable distortion of salt formations, presents a distinct and enduring hazard to oilfield activities conducted in such geological settings. The insidious characteristic of this phenomenon is rooted in its slow and time-dependent advancement, frequently remaining unnoticed until it materializes in harmful consequences. The consequences of salt creep have wide-ranging effects on the whole life cycle of oil and gas operations, presenting significant challenges that require a focused attention and innovative solutions.[1]

Over the course of time, salt experiences deformation, resulting in a progressive increase in pressure exerted on wellbores, ultimately leading to their gradual narrowing. The aforementioned phenomenon has the potential to hinder the smooth movement of hydrocarbons, resulting in decreased efficiency in production and requiring the implementation of expensive remediation measures. Additionally, this phenomenon might present itself as a cause of pipe stuck, which can pose significant challenges for drilling operations. That resulting in operational setbacks, escalated expenditures, and higher probability of equipment damage or loss.[2]

Casing failures are an additional severe sequence resulting from salt creep. The continuous deformation of salt formation has the potential to generate stresses on well casings, which may lead to casing collapse.

One of the most concerning consequences of salt creep is the occurrence of ground subsidence, which refers to the slow sinking of the overlying land due to deformation of the underlying salt formation. The phenomenon of ground subsidence can have extensive environmental and socioeconomic consequences, encompassing infrastructure deterioration, alterations in local hydrological patterns, and the potential...
endangerment of nearby communities due to land instability.[1,2]

1- Rock Mechanics Fundamentals

Rock is a solid geological material made of consolidated mineral particles bonded together by strong cohesive forces. Nonetheless, undamaged rocks’ composition, characteristics, and behavior vary widely. Inherently, rocks are neither homogeneous nor isotropic. Rocks are anisotropic and heterogeneous due to their structure. Rock grains vary in size, shape, orientation, and mineral composition at the microscopic level. Lamination and micro-cracking cause embedded discontinuities in these grains. Grain cementation and interlocking affect mechanical rock properties spatially. Rocks also fracture, modify, and weather according to geological and environmental processes. Rocks with strength, deformability, and in-situ stresses may respond differently to stresses in different orientations. Rock mechanical properties are affected by grain orientation. However, this reliance may make practical applications in numerous technological domains difficult. In applied rock mechanics, it is usual to assume the rock is homogeneous and has low anisotropy to simplify analysis. This allows material parameters like Young’s modulus (E) and Poisson’s ratio (v) to be considered as scalar values, implying isotropicity in the volume under study. This paper does not analyze rock behavior; thus readers are directed to the cited literature for a deeper understanding. One of the most important parameters that have an essential effect on the stability of the rocks within the salt formations is pore pressure and fracture pressure that will be addressed in the following paragraphs [3].

1-1 Geomechanical parameters in Salt Formations

Geomechanical aspects in salt formations for oil wells involve the study of stress, deformation, and failure mechanisms in the subsurface. When drilling through salt layers, it’s essential to consider the following geomechanical factors:

1- Stress Analysis: The stress state in salt formations is influenced by factors such as overburden pressure ($\sigma_v$), pore pressure ($P_p$), and tectonic stresses ($\sigma_t$). The effective stress ($\sigma_e$) is critical for assessing wellbore stability and is calculated using Terzaghi’s effective stress principle:

$$\sigma_e = \sigma_v - P_p$$

Where: $\sigma_e$ is the effective stress, $\sigma_v$ is the total vertical stress, and $P_p$ is the pore pressure.

2- Salt Creep: Salt is viscoplastic and can flow over geological time scales under stress. The rate of salt creep ($\varepsilon$) can be described using the Norton-Bailey creep law:

$$\varepsilon = A \cdot \sigma_n \cdot \exp \left( \frac{-Q}{RT} \right)$$

Where $\varepsilon$ represents the creep strain rate, $A$ is a material-dependent constant, $\sigma_n$ stands for the normal stress, $Q$ represents the activation energy for creep, $R$ is the gas constant, and $T$ denotes the absolute temperature.[4]

3- Wellbore Stability: Assessing wellbore stability involves calculating the safe mud weight ($P_{\text{mud}}$) to prevent borehole collapse. The Mohr-Coulomb failure criterion is commonly used:

$$P_{\text{mud}} \leq \sigma_v - c + \mu \cdot \sigma_e$$

Where $c$ represents the cohesion of the salt, $\mu$ is the coefficient of friction, and $\sigma_e$ denotes the effective stress.

4- Thermo-mechanical Effects: Salt formations are often subjected to temperature variations. The geomechanical behavior of salt can be influenced by thermal stresses, which are calculated using the coefficient of thermal expansion ($\alpha$) and temperature change ($\Delta T$):

$$\Delta \sigma = \alpha \cdot \Delta T \cdot E$$
Where $\Delta \sigma$ represents the thermal stress, $\alpha$ is the coefficient of thermal expansion, $\Delta T$ stands for the temperature change, and $E$ denotes Young's modulus of the material.[4,5]

2. Salt Creeping Consideration

Salt creep is a significant consideration in the design and operation of oil and gas wells. When salt formations are penetrated during drilling operations, the salt around the wellbore begins to creep, causing the wellbore to be tight. This can lead to a number of problems, including:

- **Stuck pipe:** Salt creep can cause drill pipe to become stuck in the wellbore, leading to costly delays and damage.
- **Casing failure:** Salt creep can also cause casing to collapse, which can lead to the loss of the well.
- **Wellbore instability:** Salt creep can also cause the wellbore to become unstable, which can increase the risk of wellbore blowouts and other accidents.[6]

The rate of salt creep is influenced by a number of factors, including the temperature, stress, and composition of the salt. Salt creep is generally more rapid at higher temperatures and stresses. It is also more rapid in salt formations that contain impurities, such as clay.[3]

2-1 Salt Properties

Enclosed saline water evaporates and desiccates, forming salt deposits. Stress and compacting salt displace brine until the porosity is completely occluded as burial depth increases. High temperatures and stress can yield brine-filled porosity of 0.3 to 1.5%. Thin, dendritic voids at grain boundaries make up the remaining porosity. The permeability of unaltered salt is usually 10-21 m$^2$. Thus, flow is likely. via salt only occurs in non-salt lithologies around the salt body or in non-salt inclusions at well-engineering timescales. Natural rock salts range from 99% halite to diverse mineral combinations. Common salts and minerals found in salt deposits are categorized by chemical composition as follows: Sodium salts: halite (NaCl), potassium salts: sylvite, carnallite, poly-halite, sulphates: gypsum, anhydrite, langbeinite, kieserite, epsomite, kainite, and chlorides: bischofite and tachyhydrite. Halite is the most common drilling salt. However, pure halite often contains anhydrite, gypsum, and clay. GoM salt deposits are mostly huge halite deposits with an average purity of 96% and some trapped sediment inclusions. Extremely pure salt has an in-situ density of 2.16 g/cm$^3$. Due to its composition and impurities, impure salt has a somewhat higher density than pure salt. Salts with high clay impurities and shale interbedding can cause wellbore instability and tight hole conditions[7].

2-2 Salt Strength Property

Although there is little published information about sub/pre-salt formations’ strength, the limited data indicates an unconfined compressive strength (UCS) to range from 20.68 to 24.13 MPa (3000 to 3500 psi). Likewise, the same group of authors reported that the tensile strength of approximately one-twelfth of the unconfined strength was observed. In the case of polymineralic salt (non-single salt component), its strength will fall in between the strengths of their weak and strong constituents, following nonlinear proportionality between the strength values of these minerals. Therefore, proper laboratory testing is required to characterize salt strength [8,9].

2-3 Salt Formation Behavior

Salts formation considered one of the sedimentary rocks that called evaporates, resulted from the evaporation of the sea water. When under stress, salt rock acts as a visco-plastic material that tends to creep. Many factors influence the creep strain rate, such as the temperature[10].

- Temperature
- Differential pressure
- The confining pressure
- The grain sizes
- The presence of inclusions of free gas bubbles or free water.
There are two primary factors that cause salt creep: temperature differences and stress differences. If the temperatures and stresses are the same, the creeping strain rate of the rock tachyhydrite is two orders in magnitude quicker than halite rocks for the variables in the same, such as tension and temperature, Figure 1 shows the flow of salt and the deformation that occurs in the oil well string [6].

![Figure 1. Salt creeping scheme [10]](image)

2-4 Flowing Nature of Salt

Most rocks for petroleum engineering applications can be characterized as elastoplastic solids. However, materials with uncemented grains, like loose sands, immature shales, and salt do not behave elastically. These materials exhibit rheological behavior and undergo time-dependent processes such as creep (increasing strain under constant stress) and relaxation (decreasing stress under constant strain). These two processes are shown in figure 2. Creep is defined as the gradual flow of a crystalline material under a deviatoric load, which results in permanent distortion. Because of that, such materials can even fail under constant, maintained, long-term load or strain conditions. Salt is a specific engineering material with a pertinent behavior, unlike other materials such as consolidated rocks or metals. Due to their ductile characteristics, salts have a limited linear stress-strain curve extending over a small stress increment. At stress levels as low as 10 to 20% of its ultimate strength salt starts deforming plastically. Its stress-strain curve is very dependent on temperature, confining pressures, salt composition, water content, impurities, prior stress history, loading rate, etc. [6,7].
3. Aspects of Salt Creeping

It is the deformation of rock produced by dissipation of the strain energy resulting from stress reduction in an undisturbed salt rock mass. Well construction and operations are severely hindered when a well’s casing and pipe become caught and collapse due to creep closure. Casing failures in salt formations are common, even when the creep process is gradual. This is because the stress on the casing is greater than its mechanical strength, and this can lead to well closure and serious issues. Figure 3 depicts an example of an axial salt creep deformation curve [6,8].
caused by micro-fracturing during the tertiary creep stage, also known as the dilation phenomena. Tertiary creep in the surrounding salt rock is unlikely to occur during well bore completions due to the constraint on deformations. Two components can be used to define the creep rate in salt deposits as indicated above: [7,11].

one is known as the transient creep rate (εt), the second is known as the steady state creeping rate (εs). The overall rate of strain caused by creeping is given by:

\[ \varepsilon = \varepsilon_t + \varepsilon_s \]  

Because of the transient creeping that occurs immediately after excavation process & only lasts for short period of time, transient creeping is usually dissipated during cementing and drilling operations, which take days, if not weeks, to complete. So, it is reasonable to assume that the steady-state creep primarily contributes to the overall strain rate owing to creep and the relationship of is valid after the section of salt formation is cemented and cased [6,12].

3-1 Salt Creeping Determination Methods
Salt creep determination methods can be divided into two main categories: laboratory testing and simulations models. For Laboratory testing can be defined direct method for determining salt creep properties. It involves measuring the creep rate of salt samples under controlled conditions of stress, temperature, and humidity. A variety of laboratory tests can be used [13], such as:

- Uniaxial compression test: A salt sample is loaded in compression and the strain is measured over time.
- Triaxial compression test: A salt sample is loaded in compression and subjected to a confining pressure. The strain is measured over time.
- Point load test: A salt sample is loaded with two conical points. The load and displacement are measured. For Simulation models can be used to predict the creep behavior of salt formations [14]. These models are based on a mathematical understanding of the physical processes that control salt creep. Simulation models can be used to estimate the creep rate of salt formations under different conditions of stress, temperature, and humidity [15,16].

ABAQUS and FLAC 3D are two popular commercial software packages that can be used to simulate salt creep. ABAQUS is a general-purpose finite element analysis software package, while FLAC 3D is a software package specifically designed for geotechnical engineering applications. Many researchers have made significant contributions to the understanding of salt creep mechanics in oil wells through laboratory and simulation researches as shown in table 1 below:

<table>
<thead>
<tr>
<th>#</th>
<th>Author name</th>
<th>Year</th>
<th>Method</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Wang [16]</td>
<td>2004</td>
<td>Uniaxial compression testing</td>
<td>Salt creep is a time-dependent process that is accelerated by stress and temperature.</td>
</tr>
<tr>
<td>2</td>
<td>Dusseault et al [17]</td>
<td>2004</td>
<td>a tri-axial test &amp; changing the temperature repeatedly</td>
<td>The rate of salt deformation (creep rate) as shown in figure (2-4) is heavily affected by temperature in addition to being controlled by the stress variation between the salt rock and the well hydrostatic pressure</td>
</tr>
<tr>
<td>3</td>
<td>Liang et al [18]</td>
<td>2007</td>
<td>a tri-axial cyclic loading</td>
<td>The transient and steady-state strain rates exhibited a tendency to increase if the maximum applied stress increased or the minimum applied stress decreased</td>
</tr>
<tr>
<td></td>
<td>Author(s)</td>
<td>Year</td>
<td>Methodology</td>
<td>Summary</td>
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</tr>
<tr>
<td>4</td>
<td>Fjar et al [19]</td>
<td>2008</td>
<td>a tri-axial test</td>
<td>Thermos elastic strains are the result of even small variations of temperature that can be corrected if temperature during the experimental testing is recorded precisely</td>
</tr>
<tr>
<td>5</td>
<td>Nasehi [20]</td>
<td>2011</td>
<td>Tensile strength test</td>
<td>The cement-covered casings, the tensile stresses decreased with increasing cement thickness and the tangential stresses remained almost constant, whereas the majority of the radial stresses increased over the thickness of the cement.</td>
</tr>
<tr>
<td>6</td>
<td>Mansouri &amp; Ajallooeian [21]</td>
<td>2018</td>
<td>uni-axial compressional tests and creeping test</td>
<td>They found that the salt rock is ductile and that the creep rate increases with axial stress</td>
</tr>
<tr>
<td>7</td>
<td>Mohebi &amp; Jalalifar [22]</td>
<td>2014</td>
<td>Numerical model by Flac 3D</td>
<td>Over time, the higher strain caused by the absence of cement behind the casing can be reduce the casing resistance</td>
</tr>
<tr>
<td>8</td>
<td>Omoujuwa et al [23]</td>
<td>2010</td>
<td>Uniaxial compression testing, triaxial compression testing, point load testing</td>
<td>The octa-hedral shear values in salt formations prior to drilling are determined by the 3 main stresses exercised by neighboring formations, whereas the octa-hedral shear stress values in salt formations during or after drilling are determined by the minimum horizontal stress, wellbore pressure, wellbore radius, and radial distance from a selected stress center</td>
</tr>
<tr>
<td>9</td>
<td>Willson et al [24]</td>
<td>2004</td>
<td>Numerical model by Abaqus</td>
<td>Salt creep loading on well casings can be reduced by casing selection, design, well spacing, and production management.</td>
</tr>
<tr>
<td>10</td>
<td>Castagnoli et al [25]</td>
<td>2016</td>
<td>Analytical model</td>
<td>Developed a new way to monitor the wellbore diameter in salt formations while drilling. Their method uses a computer model to predict how the wellbore diameter will change over time.</td>
</tr>
<tr>
<td>11</td>
<td>Wang and Samuel [26]</td>
<td>2017</td>
<td>A 3D geomechanical model by Flac 3D</td>
<td>Salt creep behavior can be predicted by a 3D geomechanical model, which can provide information for wellbore casing design and assessment.</td>
</tr>
<tr>
<td>12</td>
<td>Gholami et al [27]</td>
<td>2017</td>
<td>A tri-axial test followed by a numerical model by Abaqus</td>
<td>Found that a thick salt layer in a well in southern Iran caused significant wellbore closure and viscoelastic salt behavior during drilling. They also observed a complex shift in the stress regime</td>
</tr>
<tr>
<td>13</td>
<td>Ghodusi et al [28]</td>
<td>2019</td>
<td>Numerical model by Abaqus</td>
<td>Casing construction flaws such as ovality, eccentricity, and residual stress could lessen the casing’s ability to resist collapsing</td>
</tr>
</tbody>
</table>
casing collapse could be significantly influenced by the creep of rock salt. Prior to reaching the constant value at oil reservoirs, the external pressure on the casing nearly doubled in comparison to the pressure at the beginning of production.

### 3-2 Mitigation Strategies of Salt Creeping

There are a number of mitigation strategies that can be used to reduce the risks associated with salt creep. These strategies include [29]:

1. Wellbore design: One way to make wellbores more resistant to salt creep is to use thicker casing. This will help to support the wellbore and prevent it from collapsing as shown in figure 4.

![Figure 4. Thicker casing for salt creep resistance](image)

2. Special casing designs: There are also a number of special casing designs that can be used to improve salt creep resistance. For example, some casing designs have a larger cross-sectional area, which helps to distribute the load more evenly. Other casing designs have a spiral pattern, which helps to stiffen the casing and make it more resistant to deformation [30].

3. Drilling in a less susceptible area of the salt formation: another way to reduce the risk of salt creep is to drill the wellbore in a less susceptible area of the salt formation. For example, salt formations often have layers of different strengths and compositions. Drilling in a stronger layer of salt can help to reduce the risk of salt creep.

### 4. Conclusion

Geomechanical factors exert significant influence on the stresses within salt formations, encompassing parameters such as pore pressure, fracture pressure, vertical stress, and total stresses. The Terzaghi equation stands as one of the foremost methods for calculating these stresses. Furthermore, the strain occurring within salt formations can be assessed through various creep laws, with the Bailey creep law being particularly pertinent, contingent upon material properties, stress levels, and temperature. Simulations such as Flac 3D, Abaqus, and Hysys prove invaluable in providing a comprehensive outlook on salt creep behavior over time, crucial for completion engineers in anticipating potential casing deformations and their consequences in oil wells. Temperature variation within salt formations emerges as a pivotal factor governing salt creep, with increased temperatures accelerating this phenomenon, corroborated by laboratory testing on salt formation samples. The temporal aspect also assumes paramount importance, as time plays a critical role in salt creep development post-drilling of oil wells. Salt creep engenders numerous challenges during and after drilling operations within salt formations. To address these challenges, it is imperative to control mud
weight effectively during drilling to manage or minimize salt formation creep. Subsequently, post-drilling, the adoption of appropriate casing designs, incorporating sufficient safety factors, becomes indispensable in mitigating the adverse effects of salt creep on oil well integrity and performance that can be optimized by Landmark software.

5. Ethics approval

The Institutional Ethical Committee (IEC) of IAU, Iran approved the study.

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References


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