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Long term creep closure of salt cavities

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ABSTRACT

We quantify the long term creep closure of salt cavities under in-situ conditions. We use an incompressible Carreau viscosity model to treat combined dislocation and pressure solution creep of rock salt. We build three material models based on the published compilations of experimental data. Analytical expressions are given for the maximum closure velocity under combined pressure and shear loads in the far field. A non-linear finite element model is used to study the apparent viscosity around a circular hole. In the low stress regime, depending on the grain size, creep rate can increase several orders of magnitude by the action of pressure solution. The influence of grain size dominates over all other parameters such as temperature or dislocation creep parameters. In general, pressure solution is dominant in cold fine-grained salts under low loads, while dislocation creep is dominant in warm coarse-grained salts under high loads. In the dislocation creep regime, the hole closure rate is n (stress exponent) times more sensitive to the far field shear stress than to the pressure differences. Significant hole closure can be reached in less than one day in very fine-grained salts under in-situ loads in the order of 1 MPa. A thorough understanding of salt grain size and water availability is needed to properly assess the relative contribution of dislocation and pressure solution creep in hole closure. A direct relationship relating grain size with deformation mechanism cannot be established in general. The closure of a cavity in a typical salt having a 10 mm grain size can either be dominated by pressure solution or dislocation creep depending on the temperature and salt type. Best practices to prevent hole closure include increasing hole pressure, and avoiding, when possible, the salt layers which are known to be fined-grained and under high deviatoric stress.

1. Introduction

Salt is present as massive bodies in many places around the world such as the Gulf of Mexico (Louann salt), North Sea (Zechstein salt) and Zagros mountain belt in Iran (Hormoz salt). Due to its properties, salt is relevant to many geomechanical applications. It creeps at engineering times scales, and it is soluble in water and fairly homogeneous. Salt has a very low permeability in the range 10^{-21} to $10^{-19} m^2$, almost no porosity, and a high thermal conductivity compared to other rocks,[1] which may lead to low geothermal gradients even below $+ 12°C$ per thousand meters.[2] Rock salt is usually considered to be halite (NaCl) in geomechanical studies, but other salt minerals exist like carnallite, bischofite or taquihydryte.[3,4] These minerals are much less viscous than halite under the same conditions[5] which results in much higher creep rates.

1.1. Applications concerned with salt creep

Due to the viscous behavior of salt, embedded cavities close with time if subjected to pressures lower than the surrounding lithostatic pressure. This time dependent hole closure is critical for geomechanical applications and a thorough understanding of the governing parameters is recommended.

Many underground applications are concerned with the time dependent closure of salt cavities including the shafts storing nuclear waste. Nuclear waste remains radioactive for millions of years and shallow salt domes around 800 m deep are used for disposal purposes as is done in the USA in the Waste Isolation Pilot Plant[6,8] and as is planned in Gorleben, Germany. The creep of rock salt combined with its excellent sealing properties insure that any access tunnel will naturally close with time trapping the nuclear wastes inside the salt formation for millions of years.

Storage caverns are another example of application concerned by the creep of rock salt. These caverns are created by solution mining and they are used to periodically store oil, gas,[7] CO_2,[2] compressed air[9] or hydrogen.[10] Their lifetime is in the order of tens of years. The ideal depth for storage caverns is considered to be between 900 and 1700 m[11] because the limited flow of salt at that depth ensures the

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sealing property of the storage and a relatively small loss of storage volume with time. The range of pressures allowed in these caverns is assessed based on the onset of tensile stress and salt dilation at the cavern wall[12] and is therefore dependent on the local conditions and use.

Other applications deal with the abandonment of the thousands of caverns that have been leached out in rock salt for storage or brine production. The characterization of cavern closure is important in this case to ensure the long term environmental safety of the abandonment.[13,14] One of the major uncertainties concerns the long term pressure evolution of the fluid trapped in the cavern. Thermal expansion of the brine due to temperature increase[1] coupled with the volume loss due to cavity closure increases cavern pressure,[15] while counteracting processes like gas leakage[16] and fluid permeation through the salt may also operate. The pressure difference during salt cavern abandonment remains therefore likely constant with time with reported values ranging from 1.9 to 7.5 MPa in shallow caverns.[1]

The oil industry also faces the problem of hole closure in rock salt but for high pressure and temperature wells going through sequences of salt up to 5000 m deep.[5,17–20] Drilling operations are very expensive, especially in deep offshore environments such as the Gulf of Mexico, and primary guidelines like increasing mud weight, reducing open hole time and cooling have been developed to minimize drilling problems associated with fast salt creep. The conditions encountered at these depths are extreme with temperatures above $100°C$ and fluctuations in pressure difference between -10 and 30 MPa[17] during drilling due to the movement of the drill string coupled with mud changes and the possible creation of washouts.

Finally, well abandonment methods have been proposed recently[21,22] that rely on the natural closure with time of wellbores in salt. The long-term prediction of well closure is critical to ensure that a proper seal is created. The choice of the emplacement of the plug is especially important and it requires that all the dependencies of hole closure are understood and accounted for before a decision is made.

1.2. Constitutive law

The modeling of hole closure in rock salt relies on the proper choice of the constitutive law. Several models have been developed to capture all aspects of salt deformation, such as the Munson-Dawson creep law,[23,24] the Lubby2 model[25] and the model based on a viscoplastic potential[26,27]. The plastic component of these visco-elasto-plastic constitutive laws can be dismissed at depths where the confining pressure is large enough to prevent dilation. A 5 MPa confining pressure is sufficient to suppress dilatancy under small to moderate deviatoric stress.[28] The viscous deformation mechanisms considered by the aforementioned constitutive laws focus on dislocation creep but do not take into account pressure solution.

Dislocation creep is a deformation mechanism stemming from the movement of dislocations inside salt grains and it is typically dominant at high rates of deformation and temperatures. It has been extensively studied under laboratory conditions and it is described using a power law stress dependence model.[29–31] Microstructural evidences showing the movement of dislocations in salt have been reported in samples from deep salt domes, where it is assumed to be the dominant deformation mechanism.[32]

Pressure solution is a water activated solution-precipitation process dominant at low rates of deformation,[33–36] during which grain boundary water dissolves salt at grain contacts and diffuses it away to precipitation sites. Primary depositional brine is widespread in natural halite[37,38] and it ensures that pressure solution is active to some extent. Around 10 ppm of brine is enough to consider salt as wet[33,39,40] and to activate solution-precipitation processes. The presence of solution-precipitation has been attested by the observation of the microstructure of deformed wet salts[4,33,41,42] as well as very slow creep tests showing water induced weakening and surprisingly high rates of deformation under low differential stress.[43–45] Pressure solution is strongly grain size dependent and efficient in fine-grained salts. Grain size in rock salt ranges from 0.5 to 1 mm in shear zones of extruding formations[32,42] to 12–50 mm in buried salt domes.[31,46–48] The grain size depends not only on the type of salt considered but also on the long-term deformation conditions such as the stress, temperature and water availability. It is therefore not straightforward to assess it in applications.

Deformation at typical halokinetic rates (1e-16 to 1e-9 s^{-1}) and temperatures (20–140 °C) falls in the transition between dislocation creep and solution-precipitation creep.[33,35,46,49–52] The grain size distributions in natural salt[35,49] also suggest that both mechanisms occur concurrently. A Carreau model,[53] an Ellis model[52] or a bi-linear model[43] can be used to simultaneously take both deformation mechanisms into account in a single constitutive law.

1.3. In-situ shear stress

The in-situ stress state in rock salt is often modeled using only pressure and shear components are dismissed.[1,17,20,21,54,55] This approach is motivated by the low viscosity of the salt, which relaxes the shear stresses over geological time scales. The deviatoric stress inside salt bodies is quite small and the methods used to measure stresses in boreholes do not have the precision to accurately quantify them. However, borehole ovalization has been recorded proving the existence of deviatoric stresses in salt bodies.[56] Estimates of the deviatoric stress can be obtained using analytical[57,58] and numerical[59] modeling, but they are usually developed by using the inverse relationship between subgrain size and stress.[50] This is referred to as stress piezometry and the original relationship[60] can be modified to include more dependencies such as temperature, grain size distribution parameters and deformation mechanisms.[39,61,62] Stress piezometry reports shear stress in the range of 1–5 MPa,[31–33,41,42,46,50] with lower stresses in buried salt structures (around 1 MPa) and higher stresses in extruding salt bodies (3–5 MPa).

1.4. Hole closure in salt

Measuring the closure of salt cavities directly is a difficult task due to the lack of accessibility and cost associated with it. Consequently, only limited closure data is available. Some data exist for well closure,[7,19,63,64] but it remains scarce and only shows closure under large loads in the short term (less than one year). In salt caverns used as storage facilities, closure has sometimes been recorded since their creation and more data is available. The technology used to measure the geometry of the cavern, i.e. sonars or lasers,[9,12] has however too low resolution to track changes and the cavern closure is estimated from the well-head pressure or from the flow rate of the expelled fluid.[65,66] The latter method is associated with many uncertainties which makes the interpretation of this data difficult.[43] Numerical and analytical modeling are therefore the only approaches available to study long term cavern closure in a systematic way. Complex rheological models for rock salt can be used in numerical models to investigate the closure associated with visco-elasto-plastic deformations.[25,67-69] These numerical models however often do not take into account pressure solution as a deformation mechanism. The studies that do consider it[14,21,22,43] only focus on pressure loads and dismiss the shear stress associated with flowing salt bodies. A systematic study of the combined impact of pressure solution and far-field shear stresses on cavity closure is therefore missing for rock salt.

1.5. Outline

The closure of cavities happens naturally in salt and the question arises of how fast it occurs. Dislocation creep and pressure solution are most relevant for long term salt flow and we use an incompressible Carreau model for viscosity to take both into account. In addition to