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Stability and serviceability of underground energy storage caverns in rock salt subjected to mechanical cyclic loading

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ABSTRACT

Solution-mined caverns excavated in rock salt formations are recognized as the appropriate places for underground storage of energy in the form of compressed air and hydrogen. These caverns are subjected to different loading conditions during the construction and operation time. Therefore, it is essential to investigate the mechanical response of rock salt for all life stages of the cavern such as leaching phase, debrining process, first filling as well as cyclic loading operation. To achieve this goal, proper constitutive laws are required to describe the material behavior of rock salt at different time scales. In this paper, an elasto-viscoplastic-creep model is employed to predict the stress-strain relation around the cavern during the construction and cyclic operation phases. The proposed creep law is a modified version of Norton creep law which accounts for the time-dependent volumetric deformation. Additionally, a damage parameter which is dependent on the released inelastic work is included in the model to predict the material failure. To accomplish this, first, the material parameters of the employed model are determined using the relevant experimental data available in the literature. Then, the excavation process and cyclic loading operation of a typical salt cavern are numerically simulated. The stress paths around the cavern as well as the volume convergence, damage propagation and permeability changes are evaluated considering two loading scenarios, and finally, the allowable operating conditions for the simulated cavern are identified.

1. Introduction

Nowadays, underground storage of compressed air and hydrogen in salt caverns is known as a promising technique to meet the energy demand fluctuations in electricity power grids. In contrary to the natural gas caverns which are utilized for the seasonal storage, the compressed air and hydrogen storage caverns operate with daily cyclic periods. For this reason, it is of vital importance to investigate the effect of cyclic loading operation on the stability and serviceability of this type of caverns. Obviously, accurate design and stability analysis of these underground cavities require adequate numerical simulations employing proper constitutive models to describe the material behavior of rock salt. Over the past four decades, numerous constitutive models have been developed in an attempt to predict the mechanical behavior of salt. Most of the models have been specifically derived to predict long-term creep deformations in caverns with relatively constant internal pressures. For example, an empirical creep model known as BGRa was introduced by Hunsche and Hampel[1] to describe the steady-state creep deformation of rock salt as a function of temperature and deviatoric stress. In another research, Heuserman et al.[2] introduced the Lubby2-model to describe both transient and steady-state creep phases using the Burgers viscoelastic model with stress-dependent spring and dash-pot elements. It should be mentioned that the inelastic volume changes were neglected in both BGRa and Lubby-2 models. Cristescu and Hunsche[3,4] formulated an elasto-viscoplastic constitutive law to model the transient and the steady-state creeps of rock salt considering the volumetric dilatancy and compressibility as well as the short/long-term failure. In the same line of thought, Desai and Varadarajan[5] presented a single surface plasticity model for the elasto-plastic characterization of rock salt in quasi-static tests. The extension of this model to viscoplasticity formulation was later reported in Ref. 6. Hou and Lux[7,8] proposed a modified version of Lubby-2 model by adding a plastic term which takes into account the irreversible volumetric deformations. The Hou/Lux model also accounts for damage progress in dilatancy zone and damage healing in compressibility domain for creep deformation. Similarly, Minkley and Muehlbauer[9] introduced a viscoelastic-plastic model by combining the Lubby-2 model with a plastic strain

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term derived from a modified non-linear Mohr-Coulomb criterion. Numerous investigations have been performed within the same framework. Among them, studies of Aubertine et al.,[10] Ślizowski and Lankof,[11] Fuenkajorn and Serata,[12] Ma et al.,[13] Weidinger and Hampel,[14] Munson,[15] Günther and Salzer,[16] Olivella and Gens[17] are worthwhile to be mentioned. Beside the material modeling investigations, several research studies have been conducted in order to simulate the large-scale underground storage systems using advanced numerical techniques. In these studies, various design aspects such as the optimal shape of cavern,[18] prediction of long-term failure due to the creep[19,20] and the tightness of cavern[1,22] have been investigated. Obviously, the safety assessment of rock salt caverns requires careful consideration of thermo–hydro–mechanical (and chemical) processes. These processes interact and influence each other in a complex manner. Additionally, they do not necessarily have the same spatial and temporal scales.[23] For example, the flow pathways created by the damage increase the permeability of rock and represent the potential risk for gas leakage around the cavern. Subsequently, if the pore pressure locally exceeds the minimum principal stress, the fluid infiltration in rock salt takes place and the local widening of grain boundaries occurs.[24] Under such conditions, the mechanical behavior of the rock salt is affected by the gas and liquid phases. On the other hand, the temperature of rock salt around the cavern may change due to the gas injection and withdrawal processes. This temperature change introduces additional stresses in a narrow zone around the cavern due to the thermal expansion and contraction.[25,26] Moreover, the temperature variation affects the rate of creep deformation and changes the cavern closure rate.[27,28] However, in this paper, the focus will lie on the mechanical modeling because of its fundamental role. As a consequence, the cavern model is simplified and the specific gas-brine-rock interactions are neglected for better understanding of the mechanical response of rock salt, especially with respect to the cyclic loading. In the past, rare investigations have been made to model the behavior of rock salt under cyclic loading conditions. Therefore, the modeling of salt caverns that work under cyclic loading conditions is still a challenging task. During the recent years, a limited number of experimental studies have been performed to assess the effect of cyclic loading on the mechanical behavior of rock salt with main focus on the fatigue failure and cyclic damage progress (e.g. see Fuenkajorn and Phueakphum,[29] Ma et al.,[13] Liu et al.[30] and Guo et al.[31]). The main objective of this research is to model the cyclic loading response of the rock salt around the underground storage caverns. To accomplish this, an elasto-viscoplastic-creep model combined with damage is employed. This model is implemented in the Code-Bright code which is a finite element program developed at the Department of the Geotechnical Engineering and Geosciences of the Technical University of Catalonia (UPC).[32] In most of the previous studies, the cavern construction process and its effect on the stress-strain distribution around the cavern have been neglected. Such simplifications may result in unrealistic stress state conditions at the beginning of cyclic loading operation. Therefore, in this paper, a numerical approach to simulate the cavern construction process is also given. The structure of this paper is outlined as follows: in Section 2, a brief explanation concerning the cavern construction process as well as cyclic loading operation is given. In Section 3, the employed constitutive model is introduced and in Section 4, the required material parameters are determined using the relevant experimental data. Finally, in Section 5, a numerical model to simulate the excavation process and cyclic loading operation of a typical underground storage cavern is presented. The stability and serviceability of the system are evaluated considering two loading scenarios and the allowable operating conditions for the simulated cavern are identified.

2. Construction process and cyclic loading operation of salt caverns

Caverns integrated with renewable energy systems are created in rock salt formations using solution-mining technique. A typical salt cavern is subjected to different loading conditions during the construction and operation time. In other words, the magnitude and rate of loading applied to the rock salt medium have various changes throughout the cavern's life. As schematically represented in Fig. 1, the solution mining process and cyclic loading operation of salt caverns are carried out in different phases which are explained as follows:

Initial phase: a bore hole is drilled from the ground surface down to a level equal to the bottom of the cavern. Then, two leaching pipes which are concentrically suspended into each other are run into the bore hole. Depending on the storage product and the geological formations, the depth of excavation may vary between 300 and 2000 m.[25] After drilling the well, the bore hole is cemented from the ground surface to the casing-shoe which indicates the top of the cavern (see Fig. 1a).

Leaching phase: in this phase, fresh water is continuously injected into the rock salt medium through the leaching pipes. The salt is dissolved by the water and the mixture of salt and water (brine) is transferred to the ground surface. Two different operational modes are used to ensure a controlled development of the cavern shape (see Fig. 1b). The leaching modes are defined as: (1) the direct leaching process in which the fresh water runs through the inner leaching pipe and the produced brine is transferred to the ground surface via the outer pipe and (2) the indirect leaching process in which the brine runs through the inner leaching pipe and the fresh water is injected to the rock salt medium via the outer pipe. By applying these two leaching modes and by shifting leaching pipes, the cavern is shaped. Leaching phase is relatively a long-term process. That means, depending on the volume of the cavern, the leaching time could range from one year to a few years.[33]

Debrining phase: debrining process is performed after leaching phase. In this phase, the brine remaining in the cavern is displaced by injecting gas (i.e. the storage products such as compressed air or hydrogen) into the cavern. The gas is injected through the outer pipe while the brine is extracted via the inner leaching pipe (see Fig. 1c). When the debrining process is completed, both leaching pipes are pulled out from the hole. The duration of this phase is less than leaching phase and it may take a few months to extract the brine from the cavern.

First filling phase: in this phase, the pressure inside the cavern reduces to the minimum required pressure. Then, the cavern is ready for the cyclic loading operation. This process is performed much faster than the previous phases. The time required for this phase could range from some hours to a few days.

Cyclic loading operation: the internal pressure of the cavern fluctuates within a predefined range due to the injection and withdrawal of storage product (see Fig. 1d). Depending on the type of the stored product and designed operating plans, the time period of cyclic loading could be in the range of some hours to a few days.

3. Constitutive modeling of rock salt

Polycrystalline halite rocks (rock salt) consists of grains of halite (NaCl), with diameter between 0.01 mm and several dm, containing impurities in solid solution, secondary mineral phases and fluids trapped in grain boundaries or in pores.[34] Under the influence of applied stresses, rock salt behaves in different ways in the stress space. Numerous experimental investigations performed by