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Parametric assessment of salt cavern performance using a creep model describing dilatancy and failure

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ABSTRACT

The present paper discusses a systematic approach to study the time-dependent performance of underground storage caverns in rock salt. An elasto-viscoplastic constitutive model capable of describing dilatancy, short-term failure and long-term failure during creep of rock salt was implemented in a Lagrangian finite element formulation. Using the finite element formulation, a series of numerical analyses was performed to investigate the influence of the cavern geometry and non-salt interbeds on the performance of underground storage caverns excavated in rock salt in the framework of large displacements. The attained results demonstrated the capability of the proposed approach in performance assessment of the underground caverns.

1. Introduction

As a consequence of the world's growing energy demands, underground storage caverns are being used for economical and safe storage of petroleum products. In this regard, rock salt is considered to be an ideal material for underground storage due to its low permeability, healing capacity and availability. Another benefit of the utilization of salt formations as media for underground storages is that caverns can be created in these formations by solution mining techniques, which are more economical than other conventional excavation techniques. As a result, underground storage caverns excavated in rock salt are playing a crucial role in providing storage capacity for petroleum products.

The stability of underground caverns excavated in rock salt is of vital importance for safe storage. The specific factors influencing the cavern stability are cavern internal pressure, cavern geometry, cavern depth and the mechanical behavior of the rock formation around the underground cavern. In addition, in the case of heterogeneous salt formations that are interspersed with non-salt sedimentary interbeds, the mechanical behavior of the interbeds has a dramatic effect on the stability of the caverns. Experimental evidence reveals that the crucial mechanical property of rock salt is the inelastic time-dependent or creep behavior that involves inelastic volumetric changes. The consequence of this behavior is that inelastic ground movement around an underground opening can progress for a long period of time, which brings about significant closure of the opening. Also, due to the viscoplastic behavior, stress relaxation can occur around the opening, which may lead to the instability of the cavern. Hence, in order to assure a safe storage, the influence of the above-mentioned factors should be taken into account in the stability analyses of the underground caverns.

So far, numerous viscoplastic constitutive models have been developed to describe the time-dependent behavior of rock salt. In this regard, Herrmann et al.[1,2] proposed an empirical creep model

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of rock salt for the Waste Isolation Pilot Plant known as WIPP creep model. The WIPP creep model is based on the existing creep models for metals, which neglect the inelastic volumetric changes. Aubertin et al.[3] and Yahya et al.[4] formulated a viscoplastic constitutive model in which a single set of equations and material parameters were used to represent the short-term and long-term ductile behavior of rock salt. In that research, it was assumed that the stress state remains far enough from the failure condition, and therefore the inelastic volumetric straining was not considered. Furthermore, in this regard, works of Shao et al.,[5] Zhou et al.[6] and others[7,8] are worth mentioning. Moreover, the development of efficient computational models for the time-dependent analysis of underground storage caverns has been one of the most important research activities.[9–20] In particular, Dawson and Munson[9] and Munson et al.[10] carried out research on the time-dependent deformations around an opening excavated in rock salt. In that research, a constitutive model of rock salt neglecting inelastic volumetric changes was developed and implemented into a finite element procedure neglecting large deformation effects to numerically simulate the creep deformation of rock salt around an opening. Heusermann et al.[11] presented a numerical procedure using finite element method and a creep model of rock salt neglecting inelastic volumetric changes to simulate the time-dependent behavior of underground caverns in rock salt and established a framework in which a method for the assessment of the stability and usability of the caverns is provided.

Mostly, creep models of rock salt have been developed based on existing viscoplastic models of metals. In these models, first, uniaxial constitutive equations are defined, and after wards they are generalized for triaxial stress state based on classical theory of plasticity. One of the drawbacks of these models is that they do not take into account the effects of confining stress, represented by the first invariant of stress tensor, on the creep behavior. Therefore, these models do not take into account the relaxation of confining stress during viscoplastic flow. According to these models, since only deviatoric stress relaxes during viscoplastic flow, the failure of rock salt as a function time has not been taken into account properly. In contrast, triaxial experimental measurements reveal that not only deviatoric stress, but also confining stress relaxes by time.[21–24] This means that unlike the prediction of conventional creep models, the stress state in rock salt can approach the failure criteria after a period of time. Another issue is that the conventional creep models cannot describe the inelastic volumetric changes including inelastic compressibility and dilatancy due to the opening and closing of microcracks during creep. Nevertheless, this behavior plays a vitally important role in long-term safety assessment of repositories in rock salt in terms of the seepage of stored fluid and cavern stability, particularly in case of the presence of non-salt interbeds. Therefore, these models cannot realistically reflect semi-brittle behavior of rock salt, microfracturing mechanism as well as failure mechanism in short-term and long-term. It should also be mentioned that large deformation effects are neglected in the majority of numerical models developed to analyze the behavior of underground caverns in rock salt. However, in long-term, the dimensions of deep underground openings in rock salt dramatically change which leads to large deformation of material elements near the opening surface. So far, several research works have been done to tackle the mentioned issues.[21–28] In some of these investigations, the aim is to incorporate damage mechanics into the conventional viscoplastic models to account for semi-brittle creep behavior. In this regard, investigations conducted by Chan et al.[27,28] are worth mentioning. Another remedy for the mentioned issues is to directly develop triaxial viscoplastic models based on triaxial experimental data. These models are capable of describing inelastic volumetric changes, ductile and semi-brittle creep behavior and failure in short-term and long-term.[21–26] In this regard, Cristescu[21] and Cristescu and Hunsche[22–24] proposed a viscoplastic constitutive model for rock salt to describe transient and steady state creep, inelastic volumetric changes, short-term failure and damage in the framework of small deformations. Jin and Cristescu[25] derived a transient creep model for rock salt which was more appropriate for numerical analyses. Paraschiv-Munteanu and Cristescu[26] formulated a semi-analytical procedure using finite element discretization to analyze the variation with time of the stress state in rock salt around a plane strain borehole during transient and steady state creep considering inelastic volumetric changes. This kind of constitutive model comprehensively describes rock salt behavior up to failure and provides an effective tool for the performance assessment of repositories in rock salt for long-term. However, so far, this model has not been implemented into a general numerical formulation, e.g. based on finite element or finite difference method, with the capability of modeling problems with different boundary and initial conditions to systematically conduct performance assessment of repositories in rock salt for different conditions. Another issue is that large deformation effects are neglected in this model. In this regard, Wang et al.[16] utilized the WIPP creep model neglecting semi-brittle behavior, inelastic dilatancy and large deformation effects to analyze time-dependent behavior of repositories in rock salt with the presence of non-salt interbeds using finite difference method. Then, the criteria developed by Cristescu[21] for inelastic volumetric behavior of rock salt during viscoplastic flow were employed by the authors to assess the obtained numerical results to discuss about the caverns performance in terms of seepage and stability. However, the creep model utilized in that research could not evaluate inelastic volumetric changes and relaxation of confining stress during viscoplastic flow, which forms the basis of the utilized criteria. Also, in that research, since a comprehensive failure criterion was not defined, very large displacements are predicted without indicating any failure in rock salt. In the present paper, efforts have been made to formulate a numerical model capable of resolving the mentioned issues. Also, systematic numerical analyses were performed to show the capabilities of the model in design and performance assessment of repositories in rock salt in long-term.

In the present paper, the performance of underground caverns in rock salt as a function of different factors is investigated. To this end, an elasto-viscoplastic constitutive model is employed to represent creep, dilatancy, short-term failure as well as long-term failure behavior of rock salt. The constitutive model is employed by a Lagrangian finite element algorithm to simulate the time-dependent response of underground openings excavated in rock salt in the framework of large displacements. A series of finite element analyses is carried out to investigate the influence of different parameters, namely side wall slope, cavern floor and roof shape, height-to-diameter ratio as well as non-salt interbed number and location, on the performance of the underground caverns. In these analyses, the mentioned parameters are varied to determine their effects on the cavern performance.

2. Elasto-viscoplastic constitutive model

Based on experimental evidence, it can be postulated that the creep deformation of rock salt is comprised of three phases, namely transient (initial), steady state (secondary or stationary) and accelerated (tertiary) creep.[29] In the transient phase, creep deformation continuously decreases in time up to a stable state, while, in the steady state phase, creep deformation progresses with a constant rate under constant or nearly constant stress state. Also, if rock salt reaches the creep failure condition, tertiary or accelerated creep phase is encountered where creep deformation