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Numerical modeling of thermally-induced fractures in a large rock salt mass

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ABSTRACT

Numerical modeling of thermally-induced fractures is a concern for many geo-structures including deep underground energy storage caverns. In this paper, we present the numerical simulation of a large-scale cooling experiment performed in an underground rock salt mine. The theory of fracture mechanics was embedded in the extended finite element code used. The results provide reliable information on fracture location and fracture geometry. Moreover, the timing of the fracture onset, as well as the stress redistribution due to fracture propagation, is highlighted. The conclusions of this numerical approach can be used to improve the design of rock salt caverns in order to guarantee their integrity in terms of both their tightness and stability.

1. Introduction

The fracturing of rocks developed by thermally generated stress is an important subject for many geo-structures. These include geothermal systems where large temperature variations are naturally developed in the rock mass. In this case, thermally-induced fractures are beneficial as they facilitate the fluid flow and increase the exchange surface (Tarasovs and Ghassemi, 2011; Ghassemi and Tarasovs, 2015; Pellet, 2017). In other situations, the fractures are unwanted. This is the case for underground caverns for the storage of hydrocarbons (gas and oil) or energy.

In recent years, new concepts for underground energy storage appeared to cope with the fluctuating consumer demand (Thoms and Gehle, 2000). These innovative modes of energy storage (such as compressed air energy storage (CAES), and high-frequency cycled gas-storage cavern) are characterized by large withdrawal rates and high operation frequency (Ibrahim et al., 2008). The quick gas depressurization due to the withdrawal of massive amounts of gas leads to large decreases in temperature inside the storage cavern. According to Bérest et al. (2012), the temperature drop can be in the range of several dozens of degrees, depending on the withdrawal rate.

For a long time, rock salt has been considered to be an ideal medium for energy storage caverns because of its low permeability and self-healing ability (Gloyna and Reynolds, 1961; Cosenza et al., 1999; Chen et al., 2013). However, the relatively low tensile strength of rock salt combined with the intense operating conditions raises concerns about the integrity of salt caverns (Sriapai et al., 2012; Missal et al., 2015; Wisetsaen et al., 2015). More specifically, the tensile stress induced by temperature drops can exceed the tensile strength of rock salt and generate fractures that create pathways for gas leakage. In severe circumstances, these fractures propagate deep inside the rock mass, triggering instabilities such as collapse of the cavern roof or walls. Actual observations of thermal fractures and several spalling events induced by temperature changes in gas caverns were documented and discussed in Pellizzaro et al. (2011), Zapf et al. (2012), and Bérest et al. (2014). Additionally, the thermal fractures may act as seeding fractures where high pressure can penetrate and cause stress concentrations at the tips of these thermal fractures pushing them to propagate further.

Several accidents occurred in underground storage caverns, which led to the development of more comprehensive approaches for the design of underground salt caverns (Bérest and Brouard, 2003). Several constitutive laws or stability criteria have been derived to account for the more complex behaviors observed in rock salt (Cristescu, 1993; Nazary Moghadam et al., 2015). However,

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these time-dependent constitutive laws are only relevant for describing the long-term behavior of rock salt under compressive stresses, whereas the short-term behavior under tensile stresses is predominantly elastic-brittle (Bérest and Brouard, 2003).

Meanwhile, numerical modeling using the finite element method (FEM) has been extensively utilized for cavern design (Dawson et al., 2000; Wang et al., 2013; Deng et al., 2015). However, the classical numerical approaches (e.g. FEM) do not account for discontinuities (i.e. cracks and fractures) that can be generated due to excessive tensile stress. To address this problem, new numerical methods have emerged, such as the extended finite element method (XFEM), in which fracture mechanics theory is embedded. XFEM allows modeling generation and propagation of cracks of arbitrary geometries without the need to remesh the domain under study.

The focus of the current paper is to model the fracturing process in rock salt due to rapid cooling. A large-scale cooling test performed in an underground salt mine is modeled using XFEM. In the following, we first summarize the experiment, followed by a numerical simulation of heat transfer and fracturing. The numerical results are discussed and compared with the measurements and observations from the experiments.

2. Main outcomes of the cooling experiment

The primary objective of the cooling experiment was to verify if a temperature drop is capable of generating fractures in the walls of salt caverns. If so, the secondary objective was to quantify the characteristics of the fractures (e.g. depth and aperture) in order to assess the actual consequences for a storage facility.

2.1. Test setup

The experiment was conducted in a 120 m-deep salt mine located in a thick layer of rock salt from the Keuper lithostratigraphic unit. A full description of the experiment can be found in Hévin et al. (2016).

In the main gallery (Fig. 1), a niche was purposely excavated to house the experiment. The dimensions of the niche are 17.5 m in length, 12 m in width, and 4.5 m in height. The salt block used for the cooling experiment was left unexcavated and has a thickness of 1.5 m (Fig. 1b). A section of the niche floor (dimensions of 3.6 m × 3.6 m) was isolated by a chamber (Figs. 1 and 2a), in which the temperature could be regulated by a refrigeration system and fans.

In order to release the initial horizontal stresses in the salt block, two parallel slots were dug close to the niche wall (Fig. 1a). Before starting the cooling test, these two slots (1.5 m in depth) were backfilled with salt powder that has a porosity of about 30%.

2.2. Testing procedure

During the experiment, three cooling–heating cycles were performed using the refrigeration system and the four fans installed in the cooling chamber. Each cycle consisted of a 28-d cooling stage, during which air temperature inside the cooling chamber was decreased from 14.5 °C (initial temperature in the gallery) to around −9 °C, followed by a 28-d heating phase. A fourth cooling phase, which also lasted for 28 d, followed the first 3 cycles, and the air temperature decreased to −25 °C. The time evolution of the air temperature inside the cooling chamber during the first cooling phase is shown in Fig. 2b. The temperature decreased to −9 °C within 1 h after starting the experiment. The peaks in temperature observed on days 6, 7 and 15 were due to unexpected opening of the cooling chamber's doors and power supply failures.

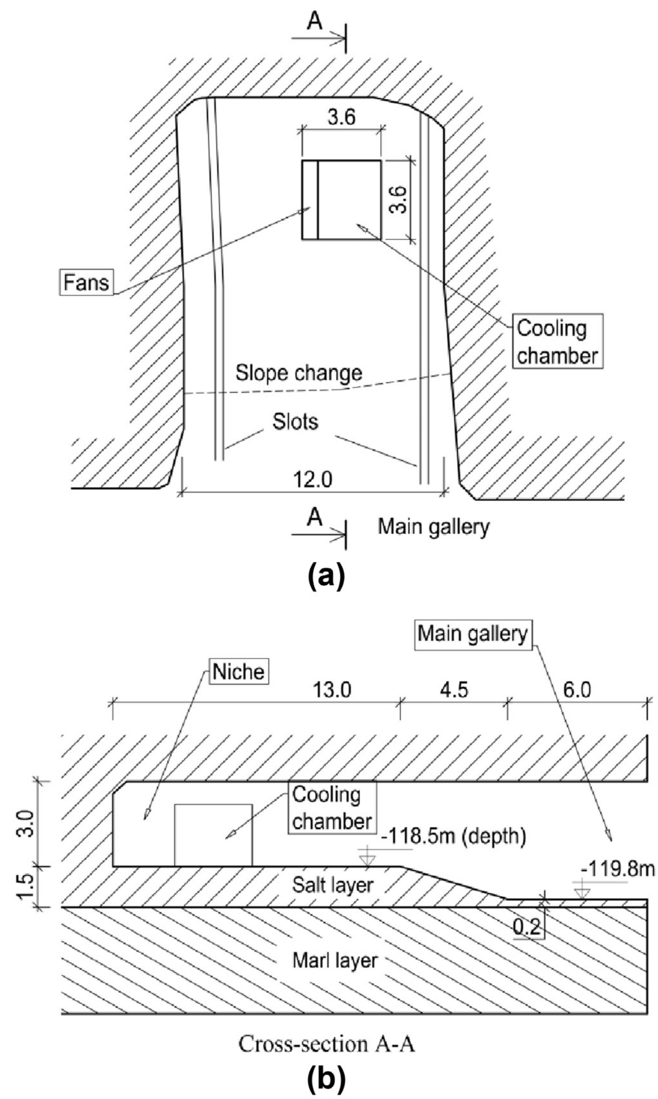

Fig. 1. Geometry of the gallery and position of the cooling chamber (adapted from Hévin et al., 2016). (a) Top view; and (b) Cross-section *A-A*. Dimensions are given in m.

To minimize heat losses by convection, the floor around the cooling chamber was covered with an insulating material. A view of the cooling chamber including the layout of the insulation is shown in Fig. 2a.

2.3. Temperature monitoring

Extensive monitoring was carried out during the test. Thermocouples were installed to monitor the temperature on the floor both inside and outside the chamber, and at different depths inside the chamber. Additionally, optical and infrared images were shot at different times to follow the initiation of cracks and their propagation. Fig. 3 shows the layout of thermocouples and a view from inside the cooling chamber. The main thermocouples of interest include the ones on the floor, designated by K and S, located along the lines $X = 2.3$ m (referred to as the main profile) and $Y = 1.4$ m (the transverse profile); and the ones at depths of 0.2 m, 0.4 m and 0.8 m from the floor's surface, respectively designated T3, T4 and T5.