International Journal of Rock Mechanics and Mining Sciences 102 (2018) 120–130

Contents lists available at ScienceDirect

International Journal of
Rock Mechanics and Mining Sciences

journal homepage: www.elsevier.com/locate/ijrmms

Experimental and numerical investigation into rapid cooling of rock salt related to high frequency cycling of storage caverns

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ARTICLE INFO

Keywords:
Field test
Temperature drop
Tensile stresses
Salt caverns
High frequency cycling
Thermo-mechanical modeling

ABSTRACT

High frequency cycling of salt caverns is becoming common practice to meet the needs of energy markets and to foster underground energy storage. In the case of rapid cooling, tensile stresses and thermally-induced fractures can appear in the surrounding rock, with potential detrimental consequences to the integrity of the storage project. To further investigate the effects of rapid cycles on the integrity of rock salt, a thermo-mechanical test was performed in a salt mine. It consisted in cooling rapidly several times a salt surface of 10 m^2 ($\Delta T = -20$ °C in about 8 h). Extensive monitoring allowed tracking the thermo-mechanical response of the rock, including possible fracture creation and propagation. Although more research is needed, the test demonstrated that tensile fracturing due to rapid cooling is possible. Thermo-mechanical modeling allowed reproducing fairly well the location, orientation and timing of the first fracture; indeed, fractures should be avoided to ensure cavern integrity, and therefore knowledge about the critical zones where fractures could appear is sufficient at the design stage.

1. Introduction

Leached salt caverns have been used since the late 1940s to store (or dispose of) fluids underground.[1–4] The main factors leading to this success are the very low porosity and near-zero permeability of undisturbed rock salt.[5–7] In addition, the deliverability rate of salt caverns is much higher than that of depleted reservoirs or aquifers.[8] Among the stored fluids, hydrocarbons (oil, natural gas) have dominated in the storage facilities worldwide. Apart from strategic storage, these fluids are typically injected when the demand is low (summer) and withdrawn when the demand is high (winter); in such scenario, caverns undergo yearly cycles during which the stress state and temperature change at the cavern wall and the surrounding rock. The mechanical stability and hydraulic tightness of salt caverns for hydrocarbon storage have been widely investigated (see for instance[5,9–14]). Since temperature changes are small for low injection/withdrawal rates, thermal effects do not propagate far from the cavern wall and are often neglected.[15]

In the recent years, the liberalization of energy markets and the use of the underground to foster renewable energy penetration in the energy matrix have brought about new scenarios in which new fluids and operating conditions are encountered. Specifically, compressed air energy storage (CAES) in salt caverns is raising attention,[16] and a move towards high-frequency cycles (i.e., weeks, days or even less) has been observed for natural gas and hydrogen.[17,18] These operating conditions need to be thoroughly investigated because in the case of a rapid depressurization, the gas cools down quickly and heat transfer with the surrounding host rock is limited. Thermal contraction of the rock occurs, which can lead to the onset of tensile stresses. Since the tensile strength of rock salt is quite small (1–2 MPa), tensile stresses must be managed (better avoided) to preserve the barrier integrity of the salt rock mass. Some numerical studies suggest that tensile stresses induced by rapid cooling are transient by nature, and also that the depth of penetration of possible thermally-induced fractures is small; consequently, cavern integrity is unlikely to be threatened.[17,19–23] Since salt caverns are not accessible, experimental evidence that could support or contradict the numerical predictions is limited,[24,25] and as a result a sound conclusion has not yet been reached. In order to gain more insight, the Solution Mining Research Institute (SMRI) has launched a research program to further investigate the effects of high frequency cycling on the integrity of rock salt.

In the context of the SMRI research program, a thermo-mechanical

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https://doi.org/10.1016/j.ijrmms.2018.01.008
Received 31 July 2017; Received in revised form 4 December 2017; Accepted 1 January 2018

test was performed in a salt mine in North-Eastern France. This unique test consisted of three cooling-warming cycles followed by two cooling stages applied to a salt surface of 10 m^2. The cooling was applied rapidly ($\Delta T = -20°C$ in about 8 h), and monitoring of the test was extensive to allow investigating the thermo-mechanical response of the rock, including possible fracture creation and propagation. In this paper, we first describe the field test and its principal outcomes. Then, we present results of thermo-mechanical modeling performed after the test to help interpret the experimental data and to evaluate the capabilities of the numerical tools commonly used in cavern design to reproduce the test results, and in particular, the location, orientation and timing of the first fracture. A continuum approach is used, since fractures should be avoided to ensure cavern integrity, and knowledge about the critical zones where fractures could appear is sufficient at the design stage. As it will be shown, the agreement between measurements and simulation results is quite satisfactory. Overall, even if more research is necessary, this experiment has demonstrated that rapid cooling of rock salt can lead to thermally-induced fracturing. In this sense, current design criteria and operational conditions of salt storage caverns should be adapted to minimize the effects of rapid depressurizations.

2. Field test at the Varangéville mine

A salt slab was selected to investigate the impacts of rapid cooling on the thermo-mechanical behaviour of rock salt. The test was performed in the Varangéville salt mine (North-Eastern France). This mine is operated by the room and pillar method and is located at the base of the third layer of the Keuper salt formation, where the global salt content is around 94%. The salt layer sits above a marl layer and underneath a sandstone-marl layer. For the purposes of the experiment, a dead-end gallery (niche) was excavated at a depth of about 120 m, with dimensions $17.5 \times 12 \times 4.5$ m^3 (length, width, height). To perform the test, a $13 \times 12 \times 1.3$ m^3 slab was left unexcavated at the floor of the niche. The distance from the top surface of the salt block to the salt-marl contact is about 1.5 m.

In order to isolate the effects of rapid cooling on the stress state, the influence of the in situ stress field was minimized. For this purpose, two vertical slots were cut parallel to the niche axis, at a distance of 1.1 m and 0.7 m from the West and East walls, respectively. The slots were 0.1 m wide and 1.5 m high, and were backfilled prior to the test to prevent heat convection. Thanks to the slots, the salt block is free at four surfaces: top, front and two sides. Fig. 1a shows a plan view of the experimental niche.

After excavation, the block was analyzed to identify possible cracks caused by the niche excavation or related to the salt structure (desiccation cracks, etc). Based on this analysis, it was decided to conduct the experiment in the rear part of the slab, close to the niche end. A square surface of 10 m^2 was conditioned on top of the salt block to perform the test. The experimental surface can be seen in Fig. 1a. On this surface, an experimental chamber was built; it allowed cooling the salt surface and the underlying salt rock mass. Fig. 1b shows an outside view of the chamber and Fig. 1c shows a view of the inside with some equipment (details will be given below). The chamber was designed so that a temperature drop of 40 °C could be applied to the salt surface (from the ambient temperature to about −25 °C). The cooling device consists of a 7.5 kW refrigeration unit that cools down the air inside the chamber. In order to keep the niche temperature as constant as possible, the compressor was placed in the access gallery, next to the niche entrance. The mine is ventilated, and temperature is about constant in the drifts (14.5 °C approximately at a depth of 120 m, corresponding to the geothermal gradient).

To ensure a uniform cold production inside the chamber, the cold air was blown through an evaporating system placed in the ceiling along the right (East) wall of the room. To reduce heat losses below the walls and through the rock mass outside the chamber, a 20 cm thick rockwool insulation cover was placed on the salt floor around the chamber during the cooling stages. The insulation cover is displayed in Fig. 1b. The optimal distance from the chamber that should be insulated was estimated numerically to be about 2.5 m.[26] This way, the energy required to cool down the salt surface is reduced by 30%, yielding 150 W/m^2.

In order to enhance the convective flux inside the chamber (and therefore, the transfer of thermal energy with the rock), eight fans were placed on the floor next to the left wall (nominal range of 9.5 m/s); they can be seen in Fig. 1c. The air speed is thereby increased, which increases the heat transfer coefficient between the air and the salt surface.

During the experiment, three cooling-warming cycles were performed, followed by two additional cooling phases. For each of the cycles, the cold air flow was applied for 28 days and the average temperature of the salt surface decreased to about −6 °C. Then, the air flow was stopped for at least six weeks so that temperature inside the chamber and in the salt block could equilibrate with the mine temperature (to facilitate warming, the insulation cover was removed during the warming periods). The last two stages consisted in cooling the salt surface down to temperatures of −6 °C and −25 °C for a time period of 14 and 21 days, respectively. They were conducted to investigate the effects of a further decrease in temperature on the stress state and on the onset and propagation of possible cracks. Fig. 2 displays the loading history (measured air temperature in the chamber over time). As the figure shows, during each cycle the air temperature reached −8.5 °C (−27 °C for the last stage) in a very short time (about 8 h). Likewise, the temperature rise was very fast during the warming phases, although about three times slower than the cooling rate. At the end of the first four cooling stages, the air temperature reached −9 °C (−27.6 °C for the fifth stage).

An extensive measurement program was defined to get as much insight as possible.[26] Temperature sensors (Pt100 and thermocouples) were installed at different locations inside the chamber and outside the chamber below the insulation cover. Inside the chamber, they were placed at the salt surface, at 1 cm depth and in a vertical borehole drilled at the center of the room, allowing to sample temperature as deep as 80 cm. Outside the chamber, the sensors were placed at a depth of 1 cm. The heat flux between the air and the salt surface was also measured, using a flux sensor placed on the floor, in the central part of the chamber. Strain gauges were placed on the salt surface and in the central borehole. An ultrasonic network was also set up, comprising 5 emitters and 12 receivers (see Fig. 1c). To get three-dimensional gridding, the receivers were placed on the salt surface and underneath; for this purpose, 4 inclined boreholes were drilled from outside the chamber to a depth of 60 cm below the test surface. An imaging system was also set up; it allowed tracking the formation and propagation of possible fractures. Four digital cameras (resolution of 3 px/mm) attached to the ceiling of the room covered the entire floor of the chamber. A rotating infrared camera was also placed at the ceiling to track the room surface temperature. All these techniques allowed a full characterization of possible fractures: time of creation, location and orientation, size, number, etc.

During the first cycle, a macro-fracture was visible after about six hours of cooling. It was located perpendicular to the air flow, about one meter from the fans (area with coldest temperature), and extended rapidly over more than one meter. At the end of the first cycle, the crack aperture was less than 1 mm (measured with dial gauges). In addition to this macro-crack, many micro-cracks (imperceptible to the naked eye) were present over the entire surface at that time. They were closed and shallow in appearance. In subsequent cycles, pre-existing fractures reopened and spread. Additionally, new cracks were created. Therefore, a fracture network developed progressively during the cycles; however, it should be noted that the extension of the cracks decreased with the number of cycles. Measurements from acoustic emission are consistent with the images interpretation[27]: the number of events reduced from one cycle to the next, with the first cycle producing 2–3 more events than the rest. Fig. 3 shows the visible fractures developed throughout the experiment. It can be seen how these fractures tend to join over time. At the end of the test, the maximum crack width was 1–1.2 mm. The analysis of the last cooling stage shows that a further temperature