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Acoustic monitoring of a thermo-mechanical test simulating withdrawal in a gas storage salt cavern

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ABSTRACT

Natural gas storage in salt caverns requires fast injection / withdrawal cycles due to the increasing dynamics of the energy market. High rates induce rapid changes in the internal pressure of the stored gas causing important temperature changes susceptible to damage the rock salt mass. To experimentally observe this, the Starfish project aimed to characterize the damage caused by purely thermal stresses at the surface of a large bloc of rock in the salt mine of Varangéville (France). The objective was to determine the type of failure mechanism involved with repeated cooling stages. Since the salt is favourable to the generation of Acoustic Emissions (AE) and the propagation of stress waves, acoustic monitoring was chosen as one of the methods to follow the impact of the salt cooling. In addition to thermal and mechanical sensors, an acoustic monitoring device consisting of 16 ultrasonic sensors was installed on the free surface and in boreholes. It enabled to record and locate a large number of AE (58,426) located with good accuracy (2.5 cm). Those AE can be correlated to the evolution of salt fracturing. Acoustic activity is very intense at the start of each cooling cycle, then decreases with time to reach a very low level (background) after about 15 days. The average localisation depth reached by the AE is about 90 cm during the first cooling period. For subsequent cooling cycles, this depth is limited to 74 cm. These results show that the first cooling period is decisive, as it contains the strongest and deepest acoustic emissions.

1. Introduction

Natural gas storage in salt caverns requires increasingly rapid injection / withdrawal cycles due to the new dynamic energy market. These cycles are accompanied by rapid fluctuations in the pressure of the stored gas, and then by major temperature variations that may damage the salt cavern. This type of thermal damage due to hot exhaust gases has been observed in the case of a granite formation.[1] Several theoretical studies have been carried out to estimate the amplitude of induced damages in the salt.[2,3] In order to observe this damage in situ, the SMRI (Solution Mining Research Institute) selected the Starfish project led by Storengy in partnership with Mines-ParisTech, Ineris and Salins du Midi. The purpose of this project was to cool down a salt block to reproduce the thermal solicitations applied to the surface of a salt cavern. The main objective was to initiate and describe the damage caused to the surface of the deposit by stresses of a purely thermal origin. It involved finding out the type of fracture mechanism that occurred and the nature and extent of the fractures. It also involved highlighting possible regression or amplification phenomena damaging the rock salt with repeated cooling cycles. The study was carried out in partnership between the parties involved in the project. Excavation and development of the mine gallery were performed by Salins du Midi, designing and setting up the cooling system, the visual monitoring and part of the geotechnical monitoring by Mines-ParisTech, and a second part of the geotechnical and acoustic monitoring by Ineris. This last part is presented in this paper.

Acoustic monitoring of the rock damage has been used several times during mechanical tests. King et al.[4] highlighted a correlation in the laboratory between acoustic emissions (AE) and fracture density during triaxial tests on sandstone. Dahm[5] and Moriya et al.[6] studied acoustic activity in the salt. They demonstrated that this material shows an intense acoustic activity under mechanical loading with dominant shear mechanisms and minor attenuation of the mechanical waves due to its crystalline structure. Acoustic emissions of thermal origin were studied

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essentially during warming phases that exceeded the thermal amplitude expected in gas storage: 550 °C in salt,[7] 200 °C in marble and sandstone,[8] or 800 °C in concrete.[9] Dahm[7] and Vasin[8] indirectly studied ae during cooling phases after preliminary warming. They demonstrated that acoustic activity reached a peak when cooling began, i.e., when the heat source was cut off. However, this comparison is narrow-limited, as the damage mainly occurs during the warming phase. The starfish experiments could have followed a similar, and hence better-known protocol. Instead of this, the focus of the experiment was to control the cooling phase to analyse the damage due to cooling. Indeed, thermal contraction of the rock occurs, which can lead to the onset of tensile stresses that can exceed salt resistance (around 1–2 MPa) and therefore initiate damage. Warming can also generate damage with shear stresses (spalling). However, it is necessary to have larger thermal amplitudes than for cooling to exceed the salt resistance. This mode of damage is not observed in this study.

As salt is a favourable medium for the generation of AE and the propagation of their signals, the acoustic monitoring method was chosen for monitoring the cooling phases. It is expected that this method will enable to quantify and locate the damage in the stressed deposit. Several special methods were used in this study for locating acoustic emissions and estimating their magnitude and mechanisms. The implementation of the experiment and the results obtained are set out in this paper.

2. Experimental design

2.1. Experimental setting

The experimental site is located in a blind gallery in the Varangéville salt mine excavated for this purpose by the operator, Salins du Midi (Fig. 1). The experiment covers a 10 m^2 horizontal area of the salt deposit at the most homogeneous location in the gallery. In particular, the experiment had to take place at a distance from the walls and to avoid the drying cracks (dotted line on the Fig. 1) that formed at the time when the salt was deposited to have an homogenous rock volume. To perform the test, a $13 \times 12 \times 1.3\,m^3$ slab was left unexcavated at the floor of the gallery. 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 a 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 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.

This salt (94%) is mineralised on a macroscopic level with centimetre-sized crystals. Its mean density is 2.2. The Young's modulus and Poisson's ratio of the salt are 25 GPa and 0.25, respectively, with a uniaxial compressive strength of 30 MPa, and a tensile strength of 1–3 MPa. Its thermal expansion coefficient is 3.8×10^{-5}/°C. For the rest of the study, the tensile stress-strain values are negative by convention.

A cold chamber was installed by Armines[10] over the prepared area. The cold chamber comprises five insulated faces with two access doors (north and south faces); the evaporator of the cooling system was fixed on the ceiling along the east side and a ventilator unit was set up on the floor along the west side. 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 mine is ventilated, and temperature is nearly constant in the drifts (14.5 °C approximately at 120 m depth, according 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 chamber.

The salt deposit was subjected to four cooling cycles with a set point temperature in the cooling chamber of −9 °C over a minimum period of twenty-eight days for the first three cycles. The main purpose was to compare how the damage develops as the cooling cycles progress. The warming phase between cooling cycles varies (from one month between the 1st and 2nd cycle to 2 months between the 2nd and the 3rd cycle) (Fig. 2) as it is not controlled and is accompanied by substantial condensation which required the surface and the sensors to be systematically reconditioned. The last cooling phase, not planned in the experiment, took place in two stages, the first one lasted fourteen days only at −9 °C and the second one 22 days at −27 °C. The main purpose of this last cycle was to monitor the damage under increased stress.

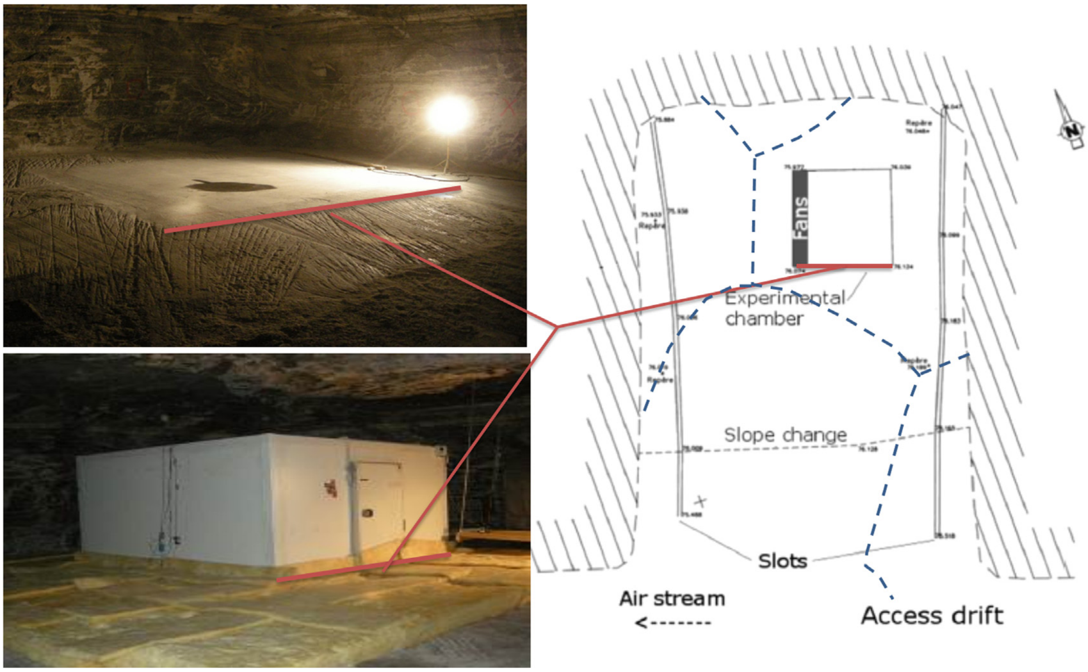

Fig. 1. Localisation of the deposit and position of the cooling chamber in a Varangéville mine gallery (Salins du Midi).