Mechanical stability of a salt cavern used for hydrogen storage

Hippolyte Djizanne
Ineris, Verneuil-en-Halatte, France

Benoit Brouard
Brouard Consulting, Paris, France

Grégoire Hévin
Storengy, Bois-Colombes, France

ABSTRACT: Underground salt cavern storage is recognised as one of the most suitable technologies to meet the challenges of the new European energy system. With the advantage of being mostly impermeable to gases, salt caverns are currently the only structures used to store hydrogen on a massive scale underground. This paper studies the consequences of a rapid withdrawal of hydrogen on the mechanical stability of a salt cavern. Gaseous hydrogen cooling could generate rock salt dilation, cavern closure and tensile stresses at the cavern wall. Numerical computations using the finite element method help to evaluate the geomechanical consequences of a rapid depressurisation in a selected cavern for an underground hydrogen storage demonstrator in France.

Keywords: salt cavern, hydrogen, worst-case scenario, salt dilation, effective stress.

1 CONTEXT

Europe has made the development of green hydrogen a priority in its strategy to address climate change. This ambition paves the way for a decarbonised hydrogen industrial sector. Hydrogen as an energy vector provides viable solutions to replace polluting and carbon-emitting fossil fuels. In recent decades, underground hydrogen storage in salt caverns has emerged and is already in operation in the United Kingdom and the United States. Underground storage of large quantities of gaseous hydrogen in salt caverns (based on the example developed for natural gas by providing seasonal capacity) is a solution to promote the decarbonisation of energy by making renewable hydrogen available anytime for mobility, industry and domestic heating.

The European HyPSTER project (2021-2023), coordinated by Storengy, aims to demonstrate the feasibility of operating underground hydrogen storage in salt caverns on an industrial scale, i.e. to ensure storage replication across the European Union. In this context, a pilot site is planned in France in 2023 at Bresse Vallons (Ain) for storage replication on France's most studied salt cavern (Djizanne et al. 2022). The control of industrial risks around this emerging technology and its environmental impact remains essential for public acceptance. The safety of hydrogen storage includes tightness issues but also structural stability. This paper focuses on the mechanical stability of a salt cavern submitted to a rapid gas depressurisation following a fast hydrogen withdrawal from the cavern.

2 INTRODUCTION

Hundreds of gas storage facilities in salt caverns, mined caverns, depleted reservoirs or aquifers have been in operation for decades. Underground hydrogen storage thus benefits from the experience acquired in "mature" technologies. The containment of products, the tightness of wellheads and cementing, the mechanical stability of structures, the operation of structures, and their monitoring are well known. From the rock mechanics perspective, there are still questions about the structural stability of a salt cavern under severe solicitations: blowout, high-frequency cycling or rapid pressure drop. This paper presents a theoretical and numerical analysis of the consequences of severe gas depressurisation following a fast withdrawal (2 MPa/hr) of the hydrogen stored in a salt cavern selected for a demonstrator in France. A rapid cavern pressure drop can cause significant hydrogen cooling, fast creep closure and large shear stresses. The main mechanical stability criteria can be described as follow (Djizanne et al. 2012, Bérest et al. 2013, Brouard et al. 2022): the onset of salt dilation, the onset of effective tensile stresses at the cavern wall, the onset of tensile stresses at the cavern wall, the overstretching at cavern roof, limited volume loss and volume loss rate and limited subsidence. The first two criteria are discussed here:

- The onset of salt dilation; salt micro-fracturing and dilation occur when the shear stresses are significant compared to the mean stresses. These lead to a permeability increase, a drop in wave speed, an increase in acoustic emission and a loss of rock strength.
- The onset of effective tensile stresses at the cavern wall ($\sigma_{eff} = \sigma_{\max} + P_c < 0,$ where σ_{eff} is the effective stress, $\sigma_{\max}$ is the least compressive principal stress, and P_c is the cavern pressure); when tensile stress develops at the cavern wall, there is a risk of salt fracturing and spalling. Thermal contraction of the salt near the surfaces of the cavern is likely to cause stresses to become tensile.

The numerical computation allows studying the geomechanical consequences of a withdrawal of nearly 50 tons of hydrogen in 6 hours on the mechanical stability of the EZ53 salt cavern as one of the worst-case scenarios of the risk analysis.

3 NUMERICAL MODELLING

The numerical modelling presented in this paper was performed within LOCAS. LOCAS includes modules that simultaneously predict cavern and wellbore behaviour as fully coupled thermo-hydro-mechanical finite element software. The properties of modelled rock units are in Table 1. The Munson-Dawson multi-mechanism constitutive model describes salt viscoplastic transient and steady-state behaviour (Munson 1999). The set of parameters for Etrez salt comes from Brouard & Bérest (2022). The selected cavern EZ53 was leached out in 1982 and has always been filled with brine and used for scientific *in-situ* measurements and tests. The cavern roof is at 920 m depth, a gully is at 930 m depth, and the bottom of the cavern is at 964 m depth. The cavern shape is axisymmetric but irregular, with a free volume of 7,390 m^3 (Djizanne et al. 2022); see Figure 1.

Table 1. Properties of the considered rocks.

Rock	Thickness (m)	Density (kg/m^3)	E (MPa)	ν (-)	Constitutive law
Overburden	700	2,300	1,500	0.25	Elastic
Salt	500	2,191	16,809	0.25	Munson-Dawson

The model boundary conditions are: no radial displacement along the centerlines, geostatic pressure applied along the outer radius (300 m), and no vertical displacement along the bottom surface at a depth of 1,200 m. Isothermal boundaries also are assumed in all four boundaries of the model. The mesh area is 1,200 m high and 300 m wide. The meshing is subdivided into three parts (Djizanne et al. 2014): close to the cavern wall (10 m), there is an increased high-density area in which the maximum distance between nodes on the cavern wall is 0.2 m and the maximum elements size at the outer boundary is 1 m (Figure 1). Then, there is a normal high-density area, where the maximum size of elements is 2 m. Finally, there is a low-density area in which the maximum size of elements is 6 m. The number of mesh elements is 71,934, and the number of nodes is 36,539.

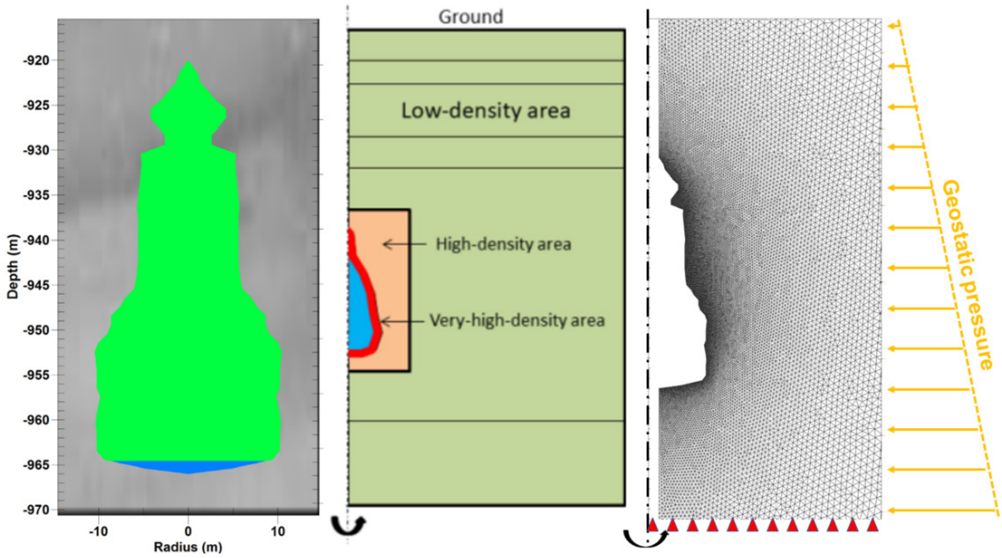

Figure 1. Finite element modelling – mesh size and strain and stress boundary conditions.

4 MODELLING RESULTS

The consequences of a rapid hydrogen depressurisation on salt cavern safety and tightness are evaluated through numerical simulation. The rapid pressure drop is theoretical, but the salt cavern is a real cavern selected for a demonstrator in France. The main steps of the numerical computations are in Figure 2: step 0 – *at the end of the debrining*; step 1 – *before the withdrawal* or ten days after the end of the debrining with the cavern at the maximum pressure (15.2 MPa); step 2 – *at the end of the withdrawal* where the cavern reaches the minimum pressure (4.6 MPa) and step 3 – *after the rapid withdrawal* where the cavern is kept one week at the minimum pressure.

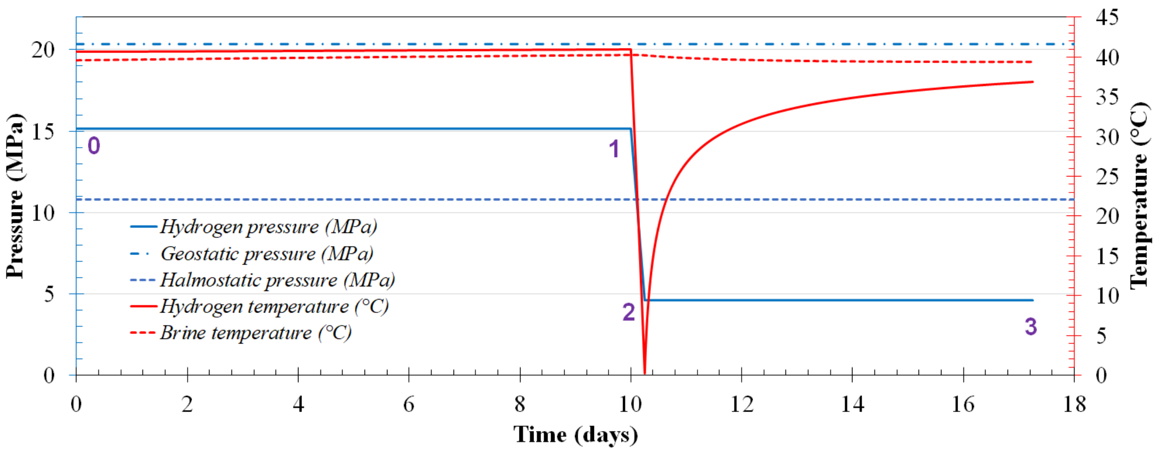

Figure 2. Evolution of cavern pressure and temperature as a function of time.

Figure 2 shows the evolution of the fixed hydrogen pressure and the calculated hydrogen and brine temperatures. The hydrogen temperature drops from 40 °C to 0 °C is almost adiabatic during the fast hydrogen withdrawal (2 MPa/hr). After that, the hydrogen temperature increases due to the rock mass heat flux that contributes to balancing the initial hydrogen cooling caused by the rapid pressure drop. Following the hydrogen cooling, the thermodynamic equilibrium of the cavern in its environment also leads to a slight warming of the residual brine from 39 °C to 40 °C. Figure 3 shows the temperature contour plot inside the cavern and the surrounding rock mass. The stored hydrogen temperature goes from 40°C, reached ten days after debrining at maximum pressure, to 0°C at the end of withdrawal. Then, one week following the minimum pressure release, the hydrogen temperature rises gradually to 39°C to reach thermal equilibrium.

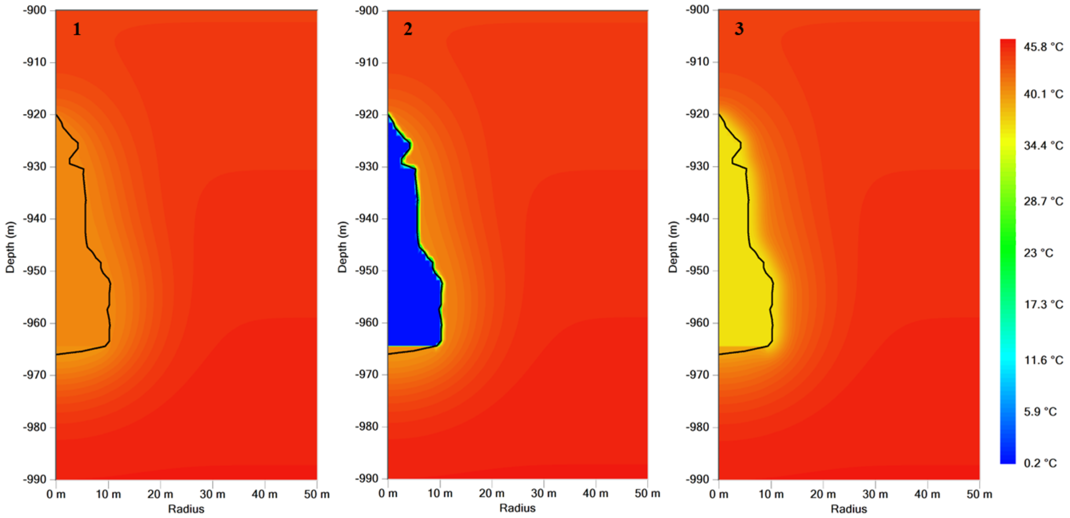

Figure 3. Temperature contour plot before (1), at the end (2) and after (3) the rapid hydrogen withdrawal.

Rock salt is a viscoplastic material that is difficult to fail under moderate levels of confining pressure. When the induced shear stresses exceed the strength of the salt, it will then microfracture and create additional porosity, increasing the permeability and volume, referred to as dilation. The selected dilation criterion in this study is the RD criterion (with the Moss Bluff set of parameters) developed by RESPEC (DeVries et al. 2003). The criterion is based on a Mohr-Coulomb-type failure criterion to represent salt failure as a function of shear stress, mean stress, and Lode angle. Figure 4 shows the salt dilation contour within the RD criterion during the three computation steps. Dilating areas are drawn in magenta and correspond to a Factor Of Safety of less than 1. The rapid pressure drop of the hydrogen in the cavern of 2 MPa/hr causes a zone of dilation from the cavern wall equivalent to about one cavern maximum radius (10 m). The dilating zone develops slowly when the cavern is maintained at minimum pressure seven days after the fast withdrawal.

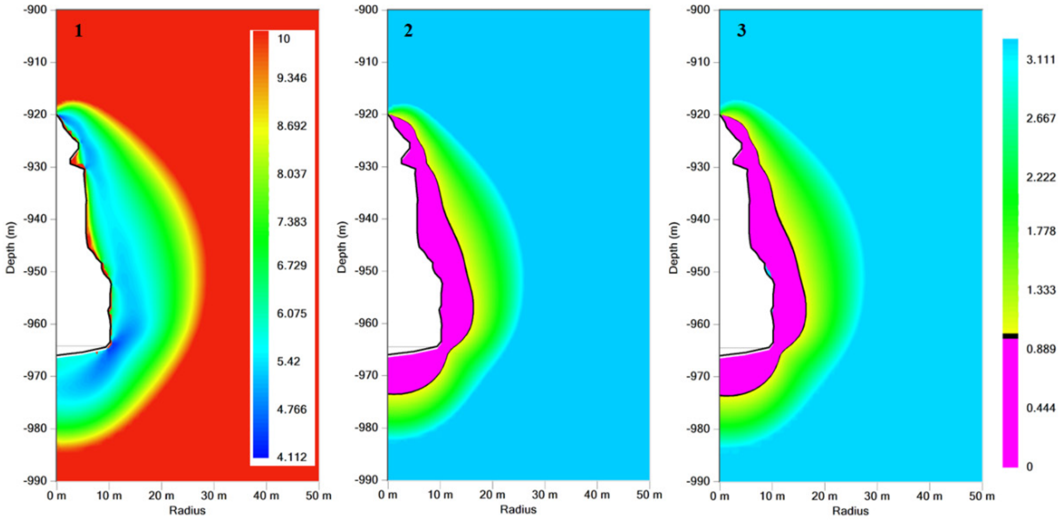

Figure 4. Salt dilation contour plot before (1), at the end (2) and after (3) the rapid hydrogen withdrawal. Salt dilation occurs when the shear stresses are significant compared to the mean stresses.

5 DISCUSSION

This discussion concerns the consequences of stress relief on the mechanical stability criteria. In the upper part of the cavern (at the cavern roof and in the gully), the least compressive principal stress is not tensile before, at the end and even after the rapid hydrogen withdrawal. Nevertheless, Figure 5 shows that effective tensile stresses, although very localised, appear at the cavern wall ten days after the debrining at the maximum pressure. The tensile areas did not develop during and after the fast withdrawal, i.e. even when the cavern remained at minimum pressure for one week. As the formation temperature returned to the *in-situ* formation pressure, stresses became less tensile, and after one week, the stresses in the salt surrounding the cavern were less than the salt tensile strength.

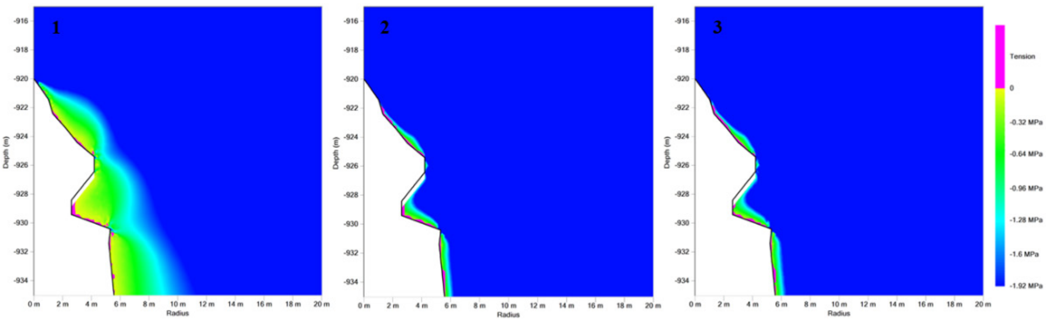

Figure 5. Effective stresses before (1), at the end (2) and after (3) the withdrawal. Tensile stresses in magenta.

The cavern volume relative variation is 0.6% one week after the fast withdrawal. Figure 6 shows displacements along the cavern wall following the three main computation steps. Displacements along the cavern wall continuously increase before, at the end and after the rapid withdrawal.

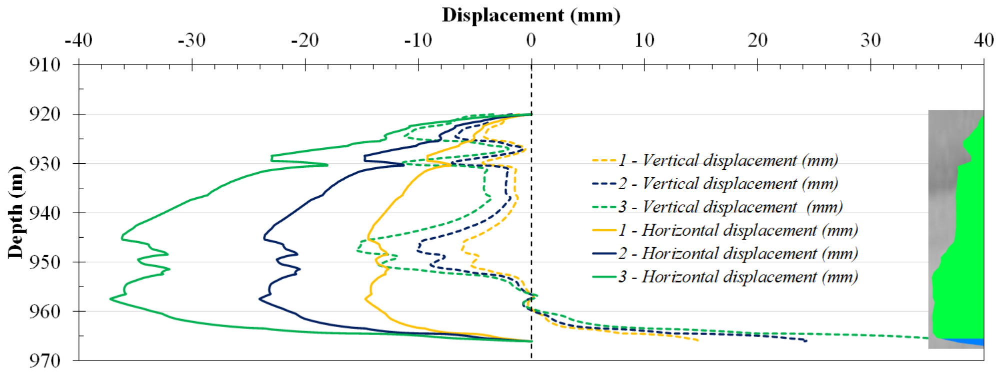

Figure 6. Distribution of displacements along the cavern wall before, at the end and after the withdrawal.

The computed temperature variations following a fast withdrawal of gaseous hydrogen stored in the salt cavern are significant. *In-situ* measurements from the Etrez demonstrator with hydrogen are expected to compare the thermodynamic models already proven with the natural gas caverns. This paper shows that an intensive operation of underground hydrogen storage can lead to salt damage, mainly related to salt dilation. Salt micro-fracturing and dilation lead to additional salt porosity and increased salt permeability.

The evolution of this micro-fracturing must be understood. Sicsic & Bérest (2014) demonstrated that for a highly severe thermal chock inside a natural gas cavern, the damaged zone self-organises into bands, and cracks propagate as long as the temperature drop propagates, their spacing increase following Griffith's theory. However, beyond thermal damage, other damages can also develop and affect the integrity, performance and safety of operations on underground hydrogen storage in salt caverns. The time-delayed damage (subcritical crack propagation) and the fatigue damage due to cycling can be highlighted. The influence of these mechanisms on the thermal-hydraulic transport properties and their evolution in time should also be assessed.

6 CONCLUSION

A two-dimensional axisymmetric thermomechanical finite element simulation of a cavern submitted to a fast withdrawal was performed using LOCAS. The case modelled here contributes to risk control and represents one of the worst-case scenarios during the operation with hydrogen. The analysis helps to evaluate the effects of fast gas withdrawal (2 MPa/hr) on the temperature and induced stresses at the cavern wall. Following the rapid depressurisation, the cavern surfaces experienced significant thermal contraction due to heat exchange with the cool gas in the cavern. Therefore, the risk is high of generating salt dilation, thus violating the mechanical stability criteria. The mesh fineness at the cavern wall allowed considering the cavern temperature variations. Tensile effective stresses, although very localised, appear at the cavern wall but do not develop when the cavern remains for one week at the minimum pressure after the rapid hydrogen withdrawal. According to the RD criterion, dilatancy is observed at the cavern wall because of rapid pressure drop. Salt dilation leads to increased permeability, a decrease in wave speed, an increase in acoustic emission and a loss of rock strength.

Considering rock salt impurities and the criteria of nucleation and propagation of low-temperature induced microcracks must be carefully studied prospectively to ensure the tightness of salt caverns that store large quantities of hydrogen. Numerical computation of cracking raises difficulties that need to be resolved. Sicsic & Bérest (2014) suggested a variational approach to fracture mechanics. Cohesive zone models implemented in finite element codes also are increasingly used to model fracture initiation and propagation in geomaterials. For instance, by implementing cracking criteria in the finite element code, Disroc could make it possible to simulate potential cracking at the wall under the effect of combined thermal and hydraulic stresses and to analyse the consequences on the mechanical and hydraulic integrity of the structure.

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