IOP Conference Series: Earth and Environmental Science

PAPER • **OPEN ACCESS**

Consideration of the mechanical damage behavior of rock salt during calculation of infiltration-cracks in the edge zone of gas storage caverns

To cite this article: S Yildirim 2021 *IOP Conf. Ser.: Earth Environ. Sci.* **833** 012183

Consideration of the mechanical damage behavior of rock salt during calculation of infiltration-cracks in the edge zone of gas storage caverns

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Abstract. Underground storage in salt caverns is a preferred method for the intermediate storage of natural gas to cover seasonal fluctuation in consumption and commercial gas storage. The prove of the stability and tightness of the storage required for safe operation is continuously adapted to the current state of the art. For many years, an intensive scientific investigation has been carried out within the frame-work of repository research with continuous optimization of the rock mechanical modelling of the material behavior of rock salt. From the elaboration of the research results on the pressure-driven infiltration processes into the primarily non-permeable salt rock, it emerges that during gas storage operation, in addition to the areal infiltration, the formation of macroscopic infiltration-cracks in the cavern surrounding salt rock is to be expected as well. This thesis deals with the computational simulation of macroscopic infiltration-cracks within the scope of theoretical modelling of salt cavern behavior during gas storage, taking into account additional mechanical damage processes in the rock salt. On the basis of variational calculus, the infiltration fracture propagation will be evaluated, considering different model approaches in material behavior of the cavern surrounding rock salt mass. As a result of the present work, it should be noted that with regard to the propagation of infiltration-cracks in gas caverns, constitutive model approaches for the description of the mechanical damage and healing behavior of rock salt can be neglected for a conservative assessment.

1. Introduction

For many years, an intensive scientific investigation has been carried out with continuous optimization of the rock mechanical modelling of the material behaviour of rock salt. From the elaboration of the research results on the pressure-driven infiltration processes into the primarily non-permeable salt rock, it emerges that during gas storage operation in salt caverns, in addition to the areal infiltration, the formation of macroscopic infiltration cracks in the cavern surrounding rock salt is to be expected as well.

Experimental investigations in laboratory and field clearly indicate the occurrence of pressure-induced infiltration cracks in rock salt when a critical limit value is exceeded in the material. Since a rupture or frac failure only occurs at higher fluid pressures, which could only be generated in the laboratory at very high-pressure rates (4 to 40 MPa/h) and are not comparable with the pressure rates in a gas cavern (in magnitude up to 100 times slower), the occurrence of macroscopic separation cracks was neglected in cavern design for many years. In gas caverns, however, the near-contour rock salt mass is exposed to additional thermal load during usual storage operation due to the rapid temperature change in the storage medium. Compressive stresses are partly compensated by the thermally induced additional stresses, so that the stress components directed vertically and tangentially to the cavern wall show much lower compressive stress values than the fluid pressure in the cavern.

It can be assumed that the formation of infiltration cracks cannot be avoided in cavern operation. Their influences on the stress state in and around "cracked zones" cannot be neglected anymore and must be considered in the rock mechanical investigation of gas storage caverns in the Salinar rock. The occurrence of infiltration cracks in the vicinity of gas storage caverns and the influence of different crack configurations are shown in Yıldırım et. al. 2020.

This work deals with the computational simulation of macroscopic infiltration cracks within the scope of theoretical modelling of salt cavern behaviour during gas storage, considering additional mechanical damage processes in the rock salt. On the basis of variational calculus, the infiltration crack propagation will be evaluated, considering different model approaches in material behaviour of the cavern surrounding rock salt mass. The results are discussed with regard to the extent to which of the in detail examined mechanical model approaches has to be considered in a rock mechanical investigation of gas storage caverns or can be neglected from an engineering point of view.

2. General assumptions and Calculation Model

During gas storage operation the formation of macrocracks in the cavern surrounding salt rock is to be expected. If the difference between the radial and vertical resp. tangential stress components exceeds a certain value macroscopic crack formation due to infiltration processes is expected. In fact, so-called infiltration-cracks in macroscopic range will arise when the acting internal pressure $|p_i|$ is greater than the minimum compressive mean stress $|\sigma_3|$ and the effective tensile strength $\beta^T_{eff.}$ of the material, which is for rock salt given as about 2 – 4 MPa. After opening such cracks, whether vertical or horizontal, the gas will penetrate into the cracks with the appropriate pressure.

Decisive for the assessment of the stability and the tightness of the cavern is the state of stress in the vicinity of the gas storage cavern. As a new part of the dimensioning concept, cracking by reason of infiltration processes must be considered in the calculation model. As a new criterion it is to check how far the thermally induced infiltration cracks will extend into the salt rock.

The IGtH-IUB is considering the complex processes of changing continuum to discontinuum in the numerical code FLAC3D via discrete crack modelling. With this method infiltration-cracks can be calculated and evaluated. This approach enables a reliable determination of the stress and deformation state particularly next to gas pressure-driven macrocracks.

The discrete crack modelling describes the generation of fracture in the model by means of elimination of individual zones. Zones which fulfill the criterion for crack propagation will be deleted from the model and the model will be adapted to the new crack state. In further calculation the internal pressure acting in the occurred crack will be considered.

For the calculation of infiltration-cracks, crack-lines will be created in where crack propagation will be permitted. This requires a much finer discretization than usual. Cracks are to be expected over the entire height of the cavern, but in order to limit the number of calculation zones and thus the calculation effort, the investigation of the crack propagation will be limited to a rock section. Since the most unfavorable stress values with regard to the dimensioning of the operating rates occur in the upper region of the cavern, this region is finely discretized and considered for calculation and evaluation of infiltration-crack propagation. Figure 1 shows the calculation model with its dimensions and a zoom view of the finely discretized upper section.

It must be expected that at intervals of several meters cracks will occur. In order to consider the influence of several fractures on the stress state in the salt rock and on the progression into the salt rock, the model is created in the finely discretized roof area with five horizontal and two vertical fractures.

The criterion for infiltration crack propagation is formulated as follows (an effective tensile strength is neglected)

$$\text{horizontal crack formation:}\quad |p_i| > |\sigma_{zz}|$$

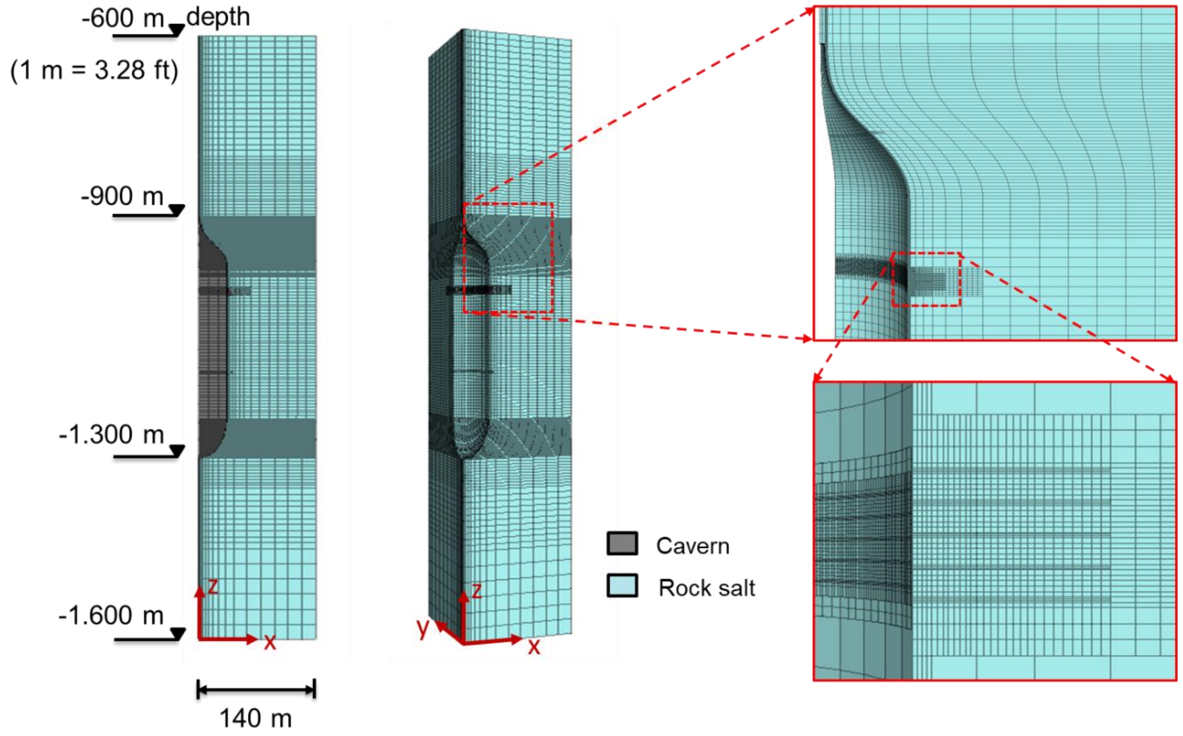

Figure 1. Calculation model with discretization of infiltration-crack-elements.

For the storage of gas in salt caverns it is necessary to assume a suitable design load case which is characterized by a high withdrawal and refill rate in a preferably large working gas capacity. By means of robust cavern dimensioning and adherence to safe operating procedures, failure conditions and damage processes in the salt rock close to the cavern contour that endanger stability must be limited to the cavern edge area and sufficient salt thickness with a primarily given impermeability as a barrier must be maintained. The proof is generally provided by physical modeling and numerical simulation of the thermomechanical processes occurring in the rock salt.

Figure 2 shows the chosen design load case for multi cycling operation. The diagram shows the internal pressure over time, which is applied as a boundary condition to the cavern wall in the creep calculations. It’s a common design load case for the dimensioning of gas caverns with several injection, withdrawal as well as standstill phases. Assumed is a maximum pressure level of 15.6 MPa and a minimum pressure of 3.5 MPa. When gas is withdrawal internal pressure will decrease. Is gas injected into the cavern the internal pressure increases. In standstill phases without any withdrawal ore injection the internal pressure remains almost constant. Four cycles are considered.

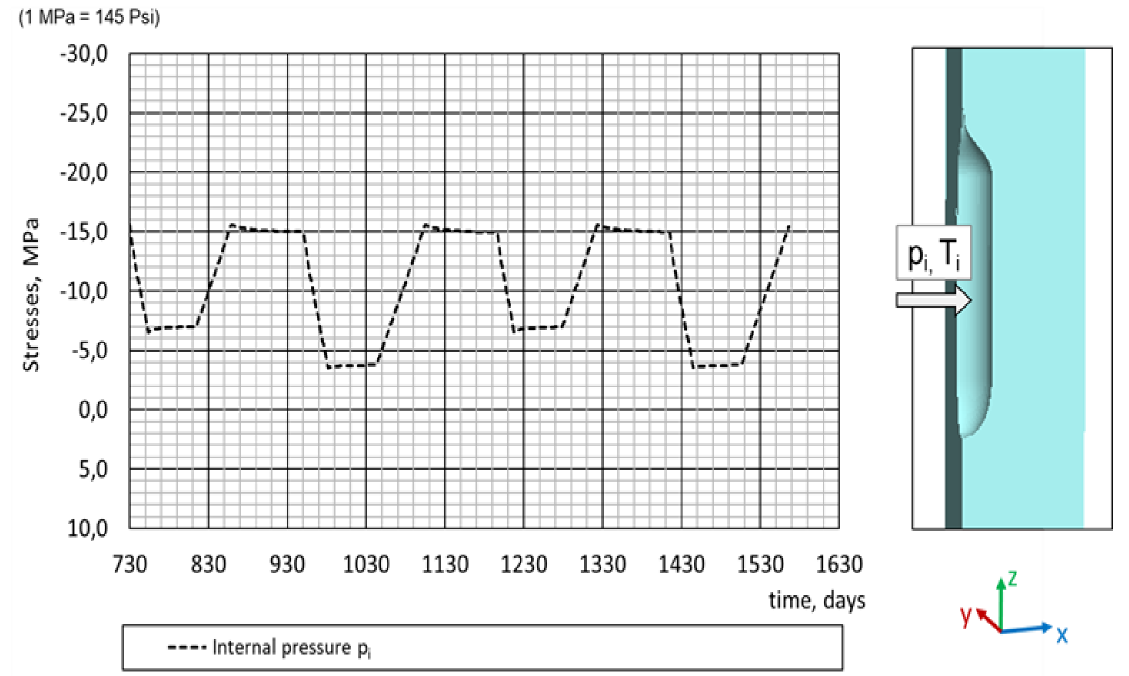

Figure 2. Design Load Case / Internal pressure vs. Time.

To describe the material behavior of rock salt the constitutive model LUBBY2 and the extended model Lubby-CF developed in the Institute of Geotechnical Engineering, Department of Underground Construction (IGtH-IUB) of the University of Hanover are used. LUBBY2 is in principle based on the rheological model according to Burgers and describes the damage-free creep behavior of rock salt by means of stress and temperature dependent model parameters was developed and presented for the first time in 1983 (Heusermann, Lux and Rokahr 1983). The constitutive model Lubby-CF is the extended form of LUBBY2 and was developed in over decades of continuous research work for the rock mechanical modelling of the stress-strain behavior of rock salt (Yıldırım 2019). It describes the time-dependent creep behavior of rock salt in its transient and stationary phase including inverse transient creep as well as tertiary creep due to dilatation, damage recovery (healing) and fracture failure. Damage- and temperature-dependent strength behavior is considered as well as reduced stiffness in case of microstructural damage.

The thermodynamic calculations been performed by means of the KavPool program code (RWE-ESK). The thermo-mechanical coupled rock mechanical calculations are performed using the program code FLAC3D (Itasca 2020).

3. Calculation

In the rock mechanical modelling of a salt cavern it is to be investigated to what extent individual processes in the material behavior of rock salt influence the stress state at the cavern contour and thus the process of infiltration crack formation in the salt rock. The focus here is on the evaluation of crack propagation in a normal operating sequence of a gas storage cavern.

In two variation calculations based on each other, in Simulation A the LUBBY2 constitutive model and in Simulation B the Lubby-CF material model is used to describe the material behavior of rock salt. That means, that in Simulation A a damage-free material behavior and in Simulation B strain hardening, damage due to shear and tensile stresses and plastic failure due to tensile loads are considered in additional to the damage free creep behavior is assumed.

The result of the crack propagation at the end of the calculations is shown in figure 3 as a contour plot for Simulation A (left) and Simulation B (right).

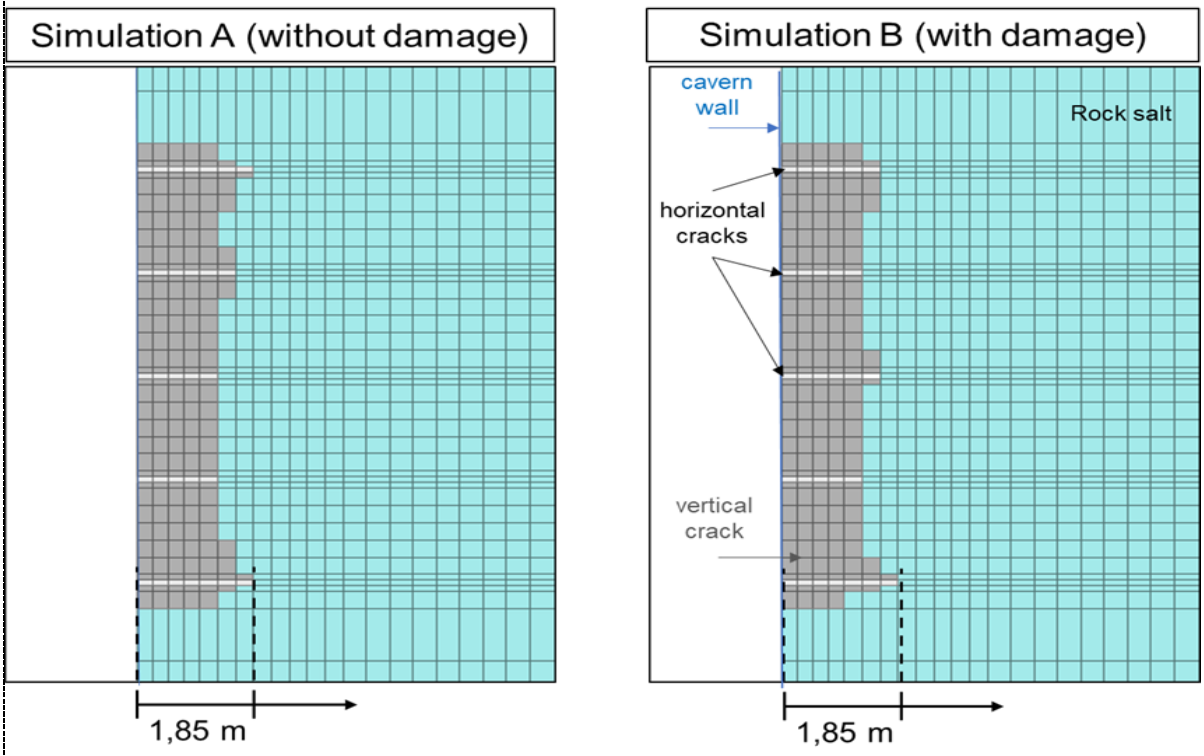

Figure 3. Crack propagation in a contour plot. Cut in plane. Left: Simulation A, right: Simulation B. In light blue: rock salt, white line: horizontal cracks, grey area: vertical cracks.

The white lines show the horizontal crack propagation and the grey area indicates the vertical crack propagation. This example shows, that the crack pattern for both Simulations A & B are nearly similar. The maximum crack length is in both examples about 1.85 m for the lowest horizontal crack. In Simulation B the crack propagation is even slightly shorter in some areas. The comparison shows that when determining infiltration crack propagation during gas storage operation using the discrete crack modeling method, consideration of mechanical damage in rock salt has no effect on the maximum crack length.

4. Conclusion

The occurrence of infiltration cracks in the vicinity of gas storage caverns is more or less unavoidable. Based on research results, the assumptions for the calculation models must be changed. The question to be answered here is how far the thermally induced infiltration cracks will extend into the salt rock and how does it influenced by considering additional mechanical damage behavior in rock salt.

The result of the thermo-mechanical coupled variation calculation taking into account the mechanical damage and healing behavior of salt rock show that the occurrence of damage is associated with larger deformations and causes an increased stress redistribution from the cavern contour to the more distant rock salt mass, thus reducing additional stresses from thermal clamping. If the additional stresses from thermal clamping in the salt rock close to the cavern contour are reduced due to increased deformability, the minimum principal compressive stress in these rock sections shows higher compressive stress values. The probability that the gas pressure criterion is fulfilled in these zones is reduced.

As a result of the present work, it should be noted that with regard to the propagation of infiltration cracks in gas caverns, constitutive model approaches for the description of the mechanical damage and healing behaviour of rock salt can be neglected for a conservative assessment.

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