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Calculation of infiltration-cracks in the edge zone of gas storage caverns with *FLAC3D*

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1 INTRODUCTION

Underground storage in salt caverns have been used for many decades for the intermediate storage of natural gas. During this period the rock mechanical design of gas storage caverns is continuously modified to the current state of the art. In the past 10 years, the rock mechanical design has taken into account temperature changes in the gas. If gas is withdrawn from a salt cavern, the stored medium and thus also the cavern wall are cooled. Until now, it has been assumed that discrete fractures will occur at the cavern wall when temperature induced tensile stresses appear in the rock salt, which should be avoided from a rock mechanical point of view.

This assumption has recently been revised at the Institute for Geotechnical Engineering, Department for Underground Constructions of the Leibniz University of Hanover (IGtH-IUB). 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 the formation of macrocracks in the cavern surrounding salt rock is to be expected. In fact, infiltration-cracks in macroscopic range will arise when the acting internal pressure is about 2 – 4 MPa greater in according to amount (comprehensive stress is defined negative) than the main stress components directed perpendicular to the internal pressure. This means that first infiltration-cracks occur before absolute tensile stresses arise. A positive effect of such more or less unavoidable infiltration-cracks is that further thermally induced fractures no longer occur because the internal pressure penetrates into the infiltration-cracks and as a result the stress state in the vicinity of the cracks cannot anymore exhibit any absolute tensile stresses.

As a new part of the dimensioning concept, cracking by reason of infiltration processes must be taken into account in the calculation model. The IGtH-IUB is considering the complex processes of changing continuum to discontinuum in the numerical code *FLAC3D* (Itasca 2019) via discrete crack modelling. In this way 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 simulation models and calculations will be presented and the results regarding the development of infiltration-cracks into the salt rock will be discussed.

2 ASSUMPTIONS AND MODELLING

The rock mechanical design concept for gas storage caverns in rock salt included recommendations for the maximum (Rokahr et al. 1997) and minimum internal cavern pressure (Staudtmeister & Stuck 1990) as well as the maximum possible withdrawal or filling rate between these two operating limits (Rokahr et al. 2008).

In the context of the stress evaluation, the occurrence of absolute tensile stresses in the region close to the cavern was of particular importance, since the tensile strength of salt rock is comparatively low compared to the compressive strength (Staudtmeister & Zapf 2015).

When the tensile strength is exceeded, it must be expected that fracture occur perpendicular to the tensile direction (Staudtmeister & Zapf 2010) (Zapf et al. 2012). After opening such cracks, whether vertical or horizontal, the gas will penetrate into the cracks with the appropriate pressure. So far there were no theoretical approaches how the secondary stress states change under the consideration of macroscopic crack formation. The demand for the entire rock salt was to avoid tensile stresses during the operation phase (Yıldırım et al. 2016).

Figure 1 shows the stress development over the time in the roof section (red dot) of the cavern edge calculated with the constitutive creep law Lubby2 (Heusermann et al. 1982). Simulated is a 400 m high cavern with a diameter of 35 m. Considered is a thermodynamically calculated design load case for multi cycling operation with four withdrawal phases. The diagram shows the stress components σ_{xx} (blue), σ_{yy} (red) and σ_{zz} (green). σ_{xx} must follow the internal pressure (p_i) curve at the edge of the cavern, while the tangential stress components σ_{yy} and σ_{zz} are influenced by the creep ability of the rock salt on one hand and the temperature changes in the gas on the other hand.

The largest change is visible for the stress component σ_{zz}. At the end of the fourth pressure withdrawal to p_i = 32 bar, the component has tensile stress values of about 1.9 MPa. From a rock mechanical point of view, these stress states at the cavern wall should be avoided as far as possible, since thermally induced fractures would not have been avoidable (Zapf et al. 2018).

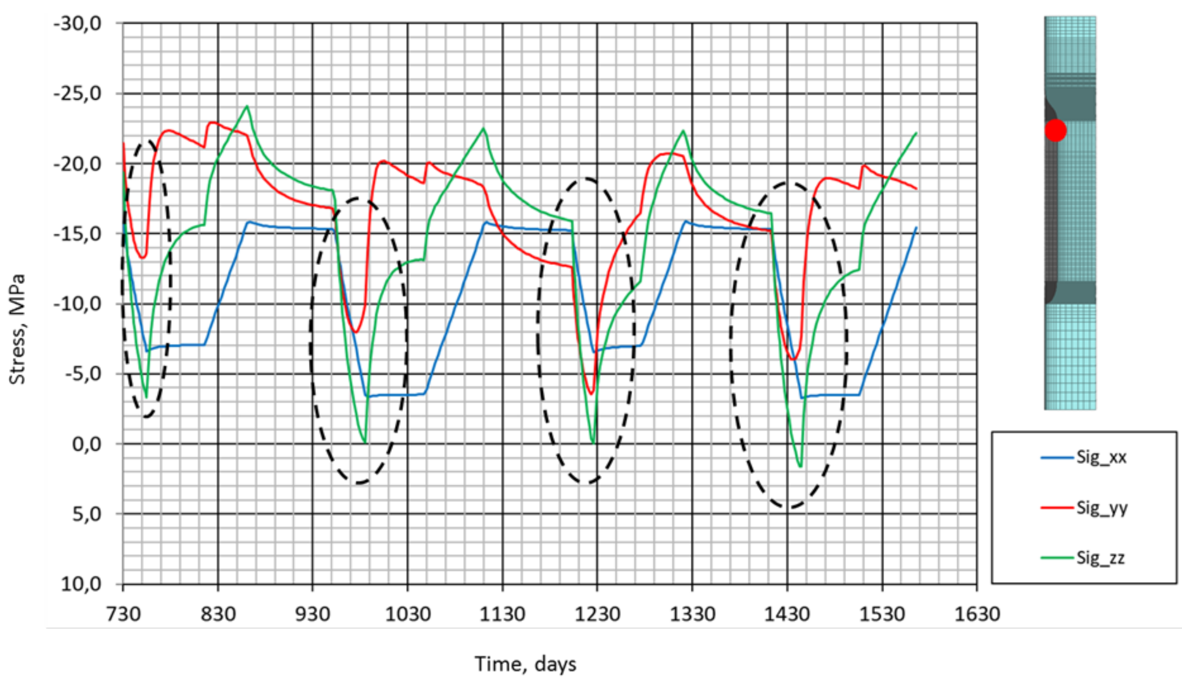

Figure 1. Thermomechanical Calculation / Stress development over the time in the roof section of the cavern edge (red dot). Sig_xx: radial stress component, sig_yy: tangential stress component, sig_zz: vertical stress component. The dashed black lines highlights regions where stress components have smaller compressive stress values as the prevailing internal pressure (which is equal to sig_xx at the cavern edge).

So far, operating rates have been dimensioned on the basis of evidence that cracking due to excessive thermal stress should not occur in the rock salt. For this reason, the temperature cooling in the cavern and thus the withdrawal rate was limited.

The increase in knowledge from the ongoing research projects of the IGtH-IUB in Germany shows that the occurrence of so-called infiltration-cracks must be expected in the wall area of the cavern as soon as one of the principal stress components has smaller compressive stress values in the range of $\Delta\sigma$ = 2 - 4 MPa, as the prevailing internal pressure. This thesis was already similarly set up by Berest et.al. (2012), Berest et.al. (2015) and Brouard et.al. (2007) in recent years.

It can be seen that during the operating phases, a main component of tension (blue curve) follows the internal pressure directly on the cavern wall. The green curve is the vertical principal stress component, the red curve the horizontal circumferential stress component on the wall. It is obvious that the green vertical stress component has smaller compressive stress values than the radial stress component immediately after the start of the first extraction phase as well as in all following withdrawal phases. In Figure 1, these areas (dashed black line) are marked in the time course of the stress components in the design load case.

If the difference between the radial and vertical stress components exceeds a certain value (2 to 4 MPa, so-called effective tensile strength) as mentioned, macroscopic crack formation due to infiltration processes is expected. As a new part of the dimensioning concept, macrocracks must be taken into account in the calculation model because they occur before absolute contours arise due to temperature.

The computational simulation of macroscopic infiltration-cracks takes place in *FLAC3D* via the method of discrete crack modeling. As part of the rock-mechanical modeling of salt rocks using the finite difference method, 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 arised crack will be considered.

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

$$|\sigma_{zz}| < |p_i|$$

On the basis of this assumption, it is necessary to modify the existing cavern models. 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 (Fig. 2).

It must be expected that at intervals of several meters, cracks will occur. In order to investigate 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 fractures.

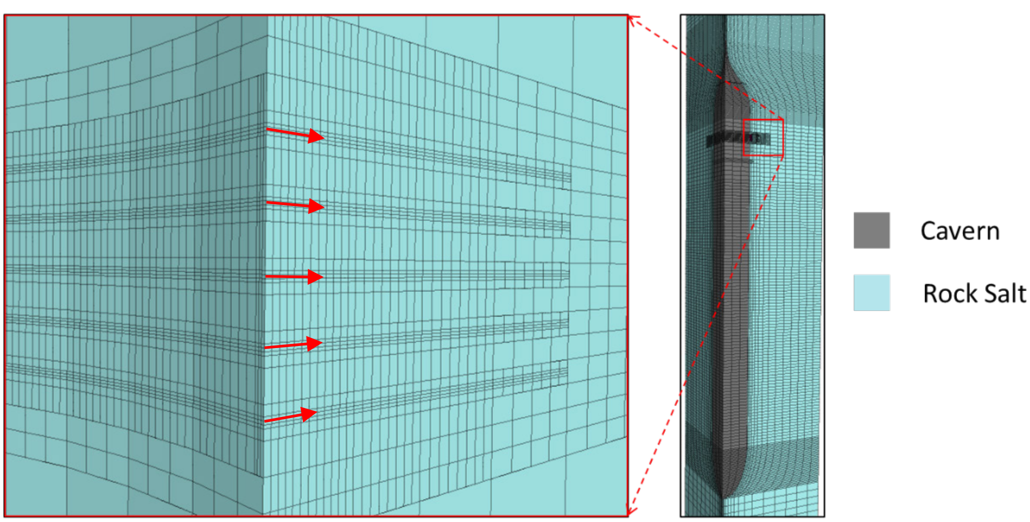

Figure 2. Discretization of Infiltration-crack elements. Possible horizontal Infiltration-crack propagation in the finely discretized five crack lines (red arrows).

3 CALCULATION RESULTS

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. Due to the infiltration-crack propagation criterion, cracks were generated in the calculation model when the vertical stress component σ_{zz} decreased in magnitude below the prevailing internal pressure p_i respectively the radial stress component σ_{xx}.

The result of the crack formation at the end of the calculated design load case is shown in Figure 3. It is visible that five cracks occur during the calculation with different propagation lengths.

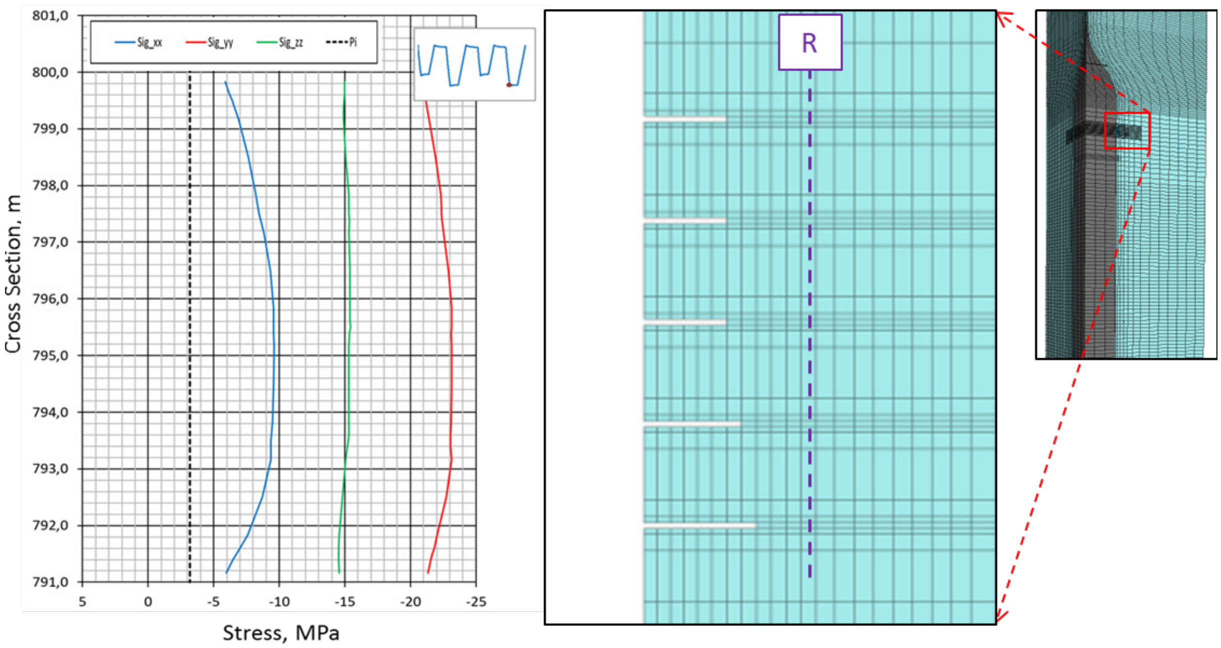

Figure 3. Occurrence of Infiltration-cracks and stress distribution at cross section R / p = 32 bar. Sig_xx: radial stress component, sig_yy: tangential stress component, sig_zz: vertical stress component. p_i = internal pressure.

The vertical section R in Figure 3 indicates the state of stress at a distance of about 3 m from the cavity edge. The illustration shows that the tangential stress components σ_{yy} and σ_{zz} in this section reach values which are larger in magnitude in the pressure range than the internal pressure p_i prevailing at that time (black dashed line). Furthermore, the values are of a similar order of magnitude as in calculations without crack elements. The calculation results show that the infiltration-crack propagation reaches a finite value of up to approx. 2 m behind the cavern wall.

At the end of the calculation, after reaching a minimum cavern internal pressure of p_i = 32 bar, a standstill phase of 60 days at the minimum pressure and a refilling phase follow to the maximum cavern internal pressure of p_i = 160 bar no further fracture propagation take place, the maximum crack length does not change and all stress components in the area of crack formation at a distance of 3 m behind the cavity edge are still greater in magnitude than the prevailing internal pressure.

4 CONCLUSIONS

The occurrence of infiltration-cracks in the vicinity of gas storage caverns is more or less unavoidable. Based on this research result, 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.

The infiltration-crack propagation is based on thermally induced stress redistribution during the withdrawal phase, in which one of the stresses directed perpendicular to the internal pressure in the environment of the cavern is smaller in magnitude than the prevailing cavern internal pressure. The dimensioning concept examines how far these infiltration-crack reach into the salt rock and whether this process will reach a finite value.

In the calculations the fracture propagation reaches a value of approx. 2 m. In particular, in the section R about 3 m (9.8 ft) behind the cavern wall, a stress state was detected, in which the three stress components have in magnitude larger compressive stress values than the prevailing internal pressure component.

Due to this condition further infiltration-crack propagation into the salt rock is prevented.

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