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Thermally Induced Cracks in Gas Caverns in Rock Salt

Abstract:

For the storage of natural gas in rock salt caverns it is necessary to carry out numerical calculations for the dimensioning of the relevant operation parameters. These are on the one hand the allowable maximum and necessary minimum internal pressure to ensure a gastight and stable cavern over decades and on the other hand the limitation of the withdrawal and refill rates between these geomechanical limits.
During the withdrawal phases of the gas the temperature decreases. The cooling of the gas can lead to stress states in tensile regions at the cavern wall. Because the tensile strength of rock salt is relatively low compared to its compressive strength it is likely that tensile stresses lead to discrete cracks orthogonal to the direction of the tensile stresses. If cracks of this kind occur at the wall the gas will penetrate into them at the relevant pressure and further extend the length of the crack.
Current research projects are working on the fracture initiation and propagation into the rock salt mass. The question that has to be answered is: If a crack occurs at the cavern wall for instance due to weakness zones with lower tensile strengths, how far is the crack going to propagate into the rock salt and is the propagation going to stop somewhere behind the gas storage cavern wall due to a higher stress state in the rock salt?
Salt caverns cannot be entered but only explored by sonar measurements, with which it is not possible to detect tensile cracks at the cavern wall. Within this paper examples from mining configurations will be shown where temperature changes lead to tensile cracks in the surrounding rock salt. These cracks have been mapped while the temperature development is documented.
The paper deals with recalculations under consideration of different salt properties of the temperature distributions and the resulting stress state in the surrounding rock salt mass. The stress calculation results and the consequences for the dimensioning of natural gas caverns are going to be discussed and assessed.

Key words: rock mechanics, crack propagation, gas storage cavern, rock salt, thermodynamics

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1. INTRODUCTION

The optimization of gas filled salt cavern operations has a lot of different aspects. Beneath the determination of the maximum allowable and minimal required internal gas pressure, the withdrawal rate between these pressures is of great importance for an operator.

The maximum internal pressure should be limited depending on the primary stress state surrounding the cavern due to the demand of tightness [1], while the minimum pressure should be limited due to the demand that no spalling of the design contour of the gas cavern occur during the operation [2].

Between the maximum and minimum pressure the withdrawal rate should be limited because the pressure drop in the cavern leads to low temperatures in the cavern and in the surrounding rock salt mass [3] [5] [6]. It is likely that these cold temperatures lead to stress states that may not remain in compressive regions [7] [8] [9]. Because rock salt has a relatively low tensile strength, tensile stresses in the rock mass probably lead to macroscopic fractures [12]. The cavern is still under a certain pressure so it is likely that the tensile fractures lengthen due to penetration of gas into such an open space.

Gas storage caverns in rock salt can be observed with sonar measurements [4]. With these measurements contour changes can be detected, for example due to spalling or convergence of the cavity, but it is not possible to detect horizontal fractures due too cold temperatures in the cavern. Because of the internal pressure in the cavern, the question has to be answered, if and where fracture propagation will stop in the cavern surrounding rock salt mass.

Experts on rock salt mechanics are currently discussing whether temperature-induced fractures can occur at the cavern wall at all [10] [11] [13]. Therefore, two examples are used in this paper which clearly show that fractures occur in the rock salt due to temperature changes.

2. GENERAL ASSUMPTIONS

In this section the general assumptions concerning the used constitutive law and the numerical program systems for the thermo-mechanical coupled calculations are going to be presented.

2.1. Constitutive Law

For the time, temperature and stress dependent calculations the constitutive equation LUBBY2 for rock salt creep is used [14]. The following equation shows the description of the creep rate including the transient and stationary creep rate formulation:

$$\underline{\dot{\varepsilon}}^{v}(t)=\frac{3}{2}\left(\frac{1}{\overline{\eta}_{k}(\sigma)}\exp\left(-\frac{\overline{G}_{k}(\sigma)}{\overline{\eta}_{k}(\sigma)}\cdot t\right)+\frac{1}{\overline{\eta}_{m}(\sigma)}\right)\cdot\underline{M}_{2}\cdot\underline{\sigma} \qquad (1)$$

with:

$$\overline{\eta}_{M}(\sigma)=\overline{\eta}_{M}^{*}\cdot\exp(m\cdot\sigma_{v})\cdot\exp(l\cdot T) \qquad (2)$$

$$\overline{\eta}_{k}(\sigma)=\overline{\eta}_{K}^{*}\cdot\exp(k_{2}\cdot\sigma_{v}) \qquad (3)$$

$$\overline{G}_{k}(\sigma)=\overline{G}_{k}^{*}\cdot\exp(k_{1}\cdot\sigma_{v}) \qquad (4)$$

where σ_v is the equivalent stress, T the rock mass temperature and $\overline{\eta}_{M}^{*}$, $\overline{\eta}_{K}^{*}$, $\overline{G}_{k}^{*}$, m, k_1, k_2 and l material parameters.

3. EXAMPLES

3.1. Shaft in Gorleben, Germany

Figure 1 shows the geometry of the Gorleben shaft in Germany. The relevant shaft 1 has a depth of 926 m. Between shaft 1 and shaft 2 a ventilation system was installed.

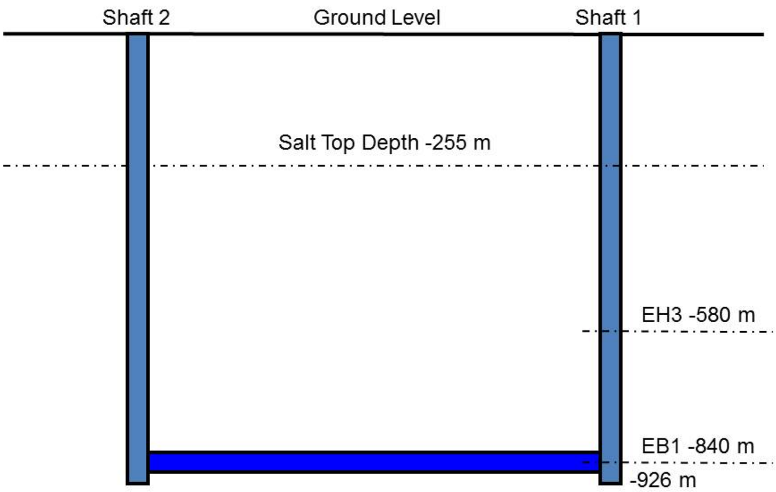

Fig. 1. Geometry of the Gorleben shaft.

Due to this connection between the two shafts there was an air circulation that led with seasonal fluctuations of the ventilation temperature to a difference in shaft 1 of app. 20 K.

Figure 2 shows an exploration of the horizon of the geological survey of the ventilation-induced fractures at a depth of about 370-380 m. More photos of later years indicate that the fractures have closed again due to more favorable mine ventilation. Noticeable in this connection is that the opening widths of the fractures are in upper horizons larger than in greater depth of the shaft. Heusermann and Eickemeier [15] have carried out first tests of numerical studies to demonstrate that the observed macro-fractures caused by the temperature cooling.

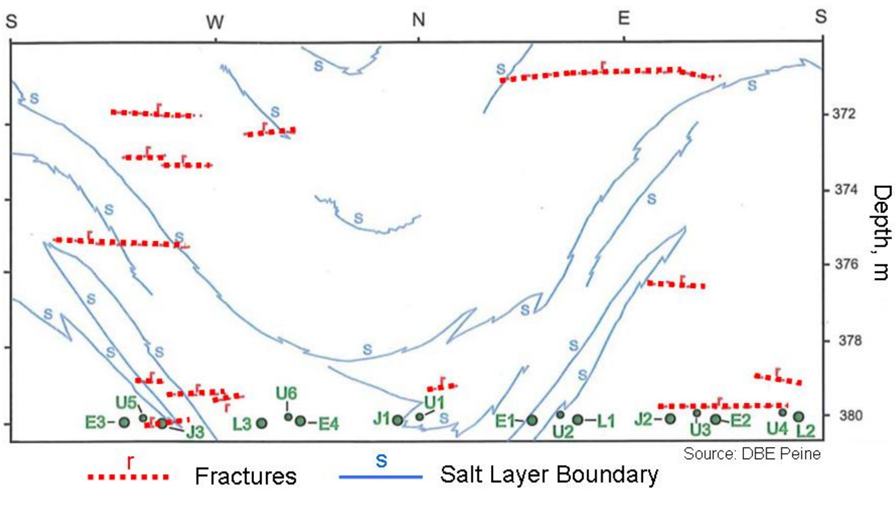

Fig. 2. Fractures in the Gorleben shaft.

This example has been calculated with the finite difference program system Flac3D. The shaft model for the calculations includes a cylindrical quarter model. The radius is 3.75 m and the discretization size at the shaft wall is set at 20 cm in the radial direction. The distance between the outer edges from the shaft axis is 200 m and the model height is set at 50 m.

The depth of the generated model ranges from 545 m to 595 m. In the middle of the model there is a homogenous and isotropic primary stress state of about -12.5 MPa. The primary rock mass temperature is estimated at 305 K with respect to the center of the calculation model.

The calculation model contains 16,875 zones and 19,136 grid points. For the rock salt the time dependent constitutive law Lubby2 is used.

Table 1 shows the elastic and viscous parameters used for the calculations.

Property	Value
E	18,000 – 25,000 MPa
ν	0.25 – 0.35
η_m^*	$6.9*10^{13}$ d*MPa
m	-0.38 MPa^{-1}
l	-0.05 K^{-1}
G_K^*	$5.6*10^3$ MPa
k_1	-0.08 MPa^{-1}
η_K^*	$4,3*10^3$ d*MPa
k_2	-0.03 MPa^{-1}

Table 1. Rock salt mass material properties

For the thermo-mechanical coupled calculations, the following thermal properties in table 2 for the rock salt have been applied.

Property	Value
λ	5.2 W/m/K
c	840 J/kg/K
α_t	$4.0*10^{-5}$ 1/K

Table 2. Rock salt mass properties for thermal calculations

The Gorleben shaft 1 showed due to the ventilation a temperature difference of about 20 K. This temperature difference over a period of approximately 80 days is applied I to the shaft wall in the model. The temperature development over time is shown in Figure 3.

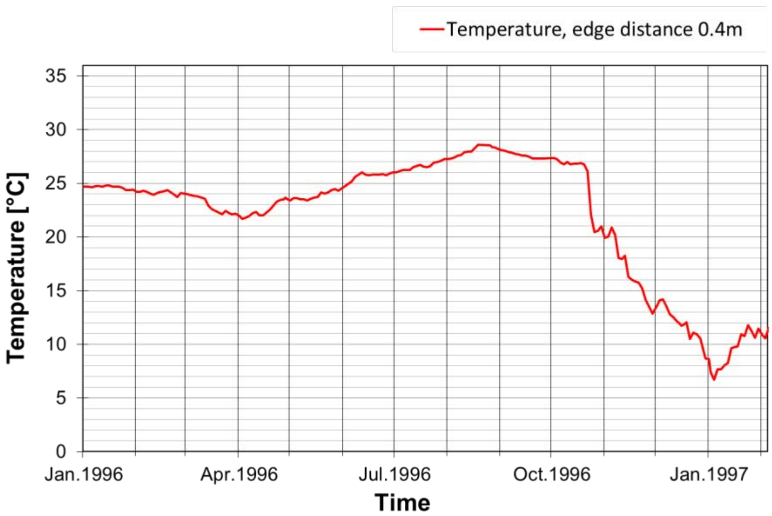

Fig. 3. Temperature development in shaft 1.

After the subsequent temperature decrease to app. T = 280 K (Figure 3) over 80 days the temperature is distributed as shown in figure 4 while the stress state distribution is shown in Figure 5. In the close range model up to a width of 50 m is shown that the vertical stress component σ_z is in a significant tensile stress region with about 8.6 MPa. The circumferential stress σ_φ has approached a range near the tensile stress boundary. Overall, the tensile stress zone extends about 1.6 m into the rock mass.

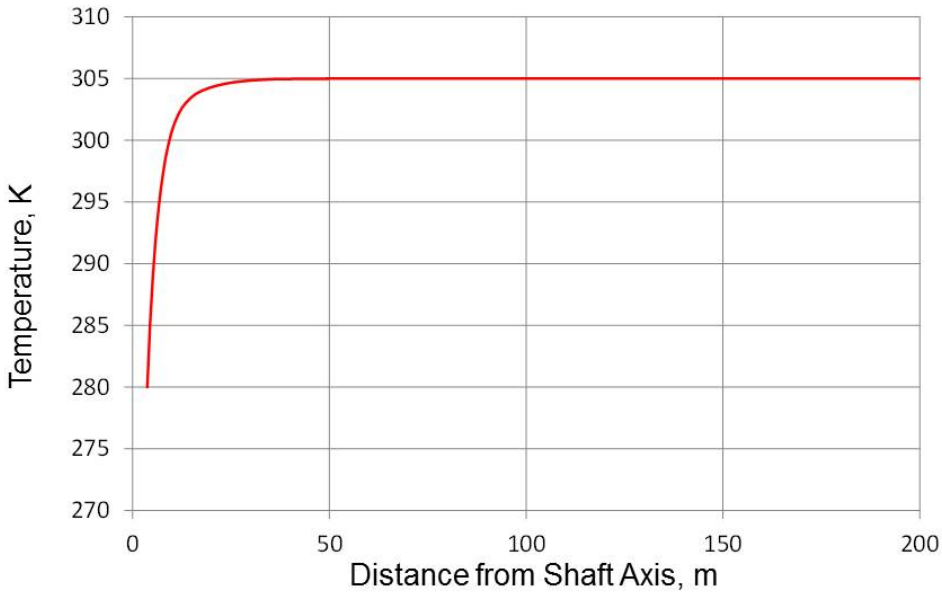

Fig. 4. Temperature distribution in shaft 1.

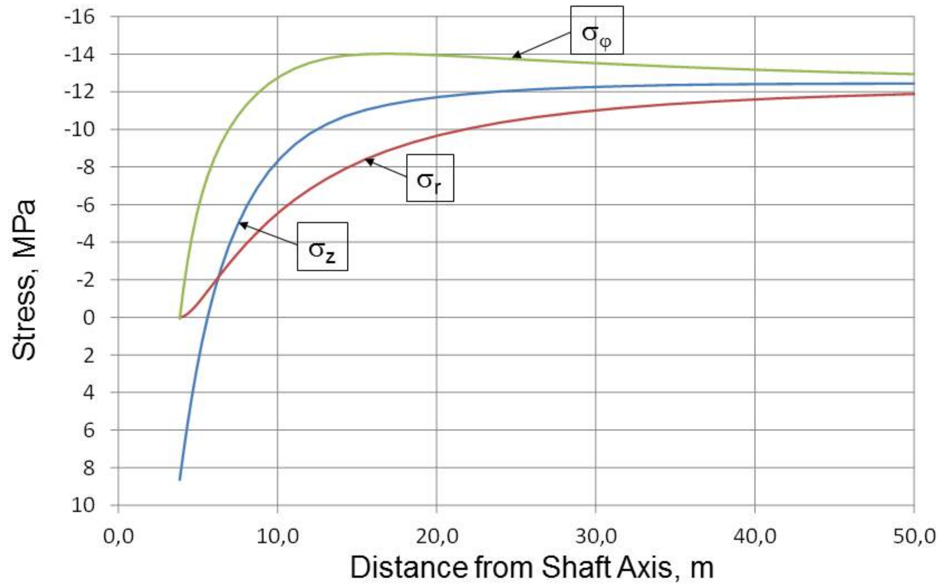

Fig. 5. Stresses in shaft 1 after 80 days of cooling.

From laboratory tests it is known that rock salt only has a very low tensile strength of about 0.5 - 1.5 MPa. In the example considered, the salt would be fractured by calculation already long before the end of the 80-day temperature drop. At this point, at least theoretically the observed evidence of tension fractures is carried out at the Gorleben shaft. With the scheduled parameters and the temperature load case can be concluded that the fractures occurred due to the temperature drop.

But, as a fractured system cannot taken up further tensile stresses, the model has to be recalculated with implemented fracture elements.

Figure 6 shows the calculation model at t = 445 days after the cooling of the shaft of ΔT = 20 K. Clearly visible here is that the fracture elements were taken out of the system during the calculation.

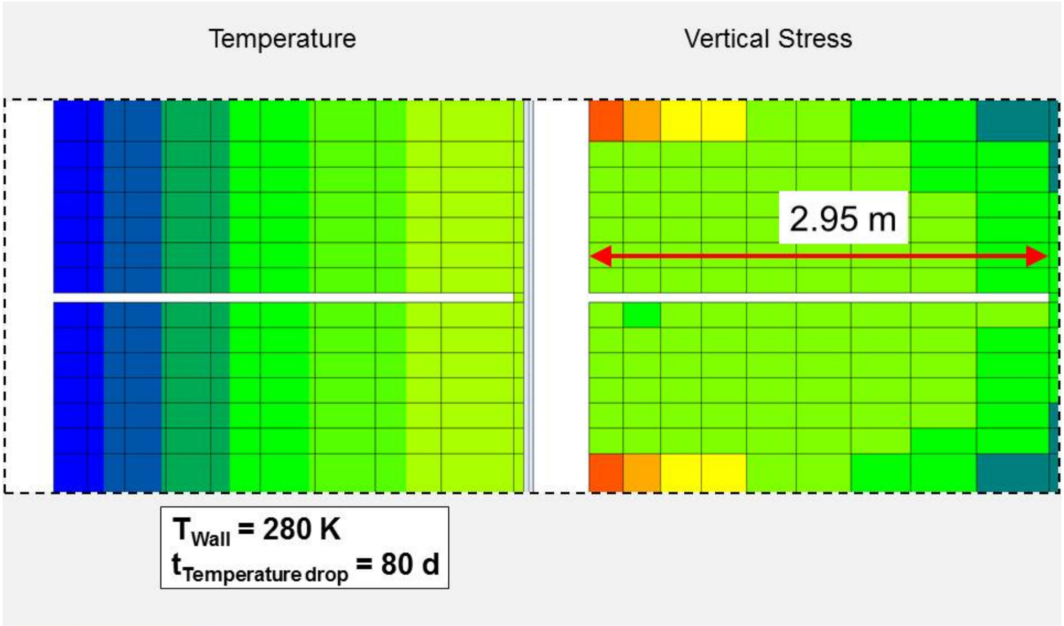

Fig. 6. Temperature and stress distribution after 80 days of cooling.

Comparing the stress state with the stress state calculated at a continuum model without fracture propagation, following facts can be observed:

- The vertical stress component σ_z does not reach the tensile stress.
- The circumferential stress component σ_φ remains clearly in the compression stress.
- After about 5 m distance from the shaft wall the stress states in the continuum and discontinuum model are almost identical.

The propagation of the fracture is approximately 2.95 m and is therefore about 1.35 m longer than the calculated tensile stress zone in the undisturbed calculation model.

3.2. Test mine in Varangeville, France

A temperature test had been performed in a salt mine in Varangeville, France [16]. Figure 7 shows the test site where a temperature drop in a frigorific room has been carried out. The goal of this test was to prove that macroscopic fractures occur due to the temperature drop in the room. With a numerical program system (Flac3D) these temperature changes were recalculated.

Fig. 7. Frigorific room in the Varangeville mine

Figure 8 shows the temperature development over time in the test room. Three cycles were performed with a temperature drop of app. 25 K.

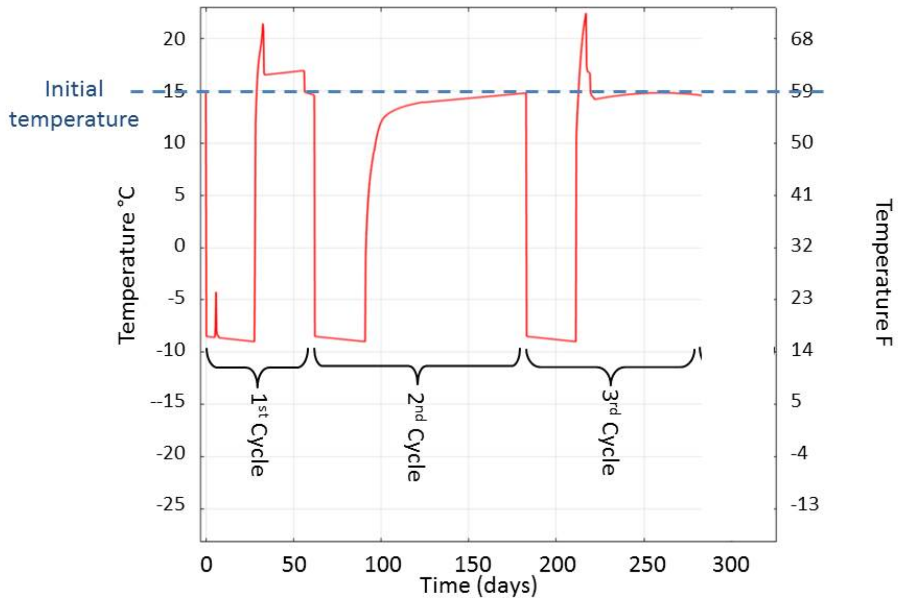

Fig. 8. Air temperature in the Varangeville mine test chamber during the experiment

After the first temperature drop one main macroscopic fracture occurs at the ground surface (figure 9).

Fig. 9. Fractures occurring due to cooling

With the numerical program system the temperature development over the time was recalculated. Subsequently, the stress distribution at the ground surface and in the rock salt below the test site was evaluated.

Over the whole simulation time orthogonal to the surface located stress component σ_z shows values of 0 MPa as this is a boundary condition in this calculation (figure 10). During the first temperature cooling phase starting at t = 100 d the stress components σ_x and σ_y show shortly after starting the cooling phase tensile stress with values of 10 MPa in the maximum. The reason is that the stress state was relatively low with app. 4 MPa before starting the cooling. The temperature drop within a short time of app. 19 K leads to this significant occurrence of tensile stresses. Furthermore due to the relatively shallow depth of the mine it cannot be expected that creep phenomena became important in these stress states.

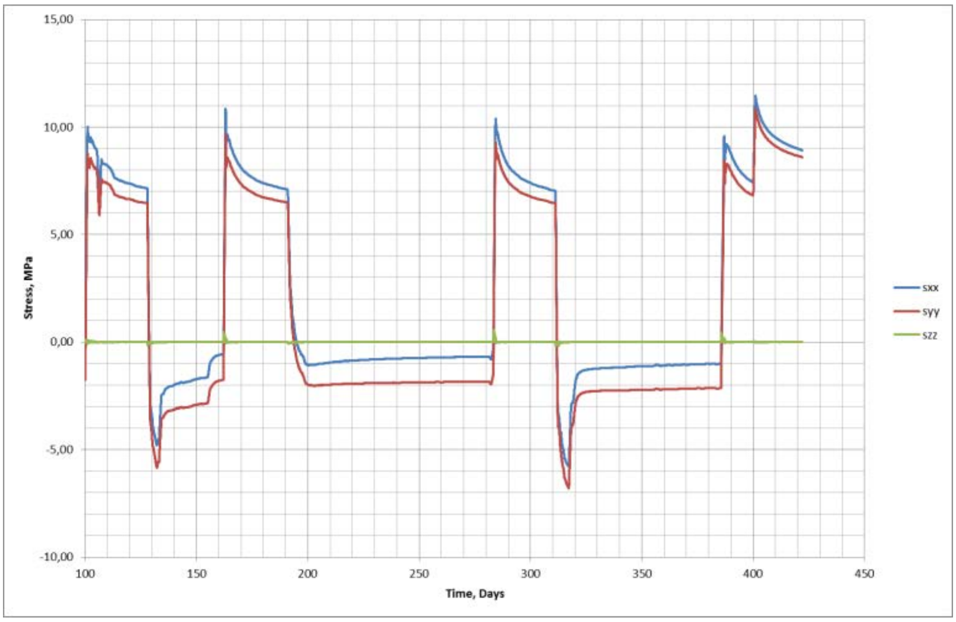

Fig. 10. Stresses vs. time at the ground surface

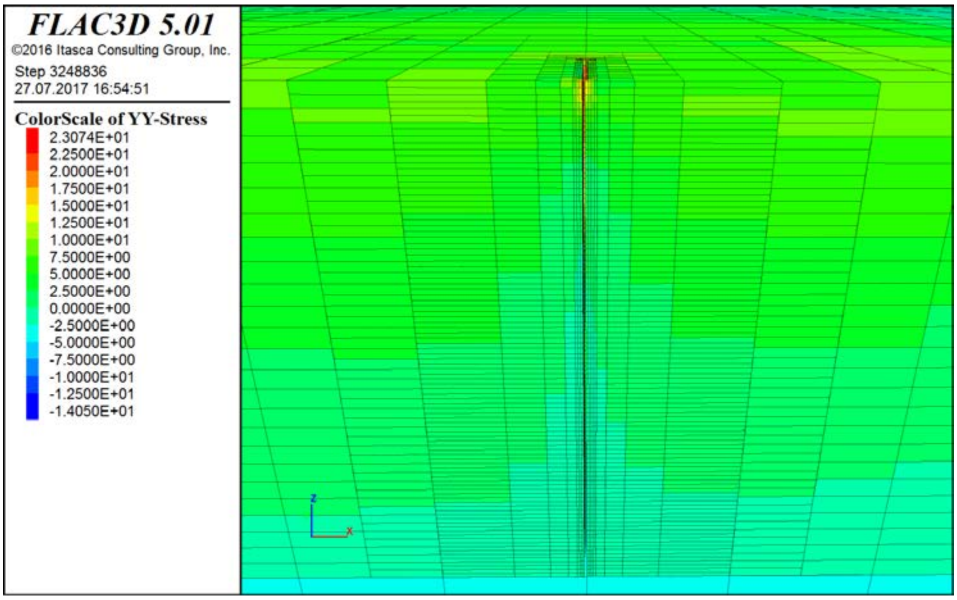

Fig. 11. Y-Stress component in the vicinity of the experiment site with fracture propagation

The results of the stress development show that even app. 100 cm (figure 11) below the ground surface tensile stresses occur in an order of app. 3 MPa. Due to the fact that rock salt has a relatively low tensile strength of 0.5-1.5 MPa it is likely that the fractures propagate into the salt bottom at the test site at least 100 cm into the salt.

4. SUMMARY & CONCLUSIONS

The two introduced examples shows that macroscopic fractures occur due to temperature changes in rock salt masses. It gives an indication of the prevalent stress state in a disturbed system with a progressive fracture (example Gorleben shaft). In the presented model, there is need for further developments, which are clearly the discretization of further fractures in the elements and the consideration of an internal pressure at a cavern wall and finally in the fracture itself.

Taking into account the solution phase of a gas storage cavern may lead to a significant change of the temperature and stress state before starting the operation of a gas storage cavern. We would recommend taking into account these temperature changes of the production phase when carrying out thermo-mechanical coupled calculations for the dimensioning of a gas storage cavern.

From geomechanical point of view it is very likely that a fracture is finite behind a cavern wall, because the primary rock mass stresses are large enough at a certain distance from the cavern to stop the fracture progression. If there are any fractures in a cavern wall (due to irregular shapes, this is likely), this may not lead to immediate loss of stability and tightness of the cavern.

The design of a gas cavern always refers to the envelope of an actual cavern form. While research has not provided proof that fractures are at some distance from the cavity wall finite, it is recommended to avoid tensile stresses when dimensioning the gas withdrawal rate for high cycling storage.

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