Rock mechanical assessment of the maximum pressure gradient and the distance of the caverns to the salt dome edge at Zuidwending gas storage site

Maximum pressure gradient for Cavern A1

For the storage gradient a value must be fixed which must meet two demands:

1. to guarantee the safety regarding the geological tightness
2. to guarantee the safety regarding the technical tightness.

Both cases are the subject of the numerical proof for long term safety, integrity and tightness.

Generally, the maximum storage gradient is determined in relation to the overburden gradient, which could be derived from the identification of geological layers in the overburden or from an in-situ stress measurement. If both methods are compared the identification of the geological layer, i.e. the determination of the different densities of the layers, is the more conservative approach because additional pressure/stress components, i.e. caused by the salt dome uprise movement, are not considered. This could be shown for different location.

Commonly, the maximum pressure gradient is between 0.75 and 0.85 of the overburden gradient.

For the Zuidwending salt dome the overburden gradient is 0.212 bar/m and the ratio is 0.85 in the case of a maximum storage gradient of 0.18 bar/m. By the numerical analysis both demands, those for the technical tightness as well as those for the geological tightness, could prove to be fulfilled when this gradient is applied.

From the practical point of view a lot of different gas storages at different location, inter alia, the salt domes in Northern Germany are successfully operated under pressure conditions resulting from a gradient of 0.18 bar/m.

That's the reason why SodM fixed the value during a meeting with the former Zuidwending VOF, a consortium between Gasunie Zuidwending BV and NUON Zuidwending BV and IfG in Den Haag on 28. May 2008.

The initial state of stress is not influenced by the salt dome edge because the suggested distance between last cemented casing shoe and the edge of the salt dome is certainly large enough to prevent an interaction. Further details are described in the following chapters.

In-Situ Stress

Over geologic time frames, salt creeps in a manner that relieves any stress differences. Stress differences in the salt will promote salt motion in direction of the minimum principal stress until stress equilibrium is reached. In contrast, the sediments outside the salt dome can sustain relatively large shear or differential stresses. This allows the in-situ stress distribution in the sediments to become highly anisotropic (i.e. the horizontal stresses are not equal to the vertical stress).
The far-field stress conditions in a sedimentary basin are normally assumed to be under gravitational loading (i.e. no lateral strain occurs during the formation of the overlying strata). This results in the far-field horizontal stress in the dome surrounding sediments being only a fraction of the vertical stress, typically between 50 and 70% of the vertical stress (0.5 to 0.7). Additionally, a negligible difference generally exists between the minimum and maximum far-field horizontal stresses (Frederich et al. 2003).

A typical approach in numeric modelling is to simulate a long-term creep (10,000 years or more) to allow the salt to reach a nearly isotropic stress state while generating a highly anisotropic stress field in the sediments. Figure 1 illustrates an example of the in-situ stress along a horizontal profile at a depth of 1,050 m for a far-field horizontal to vertical stress of 0.7 in the sediments. As shown in this figure, the stresses within the salt are nearly equal, while the sediments that are adjacent to the salt dome experience a significant increase in the radial stress and a decrease in the tangential stress when compared to the far-field horizontal stress conditions.

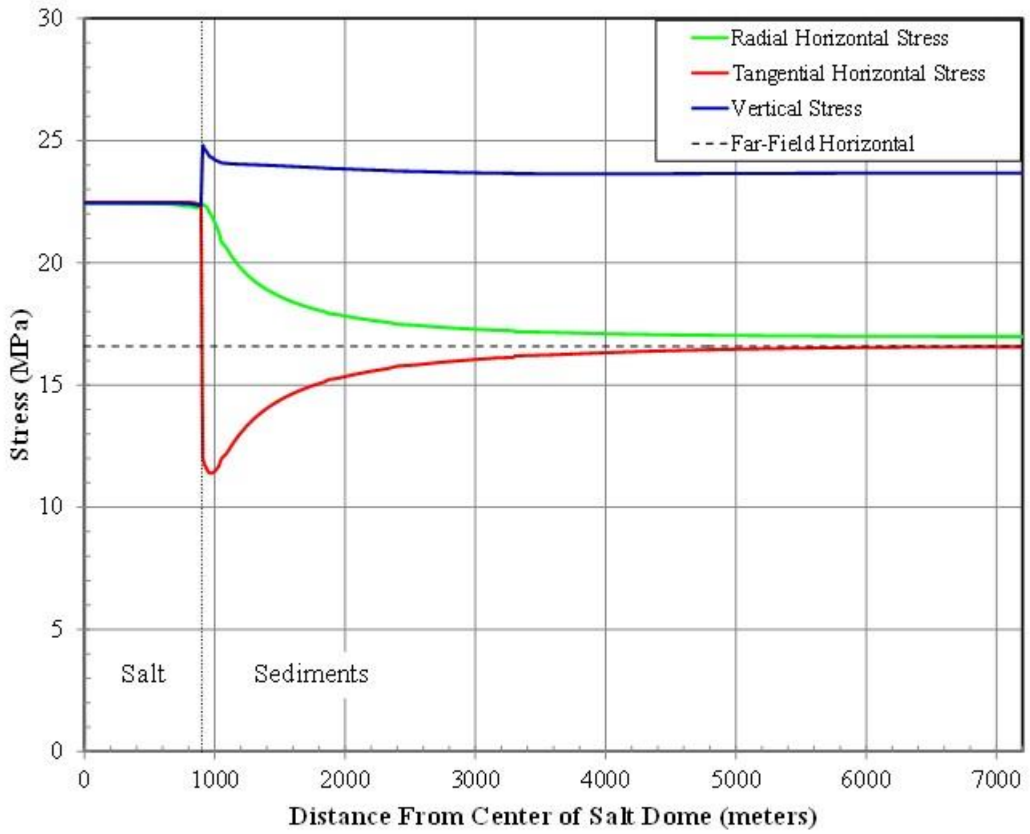

Figure 1. *In-situ stress state in the salt and sediments prior to cavern development for a Far-*field Horizontal to Vertical Stress Ratio of 0.7.[1]

[1] SMRI, RP-2017: "Caverns near domal boundaries". currently in press

Numerous researchers have used similar numerical modelling techniques to determine a representation of the in-situ stress state surrounding salt structures (Fredrich et al., 2003; Koupriantchik et al., 2005; Minkley W. et al 2010.; Sanz and Dasari, 2010, Van der Zee et al.,2011; Günther, R.-M. & Salzer, K. (2007)). The newest calculations (2017), carried out as a kind of benchmarking, bases on the initial situation for a salt dome in North Germany as shown in Fig. 2

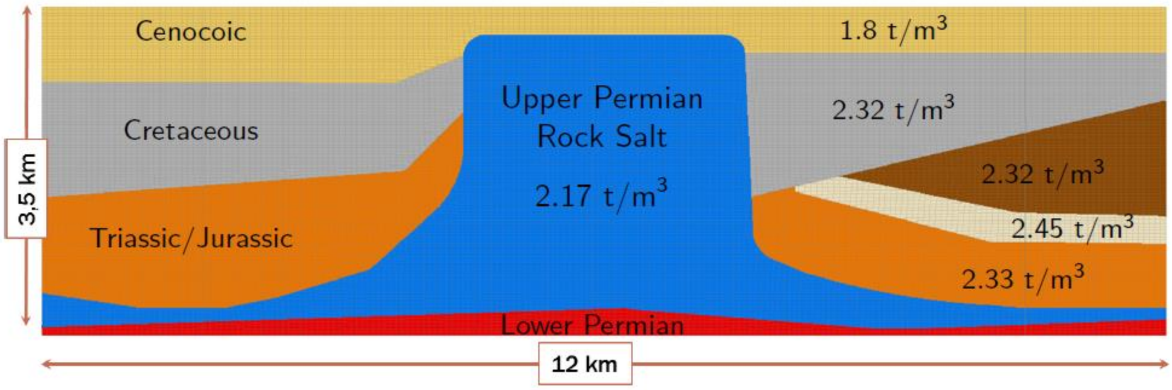

Figure 2. *Numerical simulation of salt dome uprise – initial conditions with the upper Permian salt body in the centre (density 2.17 t/m³)*

The observation that some salt domes are still continuing to evolve, to grow, or to actively deform today may indicate that stresses within a salt dome are not entirely isotropic or lithostatic (see Fig. 3). Very small deviatoric stress occur causing the salt movement. Note, the calculated uplift rates are less than 0.1 mm/a[2].

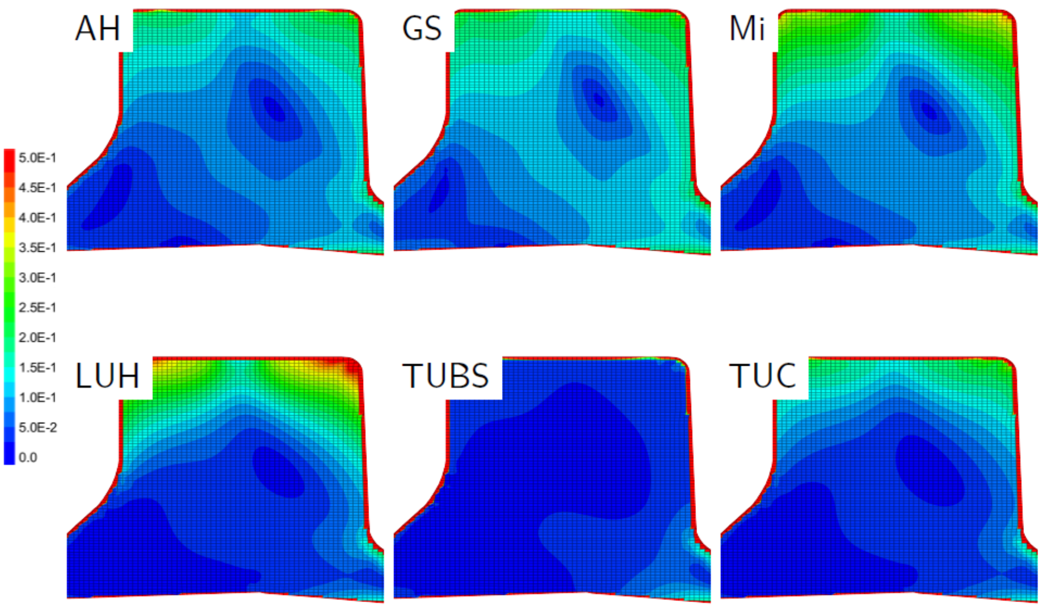

Figure 3. *Numerical simulation of salt dome uprise – effective stresses with respect to different constitutive models*

[2] Figures are from the WEIMOS research project Verbundprojekt: Weiterentwicklung und Qualifizierung der gebirgsmechanischen Modellierung für die HAW-Endlagerung im Steinsalz (WEIMOS)

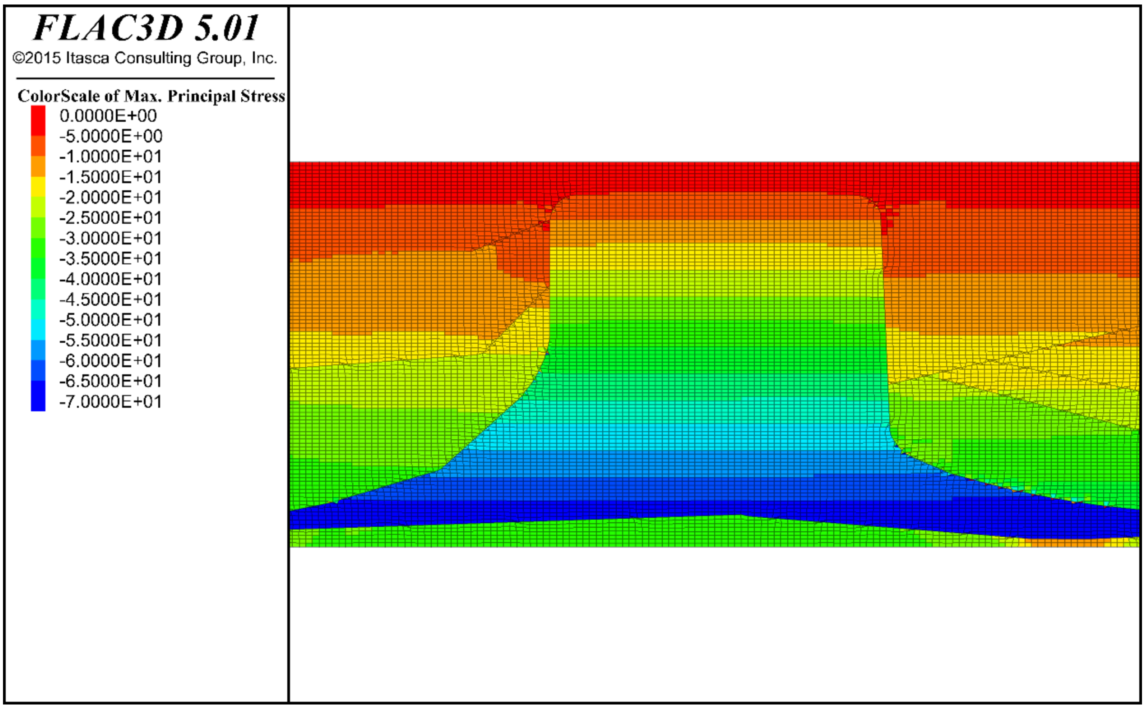

Figure 4. *Numerical simulation of salt dome uprise – minimum principle stresses as exemplarily predicted by the model* ***"Mi"*** *in Fig.3*

From the distribution of the minimum principles stress surrounding the salt dome as well as in the salt dome itself one can see a very sharp transition at the salt dome edge, like allready stated in Fig.1.

Note, there is no evidence for any kind of influence to caverns 150 … 200 m far inside the salt dome.

Cavern design

All geomechanical assessments performed so far to investigate various factors that could potentially affect the geomechanical behaviour of caverns located near the dome boundary have shown that factors like the in-situ stress, the behaviour of the salt and sediments, the salt web thickness, the cavern diameter, height, depth, and cavern pressure have to be taken into account.

Some modelling results (Zapf 2014) suggest as critical component to the design of a cavern near the salt dome boundary the ratio of the salt pillar or web thickness (P) to the cavern diameter (D). The results of these studies indicate as the P/D ratio decreases, the tangential stress becomes less compressive, and the potential for salt dilation increases in the salt web when the pressure in the cavern is increased (pressure driven permeation/percolation).

In addition to the in-situ stress state, an accurate estimate of the in-situ temperature is critical in the salt because the creep rate of salt is highly temperature dependent. Temperature variations going from centre of salt dome to the dome periphery may also change as salt has a thermal conductivity which is greater than most other rock types. Therefore, the thermomechanical behaviour of the salt should be incorporated within the model to simulate the variation in creep rate with temperature variations.

Anyhow, the influence of a possibly desired cyclic gas storage operation on the salt web, especially in respect to an associated surplus in thermodynamic loads, needs to be assessed by numeric modelling and by application of appropriate criteria. Such criteria may be the dilatancy criterion, comparable to the damage potential criterion, and the minimum principle stress criterion, also to prevent the development of hydraulic connectivity through the salt web.

Corresponding preliminary safety considerations has to be done already during the planning. From today's perspective, the approach of IfG applied already between 2005 and 2007 to fix the position of the last cemented casing shoe of cavern A1 were correct even if the newer findings are considered.

For cavern A1 which is intended to have a final maximum diameter of 90 m the distance of at least 152 m can be derived from the cavern location planning. This distance is sufficient to prevent a rock mechanical influence from the cavern to the salt dome edge as well as an influence vis versa.

References

Fredrich, J.T., Coblentz D., Fossum A.F. & and Thorne, B.J. 2003. Stress perturbations adjacent to salt bodies in the deep-water Gulf of Mexico. SPE 84554. *Society of Petroleum Engineers Annual Technical Conference and Exhibition, October 5–8, 2003, Denver, Colorado.*

Koupriantchik, D., Hunt, S.P. & Meyers, A.G. 2005. Generic and field examples of geomechanical modelling of creep behaviour in salt diapirs towards predicting localised stress perturbations. *Proc., 40th U.S. Rock Mechanics Symposium, June 25–29, 2005.* Anchorage: University of Alaska Anchorage.

Luo, G., Nikolinakou, M.A., Flemings, P.B. & Hudec, M.R. 2012. Geomechanical modelling of stresses adjacent to salt bodies: part 1–uncoupled models. *American Association of Petroleum Geologists Bulletin,* 96 (1): 43–64.

Minkley W. et al 2010. *Final Disposal in Rock Salt- Geomechanical Assessment of the Barrier Integrity. 2010 ARMA, American Rock Mechanics Association . The 44th US Rock Mechanics Symposium and 5th U.S.-Canada Rock Mechanics Symposium, held in Salt Lake City, UT June 27–30, 2010.*

Günther, R.-M. & Salzer, K. (2007): *A model for rock salt, describing transient, stationary, and accelerated creep and dilatancy.* – In: K.-H. Lux, W. Minkley, M. Wallner & H.R. Hardy, Jr. (Hrsg.): Basic and Applied Salt Mechanics; Proc. of the Sixth Conf. on the Mechanical Behaviour of Salt (Saltmech 6), Hannover, Mai 2007, S. 109–117, Taylor & Francis (Balkema), London.

Sanz, P.F. & Dasari, G.R. 2010. Controls on in-situ stresses around salt bodies. *Proc., 44th US Rock Mechanics Symposium, 27–30 June 2010*. Salt Lake City: American Rock Mechanics Association, Alexandria, Virginia.

van der Zee, W., Ozan, C. and Brudy, M. & Holland, M. 2011. 3D geomechanical modeling of complex salt structures. *SIMULIA Customer Conference*, *Barcelona, Spain, May 16–19, 2011.*

Zapf, D. 2014. Rock Mechanical Dimensioning of Gas Storage Caverns in the Salt Dome Region. *Solution Mining Research Institute Fall 2014 Meeting, Groningen, The Netherlands, September 29-30.* Clarks Summit: Solution Mining Research Institute.

Leipzig. 11.10.2017

Dipl.-Phys. D. Brückner

Project Manager