Evidence for two different creep mechanisms in rocksalt

Solution mining in the Barradeel concession

Earlier studies (van Eijs et al, 2000) on this case were aimed at predicting the land subsidence from the then limited set of production and monitoring data. Subsidence in the bowl centre after two years of production registered just a few centimetres. However, after almost 8 years of production, subsidence at the bowl centre has increased to its present level of about 28 cm and is nearing the set limit. This paper deals with the question of how subsidence can be predicted in the later production and abandonment phases by means of an integrated analysis of the available field data, using numerical modelling and supported by the available log, core and production data.

This article is based on the paper: J.N. Breunese, R.M.H.E. van Eijs, S. de Meer, I.C. Kroon (2003) Observation and prediction of the relation between salt creep and land subsidence in solution mining – The Barradeel case, presented on the SMRI conference in Chester, UK, 2003.

Solution mining off halite is being carried out at a record depth of around 2,800 metres from two caverns in the Zechstein Formation in the Barradeel concession in the Netherlands. Frisia Zout B.V. (formerly: Frima) has been mining these caverns near the west coast of the province of Friesland, near the Wadden Sea, since 1995.

An upper limit of 35 cm has been set to the subsidence in the centre of the bowl. This limit stems from the delicate water management in the area, mostly lying beneath sea level and protected from the sea by dikes and a system of pumped polders. This necessitates a specially devised operational solution-mining plan.

Geological setting of the Barradeel caverns

The overburden of the Zechstein Formation in the Barradeel concession mainly consists of near horizontal layers of siliclastic rocks and chalk.

The Zechstein Formation itself (Figure 1) also has little tectonic deformation and consists of near horizontally bedded layers in several evaporitic cycles. Halite from the second cycle (Z2, Stassfurt) is being mined. This cycle is complete and there is a layer of potassium salts (mainly carnallite) present near the top Z2. At the Barradeel site this carnallite layer is thicker (40 m) than elsewhere (on average 8 m). The third cycle (Z3, Leine) mainly contains rocksalt, and the younger Zechstein evaporite cycles are incomplete and much thinner. The two caverns BAS-1 and BAS-2 are developed in the 515 m thick Stassfurt cycle with a distance of 500 m between them and a height of 350 m.

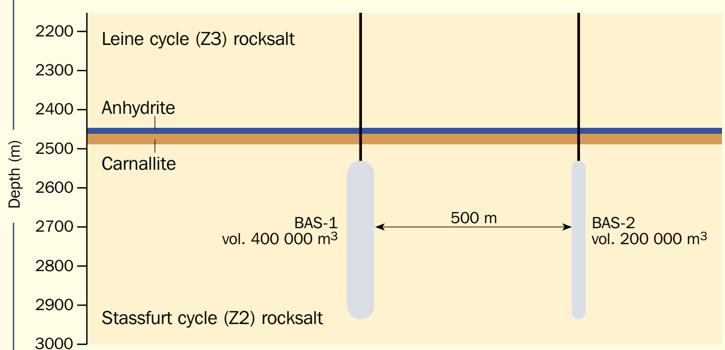


Figure 1. Setting of the caverns BAS-1 and BAS-2 (situation 2002)

Field data

The main field data used in this research are subsidence data (from levelling surveys), production rate, brine concentration and cavern volume (from echometric measurements). Mass-balance modelling using these parameters (Breunese et al., 2003) enables the calculation of the convergence volume, i.e. the volume of rocksalt which creeps (converges) into the cavern. From 1998 onwards a steady state situation of the cavern volume has existed. This implies that all mined salt is related to 'converged' salt. The most important parameters used in this study are the maximum subsidence (Z_{max}), convergence volume (V_k) and the ratio between them (Z_{max}/V_k).

Numerical modelling

Introduction

The following research objectives have been pursued:

- Create a numerical Finite Element model representing the Barradeel setting.
- Simulate cavern convergence V_k, land subsidence Z_{max} and the ratio Z_{max}/V_k using initially estimated values for the creep parameters from the material balance model and core observations.
- Make a history model match.
- Predict the effect on land subsidence of closing the caverns, using the history-matched model.

General model features

The Finite Element code DIANA (developed by TNO DIANA B.V.) has been used to perform the numerical calculations. It is based on the displacement method (De Witte, 2003). Constitutive material laws for rocksalt (primary creep and secondary creep laws) based on Fokker (1995) are incorporated in the code. An Excel routine has been written to calculate the convergence volume per time step from the incremental displacements (both horizontal and vertical) along the cavern wall.

In order to minimise calculation time an axi-symmetric model has been designed (Figure 2) on the assumption that the cavern and its surroundings are symmetrical. The model grid consists of 5000 quadratic elements (Figure 3). The vertical boundaries of the model are constrained for horizontal displacements, while the bottom of the model is constrained for vertical displacements. The pressure difference (difference between the brine pressure and lithostatic pressure) is modelled as a pressure load normal to the cavern wall.

The different geological formations have been represented in the model as horizontal layers with elastic properties (Table 1; Figure 2). The model cavern comprises the combined volume of the caverns BAS-1 and BAS-2, with a height of 370 m, a radius of 23 m and volume of 0.615 Mm³.

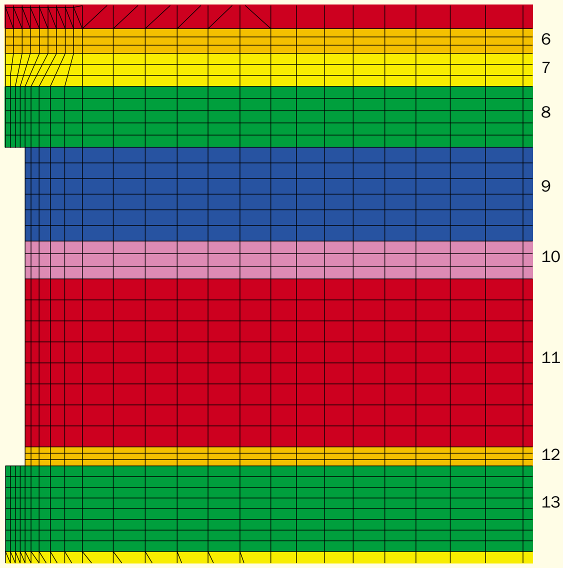


Figure 3. Cavern geometry: radius of 23 m, height of 370 m and volume of 0,615 Mm³

Table 1. Mechanical properties of the geological formations as applied in the FE-model

Layer	Layer no.	Depth (m)	*E* (GPa)	ν	ρ (kg/m³)
Quarternary	1	0 - 597	0.125	0.25	1950
Tertiary	2	597 - 1113	0.125	0.25	2300
Cretaceous	3	1113 - 1434	5.0	0.25	2250
Jurassic	4	1434 - 2240	7.5	0.3	2230
Z3 halite	5	2240 - 2432	11	0.35	2185
Z3 anhydrite	6	2432 - 2462	30	0.35	2900
Carnallite	7	2462 - 2500	5.5	0.35	1600
Z2 halite	8 - 13	2500 - 2725	11	0.35	2185
Z2 anhydrite	14	3042 - 3600	25	0.3	2700

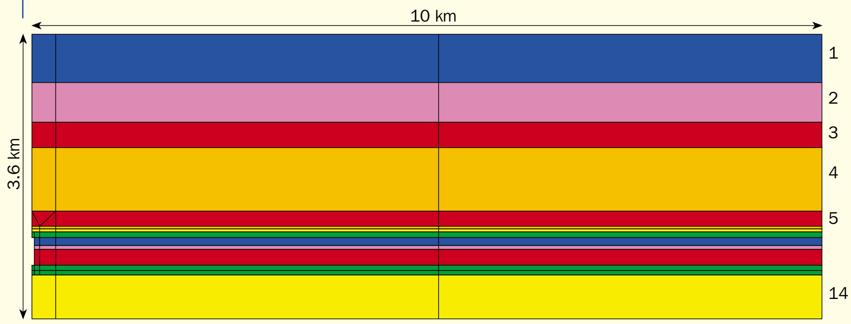


Figure 2. Geometry of the axi-symmetrical FE-model

The Initial creep model

The initial estimates for the dislocation creep parameters (Table 2) were derived from the material balance model analysis (Breunese et al. 2003) using (Brouard, 1999)

$$\dot{\varepsilon} = A_1 \sigma^n \exp\left(-\frac{Q_1}{R \cdot T}\right) \qquad (1)$$

Using these parameters for the dislocation creep, results show a reasonable fit for subsidence (Z_{max}) and production (V_k) but no fit for the Z_{max}/V_k ratio. Further research (Breunese et al. 2003) shows that another creep mechanism has to be incorporated to fit all measured data. The preconditions for this mechanism compromise a fast strain rate at low differential stresses and a low value for *n*.

Model equation

Pressure solution creep is the only creep mechanism described in rocksalt that fulfils the above-described preconditions. Micro-structural observations (Urai et al., 1987; Spiers & Carter, 1998) of experimentally deformed natural samples indicate that linear pressure solution creep is important during deformation of wet polycrystalline halite. Consequently, when modelling the mechanical behaviour of the rock salt of the Zechstein Z2 salt around the solution mined caverns at the Barradeel concession, fluid-assisted pressure solution creep has to be taken into account. The total strain rate is described by the constitutive material law

$$\dot{\varepsilon}_{tot} = \dot{\varepsilon}_{dc} + \dot{\varepsilon}_{ps} = A_1 \sigma^n \exp\left(-\frac{Q_1}{R \cdot T}\right) + B \frac{\sigma}{T \cdot d^3} \exp\left(-\frac{Q_2}{R \cdot T}\right) \quad (2)$$

where the subscript *dc* stands for dislocation creep and *ps* for pressure solution creep. Temperature ($T = 377$) is in K, stress (σ) in MPa, effective grain size (d) in mm and the gas constant (R) in kJ/mol. A_1, A_2 ($= B/Td^3$), Q_1, Q_2 and n are material parameters. B is 4.7E-4.

Figure 4 demonstrates that an effective grain size of 1.95 mm results in the best fit with production history.

Table 2. Creep parameters as applied in the initial creep model

Layer	Layer no.	Depth (m)	A_1 (MPa^{-n}·day^{-1})	n_1	Q_1/R (K)	A_2 (MPa^{-1}·day^{-1})	Q_2/R (K)	d (mm)
Z3 halite	5	2240-2432	1.71	3.6	6206	7.3E-4	3007	5
Carnallite	7	1462-2500	2	4	9021	-	-	-
Z2 halite	8-13	2500-2725	1.71	3.6	6206	14.6E-3, 7.3E-4, 7.3E-4, 7.5E-5	3007	1.95, 2.45, 5.3, 11.3

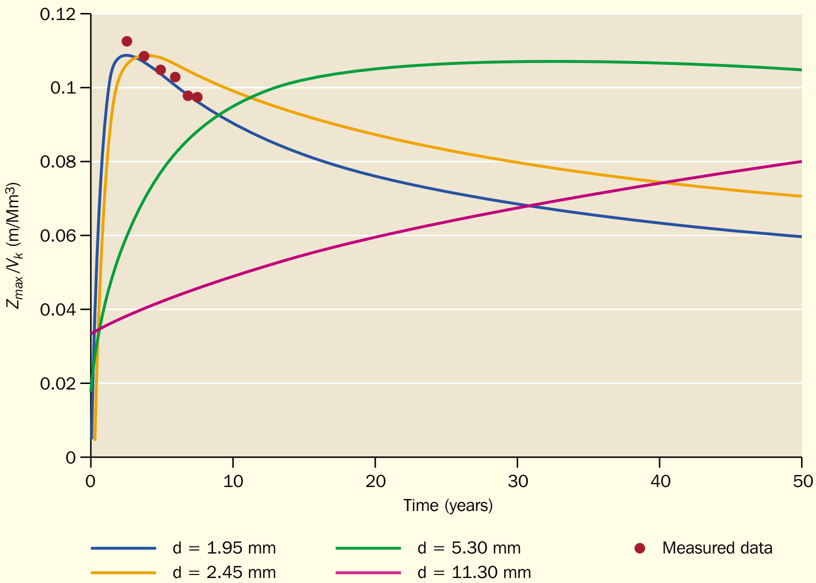
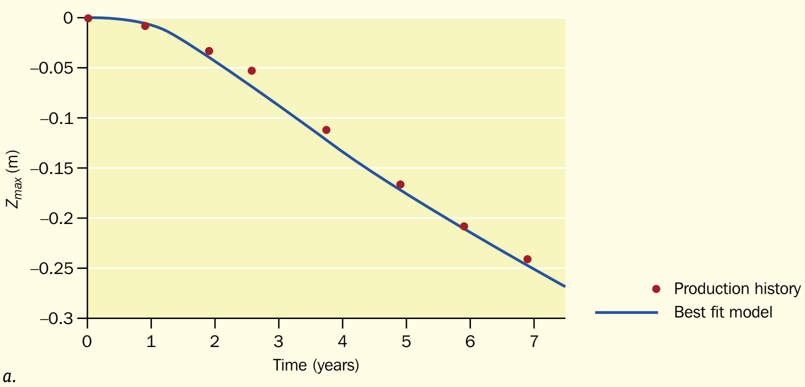


Figure 4. Z_{max}/V_k for model variations in effective grain size and, thus, pressure solution strength



The best fit model

Incorporating pressure solution creep into the model results in a good fit with the Z_{max}/V_k ratio but an overestimation of the individual parameters of this ratio due the increased total strain rate. To overcome this increase the dislocation creep 'strength' is lowered by a factor of 0.46 which leads to an excellent history match of all measured data.

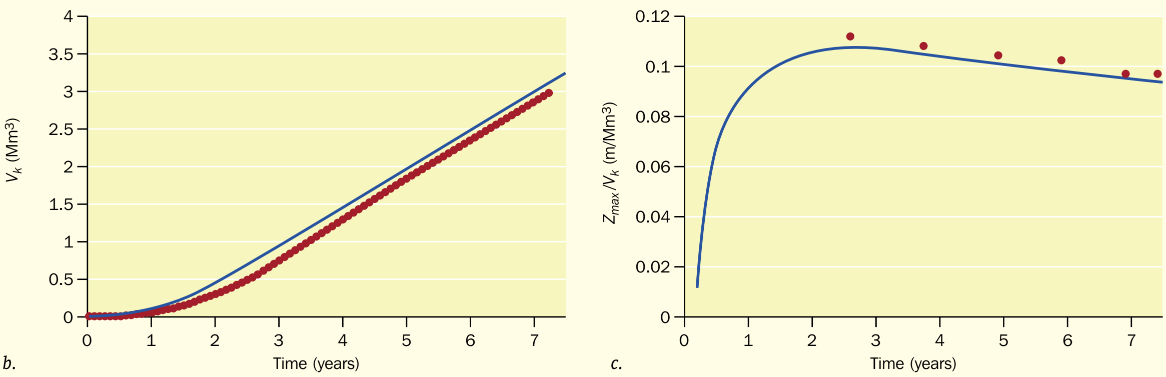


Figure 5. History match of a) the maximum subsidence at the surface, b) the cavern convergence and c) Z_{max}/V_k ratio

Discussion

The Z_{max}/V_k ratio is constrained by data, except for the first three years. In the early period, the optimum fit FE-model (as well as all other tested models) predicts a strong rise of Z_{max}/V_k followed by a decreasing trend (Figure 5c). We interpret this observation as being related to the interference between stress arching and bending forces within the overburden. Stress arching can be described as the effect of cavern geometry on the subsurface stress field.

During the first stage of production the volume of differential stress around the cavern is very small, while arching of the overburden above the cavern is highest. Stress arching hinders bending of the overburden, resulting in a low Z_{max}/V_k ratio. As time passes, the volume of differential stresses around the cavern will increase as a result of salt creep. An increase of the differential stress volume leads subsequently to a decrease of the arching effect, in turn resulting in more bending of the overburden. This is demonstrated by an increase of the Z_{max}/V_k ratio. Subsequent bending of the overburden introduces stress differences in the salt below the elastic overburden as a result of bending forces. These deformation-induced stresses from the overburden are the driving force behind the decline of the Z_{max}/V_k ratio.

A mechanism is needed to translate the small differential stresses into relative high strain rates, hindering further bending of the overburden. Pressure solution creep is the best candidate for this process. Rebound will counteract subsidence due to cavern convergence during production, but the latter is strongly dominant. It is therefore difficult to see an expression of the rebound of Z_{max} during the production. The Z_{max}/V_k ratio on the other hand can reveal rebound during production.

Subsidence prediction (example)

Assumed operational scenario

As an illustrative application of the history matched numerical model, a prediction for Zmax is presented based on the following operational scenario:

- Phase1, Year 1: development of the two caverns: linear pressure difference build-up from 0 to 26 MPa, Year 1 to year 8: production at a constant pressure difference Δp of 26 MPa.
- Phase 2, Year 8 to year 8.73: production from only one cavern, the other being hard shut-in;
- Phase 3, Year 8.73 to year 100: both caverns hard shut-in.

Phase 1 covers the eight-year production history to date. The subsequent phases represent the predictive part of the simulation, assuming hard shut-in, i.e. bringing the caverns to lithostatic pressure (i.e. $\Delta p = 0$).

Phased numerical analysis

In order to closely follow the operational scenario, a phased analysis has been used in the FE analysis. This approach allows for the boundary conditions of the model to be changed while the internal stresses of a former phase are maintained. Thus, Phase 2 of the operational scenario was simulated by halving the volume of the cavern through adding in elements. At the start of Phase 3 the cavern was totally filled .

Results and discussion

The result again shows the excellent fit with the production history during Phase 1 (Figure 6).
In Phase 2 a strongly declining subsidence rate is predicted, while production continues from only one cavern. Subsidence comes to a halt after about one year. After shutting the second cavern as well, a surface uplift is predicted with an initial rate of some 1 cm/year.
In the long term (t > 50 years), Z_{max} seems to asymptotically approach a value of around 10 cm.

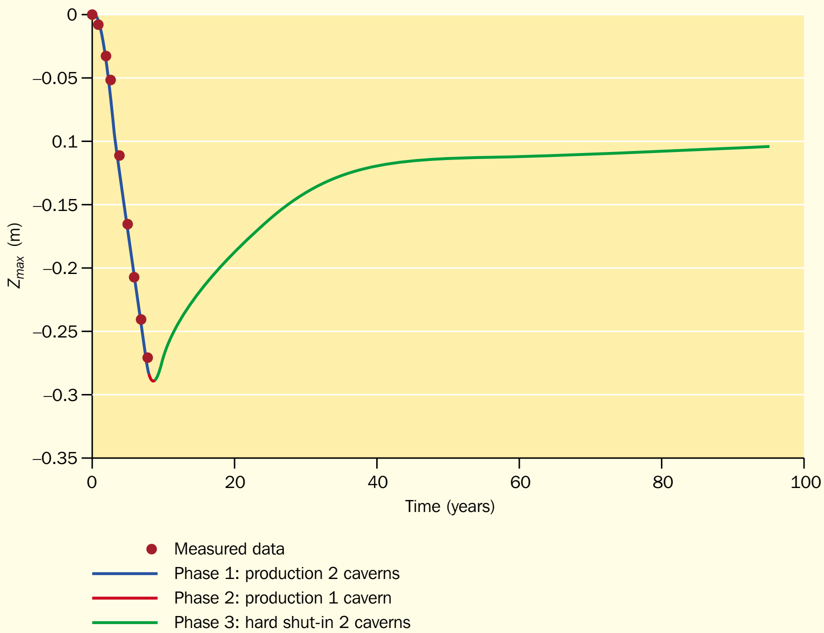


Figure 6. History match and prediction of the maximum subsidence following a phased scenario of shutting-in the caverns (see text)

Conclusions

In the illustrative example that has been presented, two creep phenomena (power law dislocation creep and linear pressure solution creep) that fit all measured data have been identified. The latter is shown to govern the deceleration of subsidence as a function of convergence, represented by the ratio Z_{max}/Vk. Cavern convergence itself is most likely governed by a combination of both creep processes The history matched numerical model can be used for subsidence predictions under prescribed operational scenarios.

The above observations are of interest from a scientific point of view: as far as we know, this is the first observation of two very different creep mechanisms simultaneously acting in situ in rocksalt. The Barradeel solution mine is indeed the deepest in the world and mechanical processes are likely to be different from other solution mines at lower depths.

From the point of view of safety and commercial interests, the following benefits have been found:

a. the net effect of the pressure solution creep is to slow down subsidence during the solution phase;

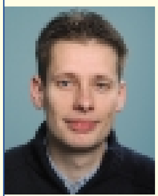
b. a significant rebound is predicted after cessation of the solution and squeeze phases. Therefore, salt production may be extended for a longer period of time than previously thought and the risk of exceeding the 35 cm limit is significantly reduced.

Acknowledgements

We thank FRISIA ZOUT B.V. for their kind permission to use the Barradeel data. We are grateful to Gerard Kruse and Jitse Pruiksma from GeoDelft for valuable discussions on pressure solution creep.

References

- *Breunese, J.N, van Eijs R.M.H.E., de Meer, Kroon I.C.* (2003) Observation and prediction of the relation between salt creep and land subsidence in solution mining – The Barradeel case. Proc. SMRI conference Chester, UK
- *Brouard, B. & Bérest, P.* (1999) A tentative classification of salts according to their creep properties. Laboratoire de Mécanique des Solides, Ecole Polytechnique, Palaiseau, France
- *Carter, N.L., Horseman, S.T., Russel, J.E. & Handin, J.* (1993) Rheology of rocksalt. J. Struc. Geol., 15, pp. 1257 - 1271
- *De Witte, F.C.* (2003) DIANA User's Manual, Release 8.1, Second ed.
- *Engelhardt, H.J., Gaertner, R., Hellberg, C.* (2000) The production of halite of high purity. In: 8th World Salt Symposium. Geertman, R.M. (ed.), vol. 1, pp. 107 - 112, Elsevier.
- *Fokker, P.A.* (1995) The behaviour of salt and salt caverns. PhD thesis. Technical University of Delft, 143 pp.
- *Fokker, P., Bakker, T., Wilke, F.H. & Barge, H.J.* (2002) Aspects of deep salt mining Salt mining by FRISIA ZOUT B.V. Technical Paper, Solution Mining Research Institute, Fall 2002 Meeting, Bad Ischl, Austria, 10 pp.
- *Spiers, C.J. & Carter, N.L.* (1998) Microphysics of rocksalt flow in nature. In: M. Aubertin & H.R. Hardy (Eds.) The Mechanical Behaviour of Salt: Proceedings of the Fourth Conference Series on Rock and Soil Mechanics, 22, TTP Trans Tech Publications, Clausthal-Zellerfeld, pp. 115 - 128
- *Urai, J.L., Spiers, C.J., Peach, C.J., Franssen, R.C.M.W. & Liezenberg, J.L.* (1987) Deformation mechanisms operating in naturally deformed halite rocks as deduced from microstructural observations. Geol. Mijnbouw, 66, pp. 165 - 176.
- *Van Eijs, R.M.H.E., Pöttgens, J.J.E. Breunese, J.N. & Duquesnoy, A.J.H.M.* (2000) High convergence rates during deep salt solution mining in the northern part of The Netherlands. 8th World Salt Symposium, 1, pp. 237 - 242.



Information:
Rob van Eijs
T +31 30 256 45 11
E r.vaneijs@nitg.tno.nl

Jaap Breunese
T +31 30 256 45 07
E j.breunese@nitg.tno.nl