High convergence rates during deep salt solution mining in the northern part of The Netherlands

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Salt is extracted from two caverns in the northern part of The Netherlands at a depth of 2890 m by solution mining, which makes it the deepest solution mine in the world. Before production start, research has been performed to predict salt production, convergence rates of the caverns and, as a result of this, land subsidence. Core experiments executed prior to production, showed secondary creep rates around $10^{-8.5}$ s^{-1} at a difference of 10 MPa between the highest and lowest principal stress. A power law fitted through the laboratory data was used in FE program based numerical experiments in combination with a proposed production process that defined the boundary conditions such as the fluid pressure in the caverns. Based on these data, a convergence rate of about 4% per year and a maximum subsidence of 0.8 cm after 2.5 years of production were predicted. Regular production started in 1996. After 2.5 years field measurements showed a considerable subsidence of 5 cm. Furthermore an echometric cavern measurement showed a smaller volume than forecasted. This pointed towards much higher convergence rates than predicted. To answer the question why convergence rates are higher than expected, the Netherlands Institute of Applied Geoscience-TNO and State Supervision of Mines were commissioned by the Ministry of Economic Affairs to investigate the discrepancy between forecast and observations and find out the underlying mechanisms. From both numerical calculations on the sensitivity of the convergence for pressure variations and a literature study, it was concluded that different boundary conditions and, mainly, too simple a constitutive creep law for the salt resulted in an underestimation of the convergence rate and therefore of the land subsidence. Additionally, an analytical mass balance model for cavern volume predictions was developed. In order to fit the model output to the actually measured echometric cavern volumes and to the measured subsidence from levelling surveys, convergence rates between 53% and 71% per year had to be put into the model, being significantly higher values than originally applied by the operator. By using a convergence rate of 71% per year, the model appears to reliably predict the land subsidence.

1. INTRODUCTION

In 1995 a Dutch company obtained a concession to exploit rock salt layers in the subsurface of the Netherlands by means of solution mining in two caverns. The salt layers belong to the Upper Permian Zechstein Group and are situated between 2470 m and 3050 m. To our knowledge, this solution mine is the deepest in the world.

Low convergence rates were predicted prior to the actual mining using a combination of laboratory data and both analytical and numerical methods. Nevertheless, it appeared that the measured subsidence by far exceeded the predictions. Therefore, the Netherlands Institute of Applied Geoscience-TNO and State Supervision of Mines were commissioned by the Ministry of Economic Affairs to investigate this discrepancy between forecast and observations and find out the underlying mechanisms. Two techniques were used in our study to answer these questions. The first method is based on numerical calculations with the DIANA FE (finite element) model to test the effect of different boundary conditions and creep parameters (see §2). The second method is an analytical model based on the mass balance between produced and dissolved salt (see §3). Van Eijs et al. (1999) describe the two techniques in more detail.

Table 1
Different lithological units and their (elastic) mechanical parameters

Unit number	Unit	depth of base (m)	lithology	density (kg/m^3)	E mod. (kbar)	Poisson's ratio ν
1	Quarternary	597	sand, clay	1950	20	0.38
2	Tertiary	1113	sand, clay,	2300	80	0.35
3	Upper Cretaceous	1434	chalk	2250	100	0.35
4	Triassic-Lower Cretaceous	2240	sandstone, claystone, anhydrite	2230	150	0.30
5	Z3 Salt	2432	rock salt	2185	110	0.35
6	Z3 Anhydrite	2462	anhydrite	2900	300	0.35
7	Z2 Salt	3042	rock salt	2185	110	0.35
8	Dolomite	3600	dolomite	2700	250	0.30

2. FE CALCULATIONS

The FE program DIANA (developed by TNO-Building and Construction) was used to perform the numerical calculations. This program incorporates constitutive material laws for rock salt (both primary creep and secondary creep laws) based on the research done by Fokker (1995). The salt is extracted from the Permian Zechstein Group consisting of almost pure rock salt. It has a thickness of 580 m at the production facility location.
The overburden consists mainly of near horizontal layers of siliciclastic rocks and chalk. A description of the simplified geology and its mechanical parameters can be found in Table 1. This simplified geology and the cavern geometry have been incorporated in a FE model.
The mesh consists of axis-symmetrical quadratic elements (Figure 1) and is refined around the cavern (Figure 2). Geometrical dimensions of the model are listed below:

- radius of the model 3600 m
- height of the model 3600 m
- radius of the cavern 50 m
- top of the cavern -2780 m
- height of the cavern 250 m
- volume of the cavern $1.81 \cdot 10^6$ m^3

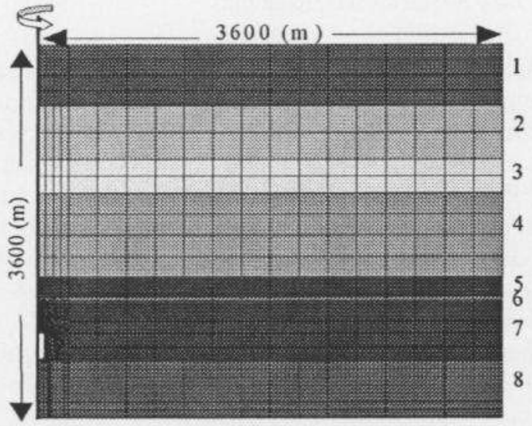

Figure 1 FE axi-symmetrical mesh. The layer indices at the right correspond with the unit numbers in Table 1.

2.1. Parameter and boundary condition variations

The objective of this study was to analyse which parameters or conditions may possibly cause high convergence rates from which the high subsidence originates. Two groups of parameters were identified as possibly different from the forecasted situation. The first group is defined by extrinsic conditions like internal pressure in the cavern or production rates while the second group consists of intrinsic conditions such as the material behaviour (creep-law, creep parameters) of the salt. Furthermore the FE method itself was considered as a possible source of error.

2.1.1. Extrinsic condition variations

The internal cavern pressure is the main condition that influences the stress state at the cavern wall. This pressure defines the radial stress at the wall and therefore also the effective stress (the virgin stress state in salt can be regarded as isotropic). A lower internal pressure results in higher effective stresses and therefore higher convergence rates. In the calculations done before the start of the mining process, the internal pressures was assumed to be a constant 80 bar above hydrostatic pressure.

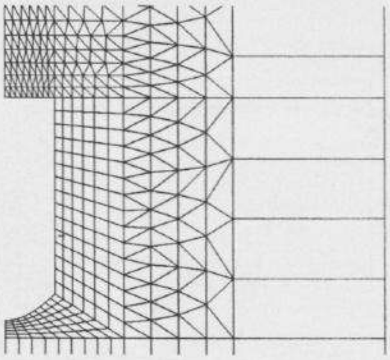

Figure 2 The mesh in the area around the cavern.

However, during the mining operation the internal pressure could not be kept constant. These changed conditions were used as new boundary conditions in the FE calculations. Different *hypothetical* scenarios (Figure 3) were studied to test their impact on the creep:

1. Constant overpressure of 80 bar (original boundary condition)
2. 1-year constant overpressure of 80 bar. Thereafter pressure fluctuation from 60 to 80 bar overpressure. Period is 60 days
3. Constant overpressure of 40 bar
4. Fluctuation from 0 to 80 bar overpressure. Wavelength is 60 days
5. The same as scenario 4, only with a period of 2 days

The creep model and parameters used are presented in §2.1.2.

Results

The results of the pressure scenarios are shown in Figure 3. It was concluded that a higher frequency in the pressure fluctuation leads to higher subsidence rates. Also fluctuating pressures result in higher subsidence rates than the mean of these fluctuations (compare case 3 with cases 4 and 5). In reality pressure fluctuations were not as severe as given in the hypothetical cases.

In addition to the pressure fluctuations it appeared that the temperature at cavern level was higher than predicted. Applying a borehole circulation corrected temperature of 104°C in the creep model instead of the temperature of 95°C used in the study by the operator, yields a 1.5 times higher strain rate.

However, both temperature difference and pressure fluctuations cannot explain the observed high subsidence rate.

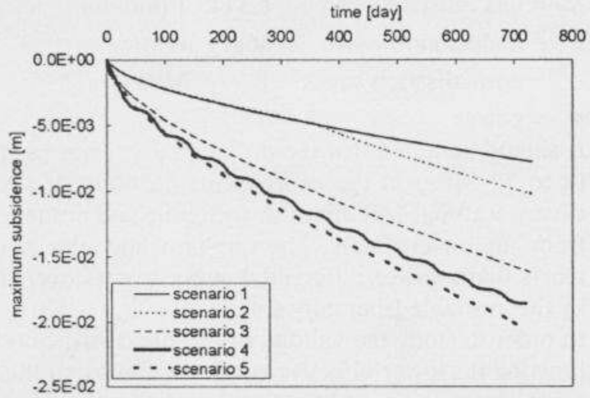

Figure 3 Maximum land subsidence as a function of time for different *hypothetical* pressure scenario's (see text for further explanation)

2.1.2. Intrinsic conditions: material behaviour of the salt (discussion)

Salt is probably one of the most debated rocks in the science of rock mechanics. Even under low shear stresses salt reacts as a highly viscous fluid. In this behaviour, two stages of creep are recognised which are important in solution mining (e.g. Fokker, 1995): primary creep (strain hardening, transient, decelerating) and secondary creep (steady state). Whether or not primary creep is important in engineering problems is still debatable among scientists. It probably results in higher convergence rates in the first stage of a pressure decrease in the cavern. Data was however not available to include primary creep in the numerical calculations and therefore only a steady state creep function was used. The secondary creep function used is of the power law or Arrhenius type function given in equation [1]. Model parameters A en n are derived from laboratory experiments on cores. Core recovery was problematic and therefore only three cylinders, pertaining to the present production level, could be prepared for creep tests. The function and resulting parameters are listed below:

$$\dot{\varepsilon} = A \exp\left(-\frac{Q}{RT}\right)\left(\frac{\sigma}{\sigma^{*}}\right)^{n} \qquad [1]$$

where:

$\dot{\varepsilon}$	= secondary creep rate		
σ	= effective stress		MPa
A	= material constant	0,15	1/day
Q	= activation energy	54	kJ/mol

R = gas constant 8,314 J/(mol·K)
T = temperature 368 K
σ^* = normalisation stress 1 MPa
n = power 5 -

It should be noted that the differential stresses used (8 to 12 MPa) in the experiments do occur at the cavern wall but will diminish with time and distance from the cavern wall. The question how the salt reacts under lower differential stress is not covered by the available laboratory data.

In order to study the validity of the fitted Arrhenius function for lower effective stress we compared this creep law with the constitutive laws and parameters used in the deformation maps presented by Spiers and Carter (1996) and the constitutive law LUBBY-2 (Heusermann et al., 1982). It should be noted that the LUBBY-2 model was originally fitted to the results of the laboratory core experiments but has not been used in the subsequent FE program predictions. According to Spiers and Carter (1996) two mechanisms of creep may be relevant in our case: climb controlled creep and pressure solution creep. For pressure solution creep, the grain size distribution is important. Core samples of the site location revealed an alternation of 25% fine-grained (1-3 mm) and 75% coarse-grained (3-10 cm) salt layers at the relevant cavern level. In Figure 4 the effect is shown for two average grain sizes (2 mm and 6.5 cm respectively) on the strain rate for pressure solution creep (Spiers et al., 1990). Climb controlled creep is applicable for higher effective stresses. This function (Carter et al. 1993) is also presented in Figure 4 but is not based on data from the site location.

Evidently, incorporation of pressure solution creep in the model would have resulted in higher convergence rates. Furthermore using LUBBY-2 as the constitutive law would have resulted in even higher convergence rates as shown in Figure 4.

The most important aspect from this study is the behaviour of the salt at low effective stresses. In the log-log domain the Arrhenius function is a straight line. Spiers and Carter (1996) and Heusermann et al. (1982) show a bi-linear or non-linear behaviour in the log-log domain at low effective stresses. This means that the contribution of pressure solution creep can not be neglected. The use of a single Arrhenius function leads in this case to a considerable underestimation of the convergence rate.

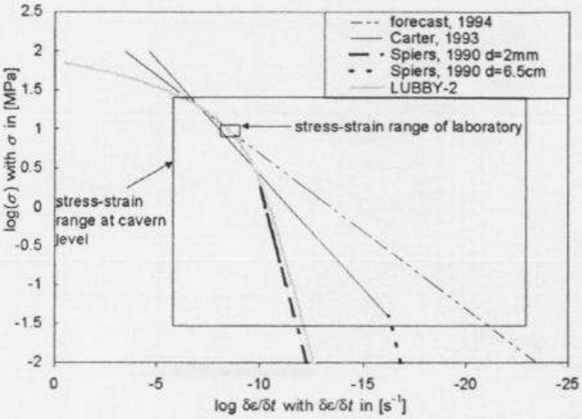

Figure 4 Strain rates versus differential stress for different grain sizes

2.1.3. Errors from the FE method

Two errors can be introduced by the FE method itself. The first error is a result of the large displacement of the salt at the cavern wall. Remeshing (geometric non-linear behaviour) is needed in such case but is not yet implemented in DIANA. Therefore convergence rates tend to be too low. The second error can be introduced from the simulation of the cavern growth. Different volumes should be modelled in a phased approach and removal of elements should be combined with remeshing. Improvements in the program will solve these problems in the coming years.

3. MASS BALANCE MODEL FOR THE SOLUTION PHASE

3.1. The model

A mass balance analytical model has been developed for determining convergence rates from field observations of cavern volume and land subsidence. In the cavern a balance exists between the produced salt volume (= extracted salt + salt in cavern brine volume) and the dissolved formation volume, in formula:

$$\frac{dP(t)}{dt} + \frac{x}{\rho} \cdot \frac{dV(t)}{dt} = \frac{dV(t)}{dt} + K(t) \cdot V(t) \qquad [2]$$

where:

$P(t)$ = salt volume extracted from cavern at time t
$V(t)$ = cavern volume at time t
x = brine concentration

ρ = specific weight of rocksalt
$K(t)$ = convergence rate at time t

Assuming a constant production rate $b\left(=\frac{dP(t)}{dt}\right)$ and convergence rate K, formula [2] reduces to the differential equation:

$$a\cdot\frac{dV}{dt}+K\cdot V-b=0 \qquad [3]$$

where $a = (1\text{-}x/\rho)$ yielding as solution:

$$V(t)=\frac{b}{K}\left\{1-e^{-Kt/a}\right\} \qquad [4]$$

Thus, for large times $t >> a/K$ and constant production conditions, the cavern volume will asymptotically reach: $V_\infty=\frac{b}{K}$.

Van Eijs et al. (1999) also derived mass balance equations for the post-solution production phase, that, however will not be dealt with in this paper.

If echometric cavern volume measurements are available equation [4] suffices to directly determine the corresponding K value. Assuming a negligible delay between the convergence of the cavern and land subsidence, the volume of the subsidence bowl at time t can be calculated as follows:

$$V_{bowl}(t)=V_{conv.}(t)=\int_0^t K\cdot V(t')dt', \qquad [5]$$

which results, by inserting equation [4] and integrating, into:

$$V_{bowl}(t)=b\cdot t-a\cdot V(t) \qquad [6]$$

From levelling surveys above the caverns an approximately cone-shaped subsidence bowl is observed, showing a radius R and maximum subsidence $Z(t)$ in the centre. The subsidence volume is as follows:

$$V_{bowl}(t)=\tfrac{1}{3}\pi R^2 Z(t) \qquad [7]$$

Combining equation [4], [6] and [7] now enables the calculation of K from results of levelling surveys.

3.2. Convergence rate determination from practical observations

For the salt production process under consideration, convergence rates are determined using the following practical (average) data:

- $\rho = 2100$ kg/m^3, $x = 300$ kg/m^3, thus $a = 0.857$
- $b = 285\cdot10^3$ m^3 per year per cavern
- Echometric volume of the cavern #1 after 1.7 years of production: $300\cdot10^3$ m^3
- Subsidence bowl after 2.3 years of production (with 2.3 years production from cavern #1 and 1.3 years from cavern #2): $V_{bowl} = 410\cdot10^3$ m^3.

Now two convergence values can be calculated.

1) Applying equation [4] yields an *echometric* based value for $K = 71\%$ per year
2) Applying [4] to [7] yields a *subsidence* based implicit expression for K as follows:

$$K=0.403\cdot\left(2-e^{-2.684K}-e^{-1.517K}\right)$$

This expression is fulfilled for $K = 53\%$ per year.

It is plausible, that the subsidence based K value tends to be lower than the echometrically based value. Firstly, in practice subsidence may be somewhat delayed relative to the cavern convergence due to visco-elastic behaviour of the overburden. Secondly, the zero-subsidence contour cannot exactly be determined from levelling surveys. The position of the zero contour has a large impact on the total volume of the subsidence bowl. Usually the zero contour is extrapolated from those bowl contours, that levelling survey data could position reliably.

3.3. Subsidence predictions using the mass balance method

For constant salt production rates and unchanged (extrinsic) production conditions, the K value remains constant. Then, the model enables a simple prediction of the convergence volume as a function of time. In Figure 5 the total convergence volume (two caverns) is shown for the echometrically derived K value of 71% per year. The convergence volumes are converted to maximum subsidence values by means of equation [7], where the radius R is determined as follows. The reference depth of the caverns is 2890 m, the outmost walls between the two caverns have a distance of about 500 m. Using an angle of draw of 45°, this configuration yields a subsidence bowl having a radius R of 3200 m. For comparison, the maximum subsidence values resulting from levelling surveys are plotted in Figure 5, including the most recent survey value of 11.3 cm, measured in August 1999 (t=3.6 year). The measured data fit to the predicted curve very well with respect to both shape and absolute value. This means, that the values chosen in the modelling for K (71%) and R (3200 m) enable useful predictions.

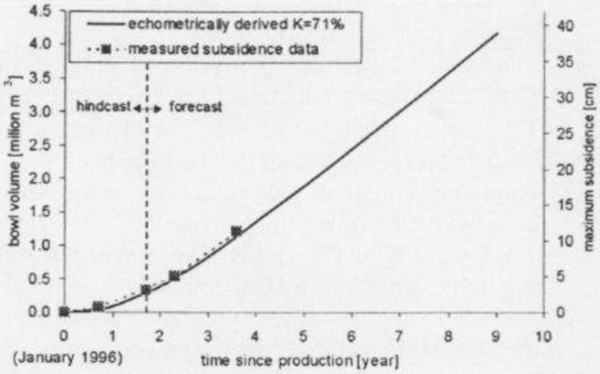

Figure 5 Measured data from leveling surveys and the results for the mass balance equation

Interestingly, Figure 5 shows that the salt production has reached stable convergence conditions. For times $t >> a/K$ (a/K =1.2 years of production) each cavern will reach a constant theoretical volume of b/K=$400 \cdot 10^3$ m^3. In practice, yearly production volume will be fully converted into subsidence after 2.5 to 3 years of production. In August 1998 (t=2.6 years) a second echometric measurement in the first cavern showed a cavern volume of about $415 \cdot 10^3$ m^3, corroborating the above prediction.

CONCLUSIONS

The convergence rate of the salt in case investigated is about 13-18 times higher than forecasted prior to production. Laboratory tests at lower stress differences would have shown that a single Arrhenius function is not adequate for a forecast of convergence rate and land subsidence in this case. A more realistic convergence rate would have been forecasted, if the combination of a more sophisticated constitutive law with the extrinsic conditions of a lower and fluctuating pressure at the cavern wall and a higher temperature was used. Including aspects as primary or transient creep in the model and considering future improvements of the DIANA FE program may result in even higher convergence rates. The analytical model overcomes the problem of choosing the correct boundaries and constitutive law as needed in numerical simulations. The model combines measured field data, both subsurface and surface, for determining the convergence rate. However, predictions prior to production can only be made using a combination of a reliable FE model and proper and sufficient laboratory measurements.

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