Subsidence Modelling for the Zuidwending Cavern Field

Dirk Zander-Schiebenhöfer  
KBB Underground Technologies, Hanover, Germany

Patrick Roordink,  
N.V. Nederlandse Gasunie, Groningen, The Netherlands

Sebastiaan Robertus  
Akzo Nobel Chemicals, Hengelo, The Netherlands

SMRI Fall 2017 Technical Conference  
25 - 26 September 2017  
Münster, Germany
Subsidence Modelling for the Zuidwending Cavern Field

Dr. Dirk Zander-Schiebenhöfer
KBB Underground Technologies, Baumschulenallee 16, Hanover, Germany

Patrick J.P. Roordink
N.V. Nederlandse Gasunie, P.O. Box 19, 9700 MA Groningen, The Netherlands

Sebastiaan Robertus
Akzo Nobel Industrial Chemicals B.V., P.O. Box 25, 7550 GC Hengelo, The Netherlands

Abstract

Subsidence is a sensitive issue in The Netherlands, because the ground elevation is low and water management is a challenging task. Therefore, subsidence induced by mining has to be thoroughly monitored, checked and predicted.

In the Zuidwending area AkzoNobel and Gasunie are operating salt caverns that are located in the Zuidwending salt dome. While AkzoNobel produces brine out of the caverns, Gasunie uses caverns for gas storage. Beside the fact that subsidence monitoring is mandatory, the individual share of the gas caverns on the overall subsidence is limited. Furthermore, gas production from the Groningen gas field also influences surface subsidence in the Zuidwending area.

Therefore, Gasunie and AkzoNobel needed a subsidence model that provides the capability to differentiate the contribution of the individual caverns/cavern types to the overall observed subsidence.

The established model incorporates the state of the art in subsidence modelling (e.g. SMRI’s SaltSubsid software, EICKEMEIER’s and SROKA/SCHOBER’s approach on subsidence modelling). Additionally it provides some special features in order to match with the field conditions. These are:

- determination of the growth of the brine production by mass balancing based on production data,
- calculation of the cavern convergence volume based on daily cavern pressure values while applying an analytic creep formula of the Norton/Hoff creep law,
- consideration of the cavern field development over time,
- verification of the subsurface part of the model by history matching of the cavern development of every cavern individually based on sonar measurements (matching of cavern volume development over time),
- applying a time dependent concept for the angle of draw,
- verification of the surface part of the model on surface measurements (levelling, GPS) and their interpretation (history matching at benchmarks).

By history matching – first at subsurface and afterwards on surface – two independent verification levels were established. As observations from the measurements contain further contributions to sub-
subsidence, such as due to gas production, water management or ground compaction, these contributions had to be evaluated, before finally the modelled results for cavern induced subsidence could be checked against surface measurements.

The described stages of model verification enabled a satisfactorily match of the model with the observations and measurements.

The following subsidence prediction for the expected lifetime of the caverns clearly showed that over the intended lifetime of the gas storage caverns the produced subsidence will stay within permitted limitations.

Key words: subsidence modelling and prognosis, different cavern types with changing cavern operations, history matching, and interpretation of surface levelling data.

1 Introduction

Since 1968 AkzoNobel has been producing brine by leaching of several caverns in the Zuidwending salt dome. Within the scope of the ‘Aardgasbuffer Zuidwending’ project that was started in 2004, additional caverns have been leached in the salt for the purpose of underground gas storage. Currently, five caverns (ZW A2, ZW A3, ZW A4, ZW A6 and ZW A7) are operated by Gasunie as gas storage caverns. Caverns ZW A1 and ZW A5 are still in the leaching process, which is managed and operated by AkzoNobel. In the medium term it is intended to incorporate both caverns after their finalisation into the gas storage facilities of Gasunie in the near future.

Salt caverns, either for gas storage or brine production, show volume losses (convergence) over time due to creep of the surrounding salt rock mass. These volume losses are transferred by a deformation process via the overburden layers to surface, where a subsidence bowl forms. Keeping cavern convergence and therefore subsidence as small as possible is of vital interest for the operator as well as for the public. Therefore, the authorities of The Netherlands demand to respect limitations on maximum subsidence for gas storage operation. That’s why operators try to optimize their operation/storage concepts in order to minimize subsidence. With regard to Zuidwending gas storage caverns the maximum allowed amount of subsidence is limited to 25 cm (9.84 in). Together with gas production this limit amounts to 35 cm (13.78 in).

In order to monitor and check this limitation, levelling campaigns are mandatory after specified periods of time. However, what can be observed at Zuidwending is the total subsidence that originated from different sources – such as gas production, salt production, gas storage, ground compaction, and erosion. They all contribute to the total surface subsidence. With regard to checking the maximum limits for gas storage caverns this means that subsidence, which is exclusively produced by the gas storage caverns, has to be back-calculated by theoretical measures. Thus, theoretical modelling has to be employed, in order to be able to check the individual contributions against their limitations.

2 General Approach

The general understanding of surface subsidence modelling is that volume losses caused by mining activities at subsurface lead to surface subsidence.

As part of surface subsidence predictions, an assumption has to be made on the deformation mechanism, i.e. how the volume losses are transferred via the involved geological formations from subsurface to surface. Finally this leads to a description of the shape and the extension of the subsidence bowl that will be created and gives information on how far it will laterally extended. The subsidence bowl will develop over time as a consequence of salt creep behavior, because cavern pressures during normal operation will always be below lithostatic stress.

A generally well accepted approach for subsidence modelling above caverns in rock salt has been developed by SROKA and SCHOFER (1982) and generalized by EICKEMEIER (2005). The principal assumptions of the SROKA/SCHOER subsidence model can be summarized as follows and are described by Equation 1 and Equation 2:
• A normalized Gaussian type function represents the shape of the subsidence bowl.

• In order to determine of the discrete subsidence value at surface point \( r \) (radial distance from the projection of the cavern axis on surface) the angle of draw \( \gamma \), the bulking factor \( a \) of the overlying rocks, and the convergence volume \( V_c \) are the influencing factors.

• The process of subsiding starts with rock mass deformation due to cavern convergence and finally appears on surface as subsidence.

• Salt creep is the driving mechanism over time which produces convergence \( c = \Delta V/V \).

• The angel of draw \( \gamma \) together with representative cavern depth \( z_{ref} \) determines the rock mass volume involved by transferring volume losses at subsurface to surface. This results in the radius of the subsidence bowl \( R \).

• The angle of draw is related to a representative cavern depth \( z_{ref} \). According to SCHOBER ET AL. (1987) the depth of cavern roof \( z_{roof} \) and sump \( z_{sump} \) can be applied for determination of \( z_{ref} \) as expressed by Equation 2.

• The bulking factor \( a \) describes the ratio of convergence volume produced at subsurface compared to the subsidence volume observed at surface.

• The convergence \( c \) describes the loss of cavern volume \( c = V_c(t)/V \) over time.

\[
v_Z(r, \varphi) = a \cdot c \cdot \frac{V}{R^2} \cdot \exp \left\{-\pi \frac{r^2}{R^2} \right\}
\]

Equation 1

\[
R = \frac{z_{ref}}{\tan \gamma} = \frac{\sqrt{z_{sump} \cdot z_{roof}}}{\tan \gamma}
\]

Equation 2

The angle of draw differs from location to location. Long term observations show that the subsidence bowl spreads over time, which indicates a decreasing value for the angle of draw over time (see GAULKE et al. (2007) and ZANDER-SCHIEBENHÖFER (2007).

### 3 Specific Approach

The specific approach for subsidence modelling and prediction at Zuidwending is described by the most essential items in the following.

**Cavern Description**

The geographically setup of the cavern field has been compiled from

- geo-referenced data of the
  - cavern wellheads, and
  - last cemented casing shoe,
- depth of roof and sump, and from
- sonar surveys.

**Cavern Volume and Reference Depth**

The reference depth has been assumed at depth of the midpoint of the geometrical volume, which has been determined from the sonar measurements. Thereby the representative depth can change over time. With the leaching process it starts at near bottom and develops upwards. Additionally a correction factor can be applied in order to adapt creep response to specific cavern shapes.

**Bulking of the Overburden**

The bulking (volume increase due to subsiding) of the overburden is not considered. This means, produced convergence volume and surface subsidence volume are of the same value.
Creep of Salt and Operating History

The applied creep model considers the following:

- the non-linear increase of the creep response with depth of the cavern because of an increasing difference between the internal cavern pressure and the lithostatic stress, and
- the non-linear increase of the creep response with depth of the cavern due to the increase of the rock mass temperature.

Creep response has been modelled by using an analytical formula as given by VAN SAMBEEK [1993]. This formula (see Equation 3) represents the long-term creep response of a cylindrical cavern based on the material law of Norton-Hoff.

\[
\dot{V} = -\sqrt{3} \left[ \frac{\sqrt{3}}{n} \cdot (P_\infty - P_i) \right]^n \cdot A \cdot e^{-\frac{Q}{RT}}
\]

with:
- \(\dot{V}\) volume change rate
- \(V\) volume of the brine-filled borehole section
- \(P_\infty\) far field formation pressure (lithostatic stress)
- \(P_i\) internal well pressure
- \(n\) stress exponent
- \(A\) structural parameter
- \(Q\) activation energy
- \(R\) gas constant
- \(T\) rock mass temperature

With regard to tall cylindrical caverns the stress profile as well as the temperature profile differs with depth. As already stated above, the volumetric midpoint of the cavern has been selected as reference depth of the caverns, but a correction factor has been introduced in order to take into account that creep behaviour is non-linear with depth.

As creep is influenced by the internal cavern pressure, the operating history has been considered in the subsidence model. Especially for the gas storage caverns, the creep response has been calculated on a daily basis during history matching process for the gas storage caverns and in the prediction phase.

Cavern Field Development

Creep response of individual caverns depends on the history of cavern field development. For a single cavern in a salt deposit the creep response is smaller than for the same cavern situated in the middle of a field with several neighbour caverns. This effect is considered by an empirical factor according to Equation 4.

\[
\dot{C}_{corr} = 2.6 \cdot \left( \frac{\text{pillar width}}{\text{cavern diameter}} \right) \frac{n-1}{n} + 1.28
\]

with:
- \(\dot{C}_{corr}\) convergence rate corrected due to field conditions
- \(\text{pillar width}\) average salt pillar to cavern neighbours
- \(\text{cavern diameter}\) maximum cavern diameter

Individual Caverns Models

Individual models have been created with the objective of combining cavern operation history and convergence development.

The cavern volume development during brine production (or leaching) has been calculated from the production data, which have been provided by AkzoNobel in terms of produced tons of salt over time. By applying a mass balance concept (see OLDENZIEL et al. (2000)).

Creep response has been calculated according to the individual cavern conditions

- geological profile,
- primary stress and temperature,
- operation history (well head pressures converted to cavern pressures), and
- cavern volume development.
Assembly for Calculation of the Total Subsidence due to Cavern Operation

All individual subsidence bowls have been superimposed by considering the specific geographical location of each cavern and the global time reference.

Consideration of Non-Cavern related Subsidence

Observed subsidence at Zuidwending contains also contributions from gas production and ground compaction (non-cavern sources).

According to isokatabase maps given by the Nederlandse Aardolie Maatschappij (NAM) subsidence due to gas production is not uniform. Values are increasing from south-east to north-west above the Zuidwending cavern area. Different authors and institutions (e.g. OLDENZIEL, ORANJEWOUD, and ANTEA) have derived subsidence contributions from gas production in combination with the levelling campaign data.

4 History Matching, confidence building and validation

Validation of the model could be achieved by history matching that has been performed in two steps with reference to subsurface and to surface.

History Matching at Subsurface

The subsurface validation process has been performed by selecting the observable cavern volume versus time as the assessment parameter. Observed cavern volumes were obtained as the results of the sonar surveys.

Starting with the measured cavern volume at the beginning of each period between two sonar measurements, the course of the cavern volume has been calculated up to the end of the period. When the calculated cavern volume at the end of the examined period matches the sonar measurement, this indicates successful validation.

Principal difference in convergence behaviour exists between brine production caverns on the one hand side and gas storage caverns as well as brine production caverns at standstill on the other hand. Whereas brine production caverns in operation show a permanent increase in volume that mostly is greater than the volume loss by convergence, the creep response is masked behind the volume versus time curves. With gas storage caverns or brine production caverns at standstill cavern volumes decrease over time. This decline can be directly related to creep of the surrounding rock salt mass.

Figure 1 Subsurface history match of a brine production cavern
Exemplarily selected results for the history matching process are shown for a brine production cavern in Figure 1 and for a gas storage cavern in Figure 2. Observed cavern volumes (green squares) are compared with theoretically calculated cavern volumes (blue lines). A relatively good match between model and observations can be stated.

Confidence Building at Surface

Confidence building at surface level referred to the following criteria:

(A) Subsidence due to cavern operation has to increase over time and the subsidence bowl has to show an increasing horizontal spread.

(B) Maximum subsidence due to cavern operation only has to be located above the centre of the caverns currently in operation.

The subsidence (isokatabase) maps for end of September 1998, end of October 2005, and end of December 2010 (see Figure 3) show that the subsidence bowl spreads horizontally over time while at the same time the maximum value increases above the cavern area (Criterion A).

The centre of the subsidence bowl forms above the cavern field and adjusts gradually with respect to time as new cavern volume has predominantly been created in the western part of the cavern field since 2004 by leaching the caverns, which were intended for storage of gas (compare top and bottom image of Figure 3) (Criterion B).

The confidence building process at surface can be assumed as successfully passed.
Figure 3  Calculated subsidence maps for 1998, 2005, and 2010
Validation process at surface

Validation of the subsidence model is demonstrated according to the interpreted results of the levelling campaigns 1998, 2005, and 2010/2011 by applying the following criteria:

(C) Theoretically calculated subsidence as shown in isokatabase maps had to match the maximum observed subsidence.

(D) Calculated subsidence curves over time at benchmarks had to match with the observed values.

(E) Subsidence rates calculated by the model are compared with benchmarks of the levelling grid as well as for GPS measurements.

In order to validate the simulation model, measured data had to be reduced by the contributions from gas production and ground compaction, before they could be compared with the values produced by the simulation model. This kind of data was provided by reports that summarized, checked and evaluated of the levelling campaign data of 1998, 2005, 2010/2011. Maximum subsidence values due to cavern operation as determined in these reports are compared in Table 1 with results produced by the subsidence simulation model.

Table 1  Compilation of values for maximum subsidence caused by Zuidwending caverns according to evaluated levelling data and to subsidence modelling

<table>
<thead>
<tr>
<th>Levelling campaign</th>
<th>Maximum subsidence (interpreted levelling data) [mm] [0.0393701 in]</th>
<th>Subsidence Modell [mm] [0.0393701 in]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1998</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>2005</td>
<td>39</td>
<td>39</td>
</tr>
<tr>
<td>2010/2011</td>
<td>40</td>
<td>48</td>
</tr>
<tr>
<td>2015/2016</td>
<td>not determined</td>
<td>63</td>
</tr>
</tbody>
</table>

The results from subsidence modelling match quite well with values determined by evaluation of the measurements. From the rock mechanical point of view the only slight increase of subsidence between 2005 and 2011, as given by interpretation of the measurement data, has been assumed as not very reliable, because the convergence process of the caverns had continued as before and also additional cavern volume had been created during that period. Thus, Criterion C could be met.

For selected benchmarks the course of calculated subsidence versus time has been compared with direct and interpreted measurement values. Benchmarks in the southern center part above the caverns, where the maximum subsidence due to cavern operation is expected, show a quite good agreement with modelling data (see Figure 4).

However, benchmarks exist, where the model under- or over-estimates observed subsidence (see Figure 5). At benchmarks more distant from the caverns, the quality of the history match is non-unique. But, the main focus of the study was to provide a conservative subsidence prediction for the center of the bowl. A quite good history match could therefore be stated with regard to Criterion D).
Figure 4  Benchmark above brine production cavern

Figure 5  Benchmark more distant from the caverns
Furthermore, subsidence rates from modelling were compared with GPS measurements. GPS antennas had been installed at near wellhead of the gas storage caverns. Measurement results show a seasonal swing and an overall average subsidence rate of about 3 mm/a (0.12 in/a) for the period 2013 to 2014, which is slightly higher than the rate of 2.6 mm/a (0.10 in/a) as determined by the model (see light blue line in Figure 6) (Criterion E).

![Calculated subsidence curve above a gas storage cavern](image)

Figure 6  Calculated subsidence curve above a gas storage cavern

Finally it could be concluded that the model is suited very well for the prediction of subsidence, which will be caused in the future by the salt caverns – brine production caverns and gas storage caverns, because the subsidence history could be reproduced not only for maximum subsidence values but also for selected benchmarks in the field.

5 Subsidence Prediction

Predictions had to be delivered in advance of the levelling campaign at end of 2015 and for the intended lifetime of the gas storage caverns. The first prediction was mandatory in order to demonstrate the quality of the subsidence model. The second prediction was required in order to show that subsidence at the end of gas storage operations will stay below the limit as fixed in the permission for operation.

For the 2015 prediction real production data were available. For the lifetime prediction until 2050 operations as intended by the AkzoNobel and Gasunie had been taken into account. Intended future cavern operation of AkzoNobel has been provided in terms of brine production per cavern per month from existing caverns as well as from additional planned caverns. In some case cavern abandonment had to be considered. Additionally the conversion of brine production to gas storage caverns has been taken into account. Future gas storage operations had been given by Gasunie in terms of wellhead over time for representative storage year.

Predicted subsidence is shown for end of 2015 and 2050 in Figure 7 by means of isokatabase plots.
A gradual increase of subsidence is predicted over the coming years. The centre of the bowl stays more or less in the same region. The planned new caverns do not yet have a significant influence on the subsidence bowl in 2050. A maximum subsidence of about 195 mm (7.58 in) is predicted due to salt cavern operation until the end of 2050 (see Table 2). At that time, brine caverns will have been operated for more than 80 years. The predicted maximum values of subsidence as related to type of cavern are about 160 mm (6.3 in) due to brine production and less than 40 mm (1.57 in) due to gas storage. Individual maxima do not match the overall maximum values, because they are not located at the same surface location. Maximum predicted subsidence due to gas storage stay at about 25% of the maximum value due to brine production.

<table>
<thead>
<tr>
<th>point in time</th>
<th>all caverns [mm] [0.0393701 in]</th>
<th>brine caverns [mm] [0.0393701 in]</th>
<th>gas storage caverns [mm] [0.0393701 in]</th>
<th>predicted maximum subsidence rate [mm/a] [0.0393701 in/a]</th>
<th>spread of the bowl (isokatabase 10 mm) [km] [0.621371 mi]</th>
</tr>
</thead>
<tbody>
<tr>
<td>31.12.2015</td>
<td>63</td>
<td>57</td>
<td>6</td>
<td>2.7</td>
<td>4.3</td>
</tr>
<tr>
<td>31.12.2050</td>
<td>193</td>
<td>159</td>
<td>36</td>
<td>4.6</td>
<td>6.3</td>
</tr>
</tbody>
</table>

The extent of the subsidence bowl measured in between the 10 mm (0.39 in) isokatabase increases by about 2.0 km (1.24 mi) from 2015 to 2050.
In a follow-up study subsidence predictions due cavern operations at Zuidwending and the neighbouring cavern field Heiligerlee were superimposed with the predictions due to gas extraction as published by the NAM. As can be seen from Figure 8 cavern induced subsidence bowls are concentrated above the cavern field. In this area the wide spread and more smoothly distributed character of the subsidence field caused by gas extraction is changed by showing two sinks.

Figure 8 Superimposed subsidence maps as predicted due to cavern operation and gas extraction.

6 Conclusions

The availability of long-term surface levelling measurements provide the fundamental base for the validation of subsidence simulation models. However, data have to be interpreted in order to filter the individual contributions to the overall observable subsidence on surface.

Subsidence prediction models can be improved by applying a two step validation process:

1. subsurface validation of cavern volume development for the individual caverns,
2. surface validation of the subsidence bowl and the subsidence rate.

Subsidence modelling above a salt cavern field affords consideration of the operation data in order to determine the convergence volume.

Investigations and observations indicate that the angle of draw decreases over time. Together with the in-situ creep behaviour of the salt the time dependent angle of draw represents a basic fitting parameter in order to adapt subsidence simulation models to observations by history matching.

Finally, subsidence modelling is not an isolated process, which can be performed on theory alone. Interdisciplinary communication is necessary to create a reliable model for predictions. This is especially true because of the several contributing sources to subsidence.
7 Acknowledgements

The authors like to thank companies Akzo Nobel Chemicals, The Netherlands, and Gasunie, The Netherlands, for providing the opportunity to use the results from subsidence prediction studies as well as from third parties reports about levelling data evaluation.

8 References


