Prediction of Subsidence above Caverns at Zuidwending, The Netherlands

Operation Phase

Report on WP2: Applied Subsidence Model

for

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1 Introduction

Since 1968 AkzoNobel has been producing brine by leaching of caverns at several locations in the Zuidwending salt dome. Within the scope of the 'Aardgasbuffer Zuidwending' project that was started in 2004, several 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 the 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 gas storage caverns at Zuidwending the maximum allowed amount of subsidence due to operation of the gas storage caverns is limited to 25 cm.

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.

DEEP. and KBB UT have been appointed by Gasunie to develop such a model that is capable of matching the so far history of subsidence and thus enables reliable predictions of the surface subsidence that will be induced only by the operation of the gas storage caverns at Zuidwending.

After screening and summarizing of the relevant documentation about subsidence due to brine production and gas storage at Zuidwending (see report '**Workpackage 1 (WP1) – Screening of Documentation'**) the simulation model can be established based on this information. The present report on '**Workpackage 2 (WP2) 'Establishing the Simulation Model'** describes the principal steps of this set-up procedure. In the subsequent **Workpackage 3 (WP3)** this model will be applied for the prediction of subsidence.

The fine-tuning of the simulation model will be carried out within the scope of WP3, which aims at subsidence prediction related to gas storage caverns in order to be prepared for the next levelling campaign in 2015.

2 Scope of Work – WP2

With the applied subsidence model the continuity with the existing studies and observations has to be assured. This refers to modelling assumptions in principle and to measurements and observations in particular. Finally, history matching of the modelling results with the observed surface subsidence enables to have confidence in the model and to validate its produced results so that it can be used for subsidence predictions.

Essential results, observations and findings as contained in the existing documents have been summarized in the report on WP1. This information forms the basis for the setup of the subsidence model. The present report describes how the subsidence model is organized and built-up, and also documents the confidence building and validation process.

A main approach of subsidence model is to provide a possibility to distinguish between the individual contributions to the total subsidence, i.e. salt caverns, gas production and ground compaction. Especially the individual shares of the caverns on the overall total subsidence have to be made accessible, because subsidence caused by the gas storage caverns is limited. Therefore, the production history from brine caverns as well as operating history of gas caverns has to be taken into account, which is organized within the subsidence model by setting-up individual cavern modules, which represents their specific volume growth and convergence behaviour.

These individual cavern modules have to be synchronized in time, and their contributions to surface subsidence superimposed, in order to calculate the total subsidence above the cavern field generated by the caverns (gas storage and brine production). As the observed total subsidence at Zuidwending contains portions due to gas production from the Slochteren field and ground compaction, these have to be included in the history matching process as well.

Confidence building and validation of the subsidence model have to be carried out in two steps: (1) at subsurface and (2) on surface:

- At subsurface, calculated cavern volumes over time are compared with sonar measurements for each cavern in order to check the applied creep model. The creep model represents the in-situ behaviour of the salt rock mass surrounding the individual cavern and directly influences the calculation of the convergence volume.
- At surface level the overall confidence building and validation process is carried out by history matching of the observed subsidence.
    - Showing that the growth of the subsidence bowl with time represents the assumed deformation mechanism a qualitative proof (confidence building) can be given.
    - Matching the observed subsidence history of selected (reliable) benchmarks above the cavern field represents the quantitative proof. History matching has been focused on the interpreted results from levelling campaigns in 1998, 2005 and 2010.

Having passed the confidence building and validation process successfully the subsidence model is ready for being applied for subsidence predictions, which will be performed within scope of WP3 and summarized in a separate report.

3 Basics of the Applied Subsidence Model

3.1 Principle Understanding of the Process

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 develop that will be created and gives information on how far it will laterally extended This means that the development of the subsidence bowl over time has to be considered as a consequence of salt creep behaviour. The creep behaviour is responsible for the volume losses of the caverns over time, because cavern pressures during normal operation will always be below lithostatic stress.

A generally well accepted model for subsidence caused by caverns in rock salt has been developed by SROKA and SCHOBER (1982) and generalized by EICKEMEIER (2005). The main ideas of this model, which are applied in this study, are briefly presented in the following.

The principal assumptions of the SROKA/SCHOBER subsidence model can be summarized as follows:

- A normalized Gaussian type shape function represents the subsidence bowl (or trough) which is influenced by some specific parameters. Among these parameters the angle of draw β, the bulking factor a of the overlying rocks and the convergence itself are of major importance for the subsidence transformation process. The subsidence process starts with rock mass deformation due to cavern convergence and finally appears on surface as subsidence. Thereby the convergence rate $V_C(t)/dt$ is the driving mechanism.

- The angel of draw β together with representative cavern depth z determines the rock mass volume from subsurface to surface that is involved in the subsidence process due to the volume losses $V_C(t)$. The angle of draw is measured against the horizontal and referenced to a representative cavern depth z.

- The bulking factor a describes the ratio of convergence volume produced at subsurface compared to the subsidence volume showing at surface.

- The convergence rate $V_C(t)/dt$ describes the loss of cavern volume over time due to rock mass deformation.

3.2 Assumptions for the Zuidwending Subsidence Model

3.2.1 Shape of the Subsidence Bowl

The shape of the subsidence bowl is assumed with by the Gaussian functions as described by Schober et al. (1987). The mathematical description according to Eickemeier (2005) follows Equation 3.1.

$$f(r) = \frac{1}{R^2} \cdot e^{\left(-\pi\left(\frac{r}{R}\right)^2\right)}$$

Equation 3.1

with:	*f(r)*	shape function related to the distance from the cavern axis
	R	maximum radial extent of the subsidence bowl
	r	point of interest at radial and lateral distance from cavern axis

3.2.2 Angle of Draw

The angle of draw differs from location to location. With regard to long-term subsidence observations above salt caverns, this value can be assumed in a range of about 25° and 45°. Over long periods it is likely that the angle of draw will become smaller due to the overall creep behaviour of the salt deposit and the extension of the salt deposit (see Gaulke et al. (2007) and Zander-Schiebenhöfer (2007). Within the scope of the confidence building and history matching process the angle of draw is considered as a matching parameter. However, it has to stay within limits of known values from other cavern sites. In principle an assumed lower value of the angle of draw leads to the prediction of smaller subsidence values while the involved surface area of the subsidence bowl will be larger.

3.2.3 Representative Depth

Together with the angle of draw the representative depth determines the extension of the subsidence bowl on surface. Different alternatives are possible to use in a subsidence model. Schober et al. (1987) recommend the reference point to be calculated according to Equation 3.2

$$R = \frac{\sqrt{z_{sump} \cdot z_{roof}}}{\tan \beta}$$

Equation 3.2

with:	z_{sump}	depth of the cavern sump
	z_{roof}	depth of the cavern roof

With respect to caverns of varying partial volumes with depth different depth ranges can be specified, as this is done for the calculation of the convergence in the studies of Eickemeier et al. (2007).

Within the scope of the present study a different approach is used. The reference depth for subsidence modelling as well as for convergence modelling is assumed by the depth of the midpoint of the geometrical volume, which is determined from the sonar measurements. Thereby the representative depth can change over time. This represents the leaching process that starts from the bottom and volume increase is developed upwards. Additionally a correction factor can be applied in order to adapt creep response to specific cavern shapes.

3.2.4 Bulking Factor

The bulking factor ***a*** is assumed to be 1. This means that the convergence volume and consequently the surface subsidence volume are of the same value and as such can be considered as a conservative assumption.

3.2.5 Creep Response

The ability of the rock salt mass to creep continuously leads to volume losses of the caverns (convergence). The driving force of the creep process is the difference between the pressure in the cavern and the far field stress state in the surrounding rock mass. As the creep process is an on-going mechanism (as long as the driving forces are not equal to the supporting forces, i.e. cavern pressures are lower than the lithostatic stress), subsidence increases over time. Furthermore, the salt creep is a highly non-linear with respect to the level of stressing and temperature.

The creep model, which is applied in the subsidence 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,
- the non-linear increase of the creep response with depth of the cavern due to the increase of the rock mass temperature.

Creep response within the scope of this study is calculated using an analytical formula as given by van Sambeek [1993]. This formula (see Equation 3.3) represents the long-term creep response of a cylindrical cavern based on the material law of Norton-Hoff. This material law is also used in the subsidence model of Eickemeier et al. (2007).

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

Equation 3.3

with:	$\dot{V}$	volume change rate
	V	volume of the brine-filled borehole section
	P_∞	far field formation pressure (lithostatic stress)
	Pi	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 (see 3.2.3) the volumetric midpoint of the cavern is selected as reference depth of the caverns, but a correction factor is introduced in order to take into account that creep behaviour is non-linear with depth.

Furthermore, the creep response of an individual cavern depends on the status and 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 of several neighbouring caverns. This effect is considered by an empirical factor according to Equation 3.4.

$$correction\ \ factor\ of\ \dot{C} = 2.6 \cdot (\frac{pillar}{diameter})^{(-1/0.6)} + 1.28$$

Equation 3.4

with:	$\dot{C}$	convergence rate
	pillar	average salt pillar to cavern neighbours
	diameter	maximum cavern diameter

Finally, as creep is influenced by the cavern pressure, pressure changes have to be considered in the subsidence model. As this is the case especially for the gas storage caverns, the creep response is calculated on a daily basis during history matching process for the gas storage caverns.

4 Implementation of the Subsidence Model

4.1 General Procedure

The implementation of the applied subsidence model has been organized in inter-connected modules of Microsoft Excel Spreadsheets, which obey a hierarchy of different levels. In the base level the general setup of the cavern field is organized. The second level represents the individual cavern modules. Calculation and super-imposing of the subsidence contributions by all caverns is carried out on the third level. Comparison of the simulation results with measurements takes place on the fourth level. At this level also contributions to surface subsidence that are not caused by caverns are considered.

Via interfaces special graphical representations such as subsidence maps can be generated. For this purpose the QGIS software under the GNU public license (see www.qgis.org/de/site) is used.

4.2 Cavern Field Setup

The geographically setup of the cavern field is compiled from the following data:

- coordinates of the cavern wellheads,
- coordinated of the last cemented casing shoe,
- depth of roof and sump,
- sonar measurements.

4.3 Consideration of Caverns

The cavern modules have to fulfil the objective of combining cavern operation history and convergence development. In this regard they represent the operation history of the caverns, apply the creep model and finally the accumulated convergence volume over time is calculated in these modules.

The cavern volume development during brine production has been calculated from the production data, which have been provided by AkzoNobel in terms of produced tons of salt over time. By a applying a mass balance concept (see Oldenziel et al. (2000)) and further assuming an average content of insolubles of 2% and an initially estimated convergence rate of 0.08% per year, the created cavern volumes at subsurface have been calculated from these data. Resulting values of dissolved tons of salt at subsurface and of back-calculated cavern volumes are represented in Enclosure 1 and Enclosure 2 respectively.

Comparing the cavern volume development, which has been derived from the production data, with the sonar survey results provides the first possibility to check the volume development versus time. However, sonar surveys often represent only a partial volume, which then has to be corrected for reasons of comparison. On the other hand, if data from production are missing, this can possibly be corrected by the sonar measurements.

Creep response is initially calculated with the same creep ability for the rock mass surrounding all caverns. From cavern to cavern there may be differences in the local creep behaviour of the rock salt zones surrounding the caverns. However, in the initial setup phase of the subsidence model the creep response is assumed to be equal all over the Zuidwending salt dome. For future fine tuning purposes this possible variation in local creep behaviour may be considered.

Besides the general creep behaviour of the salt, the specific creep response with respect to the specific cavern, as well as the specific point in time within the operating history depends on the stress difference between the lithological stress and the cavern pressure state as well as the temperature of the rock (see Equation 3.3). Thus, creep response has been calculated under consideration of

- the lithostatic pressure has been calculated based on the density profile,
- the temperature based on a temperature profile
- the internal cavern pressure by taking into account the brine column plus wellhead pressure of 20 barg for caverns in leaching status (assumed value), or
- the statically detemined gas pressure plus wellhead pressure for caverns in gas storage mode. Whenever possible it has been made use of daily average values for the wellhead pressure.
- Furthermore, the calculated creep response considers the volume development of the cavern with respect to depth.

As creep response is depth dependent, the depth at volume mid-point has been taken into account as representative depth for the calculation of creep response. Especially, for the brine production caverns this provides the possibility to take into account the leaching of preferred depth ranges. Finally, creep response has been combined with the volume development in order to determine the convergence volume with respect to time.

The assumed general creep response for the Zuidwending salt is demonstrated in Enclosure **3** where the steady state creep rate is shown versus the equivalent stress. The equivalent stress represents the stressing of the rock mass that causes deformation. In comparison to the known results from lab-testing of salt cores from Zuidwending wells the assumed initial creep ability is lower, which is often the case when lab-tests are compared to in-situ behaviour (see Enclosure 3).

Convergence volume with time has been calculated based on the *theoretically existing cavern volume*, which has been produced by the application of the creep model. The theoretically existing cavern volume is derived from the production data by ignoring that insolubles have settled in the sump. Superposition of the three volume shares of convergence volume, theoretically created cavern volume and the sump volume results in the *theoretically calculated observable cavern volume*. This volume can be compared with the volume measured by sonar survey.

Calculated and corrected individual curves for cavern volumes versus time are represented by Enclosure 4 to Enclosure 19 for each cavern respectively. Therein sonar surveys are displayed by symbols representing the measured value (red squares) as well as the corrected (green squares). The convergence volume, which results from creep calculations, is also displayed versus time related but with regard to the right hand side ordinate.

4.4 Assembly for Calculation of the Total Subsidence due to Cavern Operation

In order to obtain the resulting subsidence from calculated convergence volumes the subsidence model as described in Chapter 3.2 is applied.

In the first step the subsidence bowl parameters for each cavern have been compiled. Thereby their individual lifetime has been taken into account. It has been assumed that the angle of draw changes individually with time from steeper to more flat angles for every cavern according to their individual time of operation.

In the second step all individual subsidence bowls have been superimposed while considering the specific geographical location each cavern. The resulting overall subsidence bowl for a selected calendar date has been obtained by superposition of the individual subsidence contributions of every cavern at that point in time.

4.5 Consideration of Non-Cavern related Subsidence

As mentioned before the observed subsidence above the Zuidwending cavern area contains also portions from gas production and ground compaction (non-cavern sources).

These values have been estimated according to the information as given in the subsidence interpretation reports following the levelling campaigns. Typical values are compiled in Table 4.1.

Table 4.1 Compilation of values for subsidence above Zuidwending cavern area related to non-cavern sources with respect to levelling campaigns

	1998	2005	2010/2011
gas production [mm]	30 to 50	23 to 57	23 to 83
ground compaction [mm]	10		

Values for subsidence due to gas production have been deduced from isokatabases maps, which were provided by the Nederlandse Aardolie Maatschapij (NAM). According to these maps subsidence due to gas production is not uniform. Values are increasing from south-east to north-west above the Zuidwending cavern area. Values compiled in Table **4.1** have been taken from the reports of Oldenziel (1999), ORANJEWOUD (2006), and HOENTJEN (2011). A possible later refinement of the assumptions/interpretation may be discussed.

Ground compaction has so far been assumed by OLDENZIEL (1999) by a constant value of 10 mm and has been implicitly considered in the evaluation procedure of ORANJEWOUD (2006), and HOENTJEN (2011). As the validation process for the subsidence prediction model is based on the comparison of calculated results with observations at specified benchmarks, interpreted values from the levelling campaigns can directly be applied for this process.

5 Confidence Building and Validation

The confidence building process has been focused on the demonstration that the principal mechanisms of subsidence can be simulated by the model (qualitative proof), whereas validation means proving that the model represents the observed subsidence accurately over time also by value (quantitative proof).

Both processes have been applied to the subsurface and the surface part of the simulation model.

5.1 Subsurface

5.1.1 Confidence building at subsurface

Confidence building of the subsurface part means that the model has to show

(A) an increasing cavern volume over time with on-going brine production or leaching as long as the convergence is not faster than volume creation,

(B) an on-going cavern convergence, which increases with production,

(C) a higher convergence volume with growing depth location and/or volume of the cavern as well as lower internal cavern pressure.

Calculated convergence volumes versus time are shown in Enclosure 4 to Enclosure 19 by the light blue graph.

As can be seen from these graphs the convergence volume as well as increases over time and during leaching time and during gas storage operations (Criterion A).

Cavern volumes of the gas storage are on average much smaller than those of the brine production caverns, thus calculated convergence reveal as relatively smaller for the gas storage caverns (Criterion A).

Especially for the bigger brine production caverns, e.g. for caverns ZW-1 to ZW-7 there is an accelerated increase of convergence volume with continuation of the leaching process (Criterion B), because the absolute cavern volume has been increased.

Although cavern ZW-3 has a smaller volume than cavern ZW-5 the calculated convergence volume is greater. However, the depth location the reference point for creep calculations is deeper for cavern ZW-3. In this case the increase in creep response is stronger than the volume effect (Criterion C).

In summary the confidence building process can be regarded as successfully completed.

5.1.2 Validation process at subsurface

The validation process has been performed by selecting the observable cavern volume versus time as the assessment parameter. Observed cavern volumes are obtained as results of the sonar surveys. Theoretically observable cavern volumes are calculated by the subsidence simulation model by applying a mass balancing method based on the production data (see OLDENZIEL ET AL. (2000)) and taking into account the creep of the salt (in order to determine the convergence volume). In the validation process all influencing factors (such as creep of the salt, insoluble content, etc.) are evaluated in total.

Successful validation in this context means that the simulation model has to match the observed cavern volumes from measurement to measurement. Starting from the measured cavern volume at the beginning of each period between two sonar measurements, the cavern volume development has been calculated up to the end of this period by application of the creep model. When the calculated cavern volume at the end of the examined period matches the sonar measurement, this indicates a perfect agreement of the theoretical subsurface model and therefore a successful validation.

Difficulties originated from various aspects. First of all sonar surveys are sometimes representing only partial measurements. These values have been corrected by employing the production data. Where cavern volumes have been corrected by taking into account the production data red squares representing the sonar measurement and green squares representing the corrected value distinguish from each other. Partial sonars for example exist for cavern ZW-2 (see Enclosure 5), ZW-4 (see Enclosure 7) or ZW-5 (see Enclosure 8). In some instances cavern volumes derived from production data have been considered as more reliable (e.g. see Enclosure 6, Enclosure 7, Enclosure 8, Enclosure 9, Enclosure 10, Enclosure 15, Enclosure 19) and sonar values have been interpreted respectively.

A 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. The effect becomes evident when comparing two subsequent full sonar measurements for such caverns. In these cases the creep model can be directly validated (see for example Enclosure 14 to Enclosure 16 as well as Enclosure 18).

For all brine production caverns the applied simulation model shows quite good agreement with the sonar measurements. As represented for caverns ZW-1 to ZW-9 in Enclosure 4 to Enclosure 12, the theoretically observable (calculated) cavern volume matches with the sonar measurements. Fitting parameters used during history matching were insoluble content, bulking factor and creep ability of the salt rock mass. The *theoretically observable cavern volume* (see Chapter 4.3) over time takes into account that parts of the cavern sump are filled with insolubles that settled in the sump by showing some bulking effect, which for the long-term leaching process of the brine production caverns must certainly be smaller than due to the faster leaching process of the gas storage caverns. As a consequence the bulking factor for brine production caverns has been assumed with lower values than those for the gas storage caverns. No information has been found about the insoluble content for the brine production caverns ZW-1 to ZW-9. Values have been assumed in the range between 2 and 3 %. For the gas storage caverns information about insoluble content is available. In most cases values are higher than 3 %.

The results of history matching process with respect to cavern volume can be checked by comparing the blue curves, which represent the theoretically observable cavern volume, with the green squares, which mark the corrected sonar measurements. It can be seen from Enclosure 4 to Enclosure 19) that the curves of the calculated cavern volumes finally match very well the observed (and corrected) cavern volumes. For each individual cavern the difference between the calculated volume (blue line) at the end of each interval between two sonar surveys and the green squares, which represent the corrected measurement value, turn out to be relatively small. By applying the above described procedure it has been possible for each cavern to match cavern volume curves with the sonar surveys.

Thus the subsurface part of validation can be considered as successfully passed.

5.2 Surface

5.2.1 Confidence building at surface

Confidence building at surface level has been 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 cavern currently in operation.

As can be shown by comparison of the subsidence (isokatabase) maps for the points in time end of September 1998, end of October 2005, and end of December 2010 (see Enclosure 24, Enclosure 27, and Enclosure 30) the horizontal spread of the subsidence bowl extends over time while at the same time showing an increasing maximum value with respect to each specific location (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 been predominantly created in the western part of the cavern field since 2004 by leaching the caverns, which were intended for storage of gas (compare Enclosure 24 and Enclosure 30) (Criterion B).

The confidence building process at surface can be assumed as successfully passed.

5.2.2 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:

(A) Theoretically calculated subsidence as displayed in isokatabases maps have to match the maximum observed subsidence.

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

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

Principally the observed values have to be reduced by the contributions from gas production and ground compaction, before they can be compared with the values produced by the simulation model. In order to validate the subsidence model the interpreted subsidence values as determined in the evaluation reports on the levelling campaigns in1998, 2005, 2010/2011 by OLDENZIEL (1999), ORANJEWOUD (2006) and HOENTJEN ET AL. (2011) have been used. Modelled subsidence rates have been compared with predicted values according to the studies of EICKEMEIER ET AL. (2007). Applied reference values for subsidence and subsidence rates as given in the mentioned studies are compiled in Table 5.1 and Table 5.2.

Table 5.1 Compilation of values for maximum subsidence above Zuidwending cavern area due to interpretation of the levelling campaign data

Levelling campaign	Interpreted maximum subsidence due salt caverns	Reference
1998	30 mm	OLDENZIEL (1999)
2005	39 mm	ORANJEWOUD (2005)
2010/2011	40 mm	HOENTJEN ET AL. (2011)

Table 5.2 Predicted maximum subsidence or subsidence rate by BGR (2007)

Year	Maximum subsidence since 1969	Maximum subsidence rate at the beginning of the reference year
2007	25.1 mm	1.35 mm/a
2018	44.4 mm	1.78 mm/a
2050	92.5 mm	0.77 mm/a

Subsidence (isokatabase) maps are presented for points in time end of September 1998, end of October 2005, and end of December 2010 in Enclosure 24, Enclosure 27, and Enclosure 30. Cross sectional views, which are approximately representing the mid-section above the cavern field, are additionally presented for the W-E as well as S-N direction (Enclosure 22 to Enclosure 23 for 1998, Enclosure 25 to Enclosure 26 for 2005, and Enclosure 28 to Enclosure 29 for 2010).

It can be derived from these presentations that the calculated maximum values of subsidence in the centre of the field are matching quite well with values according to Table 5.1. Maximum calculated subsidence values for 1998 and 2005 are slightly above those given in the interpretation studies. Whereas – for 2010 – the calculated maximum value is approximately higher by 10 mm than assumed by HOENTJEN ET AL. (2011). However, it can be seen from the interpretation report of 2011 that interpreted subsidence values at the center above the cavern field e.g. benchmark 012F3600 are nearly of the same value in 2005 and 2010. This is in contradiction with the fact that the salt creep had continued within this period. Due to communication with the author of the study this phenomenon could be explained by regional effects of subsidence that might have influenced the reference points of the levelling campaign in 2010.

For selected benchmarks the calculated course of subsidence versus time can be compared with direct and interpreted measurement values by the help of Enclosure 31 to Enclosure 36. In these diagrams calculated subsidence due to salt cavern operation is represented by the dark blue line. Whereas, the dark green line stands for subsidence due to brine production caverns (ZW-1 to ZW-9) and the light green line for the gas storage caverns (ZW-A1 to ZW-A7). The light blue line shows the subsidence rate, which is theoretically calculated from all salt caverns convergence. Measured values for subsidence at the specific benchmark are shown by red diamonds. The interpreted measurements, representing only shares from the salt caverns, are marked by green diamonds. Subsidence rates due to measurement values are represented by the beige squares.

Representations for the 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 interpreted measurements, see Enclosure 32 (benchmark 012F3300), Enclosure 35 (benchmark 012F3600), Enclosure 36 (benchmark 012F3700). At benchmark 012F3100 the model overestimates subsidence. At selected benchmarks 012F0122 and 012F5012, which are located more distant from the caverns, the quality of the history match is non-unique. A quite good agreement could be reached for benchmarks 012F5012 about 800 m north of cavern ZW-A5, while theoretical and interpreted values vary by about 3.5 cm at benchmark 012F0122, which is about 600 south of cavern ZW-A4.

With regard to subsidence rates theoretically calculated values are higher than values interpreted from GPS measurements for the period 2013 to 2014. Measurements were obtained from near wellhead locations at caverns ZW-A2, ZW-A4, ZW-A6 and ZW-A7 indicating subsidence rates of 3 to 4 mm/a. Theoretically calculated rates are nearly of the same value, but they have not been corrected by the contributions from non-cavern related subsidence processes, which can be estimated to about 1 mm/a.

It can be concluded that the model is very well suited 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 can be reproduced not only for maximum subsidence values but also for selected benchmarks in the field. Thereby, it has to be considered that a perfect match by 100% could not be expected, because measurements had to be interpreted in terms of non-cavern related contributions and also benchmarks may be influenced by local effects.

This principal assessment is justified by the following arguments:

- The validation of the subsidence model is successful with respect to the levelling campaigns of 1998 and 2005. The relative small increase in interpreted maximum subsidence of the 2010 campaign may be discussed with regard to far field regional influences.
- It is unquestioned that the creep process of the salt rock mass surrounding the caverns continues with time. Thus convergence volumes increase over time and this volume loss appears at surface by increasing surface subsidence. According to the 2010 levelling campaign an increasing surface subsidence is not represented clearly enough by all interpreted benchmarks, which are located in the centre above the caverns. This may be caused by reference benchmarks from outside the cavern area, which may be influenced by gas production or other effects in an unknown and or different way as those benchmarks above the cavern area.

Generally the subsidence model produces slightly higher values than interpreted measurements. Thus predictions applying this model will give a conservative estimate.

In conclusion the validation process for the subsidence model is regarded as successfully passed.

6 Proposed Procedure for Subsidence Prediction

6.1 Proposed Steps

Having successfully passed the confidence building and validation process the subsidence prediction model can be considered as suitable and ready for application for subsidence prognosis due to operation of salt caverns at Zuidwending.

Subsidence predictions have to be shown to the Staatstoezicht op de Mijnen (SodM) in advance to every mandatory scheduled levelling campaign as well as for the date of measurement and for the intended end of operations. Furthermore, Gasunie has to show that at the end of gas storage operations in 2050 the subsidence limit of 25 cm is not violated. This limit applies only for the gas storage caverns.

As the future operating history can only be estimated, two different scenarios for prediction are suggested: a conservative case and a progressive case with respect to subsidence development. Where progressive with regard to the gas storage caverns means that an operation scenario for the gas caverns will be assumed, which on average represents lower cavern pressures. The conservative scenario will represent the opposite case. Conservative or progressive operations related to brine production caverns can be related to volume development or intended brine production/produced salt mass. Gasunie and AkzoNobel together will provide input data in order to compile these two cases of future operations. Data scenarios in terms of wellhead pressures and production data versus operation time until 2050 are required.

6.2 Capabilities

The predictions will show the total subsidence from all caverns as well as only for the gas storage caverns in order to be able to check and differentiate their partial contributions and compared them against given limitations.

Total subsidence including also ground compaction as well as gas production might be considered in the maps and graphs if required and if reliable data are available. Input data are then needed in terms of expected subsidence by gas production (by NAM) and due compaction effects of the ground.

6.3 Maps and Graphs

The results of the predictions will be presented by subsidence maps (plots of isokatabases) as well as by diagrams showing predicted subsidence versus time (at selected benchmark locations). Maps for subsidence rates will also be created.

Presentations of further parameters such as horizontal displacements, tilts, curvature and strains may be selected on request provided that non-cavern related contributions to subsidence can be determined reliable. Otherwise these maps remain in a theoretical space.

7 Summary and Conclusion

The present report describes the establishment of the subsidence prediction model which will be used for the prediction of cavern related subsidence in the Zuidwending area.

The principal assumptions and applied mechanism are demonstrated. The focus of the model is set to the representation of the individual contributions of each cavern, because subsidence due to gas storage caverns has to be differentiated from subsidence caused by brine production caverns. In this regard the model takes into account cavern pressures of the gas storage caverns on a daily base as well as salt production data for brine production caverns.

The built-up subsidence model shows good agreement with the applied confidence building criteria with respect to the subsurface and surface part of the model. This especially means that the main processes at subsurface as cavern convergence and creep are represented in a reliable way, and that at surface the development of the subsidence bowl follows the expected behaviour, which means deepening and widening of the bowl over time.

With respect to validation further subsidence contributions, e.g. due to ground compaction and gas production from the Slochteren field, have to be considered. Estimates for these contributions have been taken from third party reports, which provide interpretations of the results from the levelling campaigns (see OLDENZIEL (1999), ORANJEWOUD (2006), and HOENTJEN (2011). According to the postulated validation criteria for the surface part of the model – (1) representation of maximum observed subsidence value, and (2) matching the subsidence history at selected (reliable) benchmarks – it can be stated that the validation process has been successfully passed.

Subsidence predictions with this model are planned to be carried out for two different operation scenarios:

- a scenario that can be considered as more conservative with regard to brine production and operated minimum cavern pressures, and
- a scenario that can be considered as more progressive.

Scenarios will be compiled together with Gasunie and AkzoNobel according to their business perspective.

The first step and milestone of the subsidence prediction will be the presentation of a subsidence prognosis prior to the next levelling campaign, which is scheduled for the end of 2015.

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List of Enclosures

Enclosures