Bundesanstalt für Geowissenschaften und Rohstoffe

Zuidwending Cavern Field

05-1016-10

Review of the Subsidence Prognosis for the Zuidwending Cavern Field

Final Report

Hannover, August 2017

FEDERAL INSTITUTE FOR GEOSCIENCES
AND NATURAL RESOURCES
HANNOVER

Zuidwending Cavern Field

Review of the Subsidence Prognosis for the Zuidwending Cavern Field

Final Report

Authors:	Eickemeier, Ralf Schäfers, Annika
Client:	N. V. Nederlandse Gasunie Concourslaan 17 9727 KC Groningen THE NETHERLANDS
Order number:	50009559 / 04.06.2015
Reference no:	B3.5/B50221-01/2017-0006/001
Date:	15.08.2017

By order:

signed G. Enste

G. Enste (on behalf of the Head of Department B3)

Table of contents

Page

Number of pages: 17

Abstract

Authors:	Eickemeier, Ralf Schäfers, Annika
Title:	Review of the Subsidence Prognosis for the Zuidwending Cavern Field
Subject terms:	brine caverns, gas caverns, review, subsidence prognosis, Zuidwending

Gasunie appointed BGR to review the subsidence prognosis by DEEP / KBB UT for the Zuidwending cavern field including the methodology, application and documentation.

DEEP / KBB UT screened relevant documents, which provided a reliable data base to set up the subsidence model. They applied a commonly used subsidence model (shape and convergence model) for subsidence predictions above cavern fields, which can be considered as state of the art. The overall approach taken by DEEP / KBB UT is considered applicable to the Zuidwending cavern field.

Based on the available documentation it can be expected that the subsidence prognosis conducted by DEEP / KBB UT is capable to conservatively predict the subsidence values for the assumed operation conditions.

1 Introduction

Since 1968 Akzo Nobel is producing brine by leaching of caverns at several locations in the Zuidwending salt dome. Within the 'Aardgasbuffer Zuidwending' project that was started in 2004, several caverns were leached in the salt dome for the purpose of underground gas storage. SCHÄFER, ZANDER-SCHIEBENHÖFER et al. (2016) state that 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 Akzo Nobel. It is intended to incorporate both caverns after finalization 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 via the salt body and the overburden layers to the surface, where a subsidence trough develops. Keeping cavern convergence and thereby subsidence as small as possible is of vital interest for the operator as well as for the public. Therefore, the authorities of The Netherlands have established limits for the maximum subsidence during cavern operations. At Zuidwending the maximum allowed amount of subsidence due to operation of the gas storage caverns is limited to 25 cm.

To verify compliance with the subsidence limits, levelling campaigns are mandatory after specified periods of time. At Zuidwending different sources – such as gas production, salt production, gas storage, ground compaction, and erosion – contribute to surface subsidence. Therefore, theoretical modelling is required, when the individual contributions have to be checked against their respective limitations.

"DEEP. Underground Engineering" (DEEP) ", Bad Zwischenahn has been appointed by Gasunie to develop a capable simulation model matching the so far history of subsidence. KBB Underground Technologies GmbH (KBB UT), Hannover, has been subcontracted by DEEP. to contribute to this study. The developed model shall reliably predict future surface subsidence caused only by the operation of the salt caverns at Zuidwending. Further the model shall be capable to split this subsidence into the proportions either due to gas storage caverns or brine production caverns."
(SCHÄFER, ZANDER-SCHIEBENHÖFER et al. 2016: 3)

Gasunie appointed BGR to review the subsidence prognosis by DEEP / KBB UT for the Zuidwending cavern field including the methodology, application and documentation.

BGR's review is based on the following reports by DEEP / KBB UT:

1. Review of Documentation (Schäfer & Zander-Schiebenhöfer 2014),
2. Applied Subsidence Model (Schäfer & Zander-Schiebenhöfer 2015),
3. Subsidence Prediction (Schäfer, Zander-Schiebenhöfer et al. 2016).

BGR has not been appointed to conduct a separate subsidence prognosis. Based on the experience in the field of cavern subsidence (Eickemeier & Heusermann 2006, 2007, 2008a, b, c, 2010) BGR was asked to give an expert's opinion on the work conducted by DEEP / KBB UT, especially if the applied method can be considered as state of the art and if the subsidence prognosis is expected to give conservative predictions.

2 Review of data base underlying the prognosis by DEEP / KBB UT (Schäfer & Zander-Schiebenhöfer 2014)

As a first step (Work Package 1) DEEP / KBB UT compiled the existing documentation on surface subsidence measurements and modelling for the Zuidwending cavern field in Schäfer & Zander-Schiebenhöfer (2014). Site specific literature related to subsidence measurements and evaluation (Hoentjen & Dam 2011; Hoentjen 2014; Hoentjen & Dam 2014; Oldenziel 1999; oranjewoud 2006) and to subsidence prediction (Eickemeier & Heusermann 2007) was reviewed.

2.1 Subsidence Measurements and Interpretation

At the Zuidwending site subsidence is induced due to multiple causes including gas production, cavern operation, natural compaction, varying groundwater levels, erosion, and others. The different subsidence contributions cannot be measured separately. Because the limitation of subsidence is applied to certain causes (e.g. subsidence due to cavern operation), the necessity arises to split the total measured subsidence using model data and assumptions.

Oldenziel (1999) analyzed data from the 1969 to 1998 leveling campaigns. His objective was to distinguish between the subsidence contributions from the following processes:

– gas production from the Slochteren gas field of Nederlandse Aardolie Maatschapij (NAM),
– natural compaction of the soil,
– brine production in the Zuidwending cavern field area.

NAM set up a model to calculate subsidence induced by gas extraction from the Slochteren gas field, the so-called NAM-model. Oldenziel (1999) used the calculated subsidence from the NAM-model and the assumed subsidence due to soil compaction to directly calculate the portion of subsidence, which is assigned to cavern operation.

Further reports document the levelling data of 2005 (oranjewoud 2006) and 2010 (Hoentjen & Dam 2011), respectively. For the period between 1969 and 2005 a maximum value of 39 mm of subsidence was identified to be induced by cavern convergence. Nearly the same maximum value of subsidence was derived for the time period between 1969 and 2010. Schäfer & Zander-Schiebenhöfer (2014) notice that the fact that the interpretation of levelling data lead to nearly zero increase of subsidence attributed to cavern operation at some benchmarks between 2005 and 2010 *“seems to be a contradiction to the fact that cavern convergence is on-going due to cavern pressures below the lithostatic pressure”*.

Schäfer & Zander-Schiebenhöfer (2014) refer to results of other measurement methods (GPS and radar interferometry), which show comparable values to those derived from ground surface levelling.

2.2 Earlier Subsidence Prediction Studies

Besides the documentation of surface measurements Schäfer & Zander-Schiebenhöfer (2014) also reviewed earlier subsidence predictions for the Zuidwending cavern field. They refer to the subsidence prognosis conducted by Eickemeier & Heusermann (2007) as well as to comparisons between predicted and observed values made by Pinkse (2014).

2.3 Comments

DEEP / KBB UT screened relevant data on subsidence at the Zuidwending site. The review helped to establish a profound data base for the conduction of the subsidence prognosis. Especially the literature on subsidence measurements and models helped to interpret the measured data regarding the subsidence contributions by different causes. The review of previous reports on subsidence prognoses for the Zuidwending cavern field ensures a continuity of DEEP / KBB UT’s work to earlier studies.

3 Review of the Subsidence Model applied by DEEP / KBB UT (SCHÄFER & ZANDER-SCHIEBENHÖFER 2015)

DEEP / KBB UT apply a commonly used subsidence model (cf. EICKEMEIER 2005; SCHOBER, SROKA et al. 1987; SROKA & SCHOBER 1982) ensuring the continuity to previous subsidence studies (EICKEMEIER & HEUSERMANN 2006, 2007, 2008a, b, c, 2010).

3.1 Basics of the Applied Subsidence Model

The subsidence model is based on an influence function method as described by SROKA & SCHOBER (1982).The mathematical formulation of the influence function is given by Equation (1).

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

with: $f(r)$ influence function as a function of distance r from the cavern axis,

R characteristic radius of the influence function.

The characteristic radius R is calculated using Equation (2) and introducing the depth of the cavern sump (z_{sump}), the depth of the cavern roof (z_{roof}) and the angle of draw (β).

$$R = \sqrt{z_{sump} \cdot z_{roof}} \cdot \cot \beta \tag{2}$$

DEEP / KBB UT use a different approach for the calculation of the characteristic radius R. A representative depth (z_{repr}) is introduced representing the z-Coordinate of the centroid of the geometric volume of the cavern. The time-dependent characteristic radius $R(t)$ is calculated using Equation (3). With the objective to represent the leaching processes in the model, the representative depth is defined as a function of time, considering the time-dependent development of cavern volume.

$$R(t) = z_{repr}(t) \cdot \cot \beta \tag{3}$$

The subsidence is calculated according to Equation (4). $V_{Conv}(t)$ denotes the time-dependent convergence volume of the cavern. The transmission factor a describes the ratio of the volume of the subsidence trough to the total convergence volume. DEEP / KBB UT assume a complete transfer without volume loss by defining $a = 1$.

$$s(r,t) = a \cdot f(r,t) \cdot V_{Conv}(t) \tag{4}$$

The convergence rate k is calculated assuming a cylindrical cavern and using the material law of Norton-Hoff which results in Equation (5) for steady-state conditions (cf. BÉREST, BERGUES et al. 2001).

$$k = \sqrt{3} \cdot \left(\frac{\sqrt{3} \cdot (p_{lith} - p_i)}{n \cdot \sigma^*} \right)^n \cdot A \cdot e^{-\frac{Q}{R \cdot T}} \tag{5}$$

with: p_{lith} lithostatic stress

p_i internell well pressure

n stress exponent

σ^* normalizing stress

A structural factor

Q activation energy

R universal gas constant

T rock temperature

In SCHÄFER & ZANDER-SCHIEBENHÖFER (2015) the application of a correction factor to consider different convergence behavior resulting from specific cavern shape is mentioned but not specified.

An additional correction factor is introduced by DEEP / KBB UT according to Equation (6) for caverns situated in the center of the cavern field, assuming higher convergence rates than for a single cavern.

$$corr_k = 2.6 \cdot \left(\frac{w_{pillar}}{d_{cavern}} \right)^{(-1/0.6)} + 1.28 \tag{6}$$

with: $corr_k$ correction factor to calculate convergence rates of caverns

w_{pillar} average salt pillar width to cavern neighbors

d_{cavern} maximum cavern diameter

3.1.1 Comments

The subsidence model applied by DEEP / KBB UT is commonly used to calculate and predict subsidence above cavern fields. The method can be considered as state of the art.

The assumption of a transmission factor a = 1.0 is considered as conservative for the subsidence prognosis.

The specification of all used equations and values would facilitate the review and could also ensure the reproducibility of the results. This would include:

- cavern specific data (e. g. location, depth, etc.),
- the equation, which governs the time-dependent development of the convergence volume,
- the correction factor to consider different convergence behavior resulting from specific cavern shape,
- model parameters (e. g. $\beta(t)$),
- creep parameters (e. g. A, Q, and n).

It is not clear if DEEP / KBB UT also apply a correction factor to the calculated convergence of caverns at the outer edge of the cavern field. Earlier studies showed that these caverns tend to converge slightly faster than caverns located in the center of the field, dependent on the cavern distance (Eickemeier & Wallner 2000, 2002).

3.2 *Input and Set-up of the Subsidence Model*

DEEP / KBB UT implemented the subsidence model into Microsoft EXCEL.

As the data base for the geometrical set-up of the cavern field DEEP / KBB UT use

- coordinates of the cavern wellheads,
- coordinates of the last cemented casing shoes,
- depths of roof and sump,
- sonar measurements.

The development of cavern volumes during brine production is derived from production data provided by Akzo Nobel in terms of produced tons of salt over time. Applying a mass balance concept (OLDENZIEL & ZANDER-SCHIEBENHÖFER 2000) and further assumptions the created cavern and convergence volumes are back-calculated.

Cavern convergence of the gas caverns depends among other on the internal gas pressure. DEEP / KBB UT use available daily average measurement values of wellhead pressure to calculate the internal gas pressure at reference depth and subsequently derive the convergence rate, using Equation (5). According to SCHÄFER & ZANDER-SCHIEBENHÖFER (2015) the creep parameters are derived from lab test data on specimens from the Zuidwending site.

The overall subsidence as a function of time is derived by making use of the principle of superposition.

3.2.1 Comments

For the calculation of cavern convergence DEEP / KBB UT make very good use of available data on internal gas pressure and salt production. This leads to a very detailed input data base.

Enclosure 3 in SCHÄFER & ZANDER-SCHIEBENHÖFER (2015) shows the selected "creep response" characteristic comparing with Zuidwending lab test data. It is noted that the non-linear characteristic of the depicted curve, especially for equivalent stresses less than about 10 MPa, cannot be represented by a Norton-Hoff material law which is used in Equation (5).

SCHÄFER & ZANDER-SCHIEBENHÖFER (2015) do not present the calibration procedure of the model.

3.3 "Confidence Building" and "Validation"

SCHÄFER & ZANDER-SCHIEBENHÖFER (2015) describe the "confidence building" and "validation" procedures which are performed by DEEP / KBB UT before the model was applied to predict future subsidence at the Zuidwending site. DEEP / KBB UT define "confidence building" as qualitative proof that principle mechanisms are represented in the model, whereas "validation" is defined as quantitative proof that observed data are correctly reproduced.

"Confidence building" and "validation" of the subsidence is divided into two steps:

1. at the subsurface calculated cavern volumes over time are compared with sonar measurements to check the applied creep model which governs the development of cavern convergence volume,
2. at the surface the overall history matching of the subsidence induced by cavern operation is carried out. Subsidence measurements of reliable benchmarks are compared with calculated subsidence values in order to perform the validation procedure.

DEEP / KBB UT conclude that cavern volumes derived from sonar measurements agree well with calculated cavern volumes.

The calculated maximum subsidence due to cavern operation is in good agreement with the interpreted maximum subsidence given in OLDENZIEL (1999), ORANJEWOUD (2006) and HOENTJEN & DAM (2011). According to DEEP / KBB UT slightly smaller subsidence values of certain benchmarks derived from the levelling data base of 2010 in comparison to those from the 2005 leveling campaign are in contradiction with the on-going cavern operation. Therefore DEEP / KBB UT expect the calculated larger values to be more reliable and realistic than the interpreted values of the 2010 leveling campaign (cf. chapter 2.1). SCHÄFER & ZANDER-SCHIEBENHÖFER (2015) report: *"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."*

SCHÄFER & ZANDER-SCHIEBENHÖFER (2015) conclude the "validation" process as follows:

"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 center 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."

3.3.1 Comments

The described comparison between measured and calculated values of convergence and subsidence increase the confidence in the model approach applied by DEEP / KBB UT.

Enclosures 31, 32, 34 – 36 in Schäfer & Zander-Schiebenhöfer (2015) show observed and calculated subsidence of various benchmarks. The depicted "interpreted data" is the subsidence portion, which is attributed by DEEP / KBB UT to cavern operation. It is noted that "interpreted data" for 2010 show less subsidence than for 2005. Since the cavern operation continued during this time, a decrease of subsidence seems counterintuitive. It is recommended that the reason for this behavior is further analyzed, especially using the data from following levelling surveys.

The history match for the depicted benchmarks (enclosures 31 - 36) shows an overall sufficient agreement between calculated and "interpreted" subsidence values. The underestimation in benchmark 012F0122 can have different reasons, which cannot be identified based on the available data. However, it is noted, that the "interpreted" subsidence in this benchmark is larger than expected, considering the distance to the expected center of the subsidence trough.

It can be concluded that on the basis of texts, figures and tables contained in Schäfer & Zander-Schiebenhöfer (2015) the elaborated subsidence model is applicable to the Zuidwending cavern field.

4 Review of Subsidence Prediction (Schäfer, Zander-Schiebenhöfer et al. 2016)

The State Supervision of Mines (Staatstoezicht op de Mijnen, SodM) requested a subsidence prognosis in advance to the levelling campaign planned for autumn 2015. This prediction was to be conducted using the latest operation data. Schäfer, Zander-Schiebenhöfer et al. (2016) evaluate the predicted subsidence for the end of October 2015 as well as for the end of 2020, 2030, 2040 and 2050.

Regarding the limitation of subsidence Schäfer, Zander-Schiebenhöfer et al. (2016) state:

“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 this regard 10 gas storage caverns have initially been considered. In combination with gas production the maximum permissible value is 35 cm.”

Schäfer, Zander-Schiebenhöfer et al. (2016) calculate a maximum subsidence value due to cavern operation of 65 mm in the center of the subsidence trough for the end of October 2015. The maximum subsidence rates show values of about 3.0 mm/a.

Four additional brine caverns are introduced into the DEEP / KBB UT model after 2015. Akzo Nobel provided intended production data for the future development of these caverns. Future gas storage operation is assumed to follow annual cycles of gas storage and withdrawal. Beginning of cavern abandonment is scheduled for 2051.

Schäfer, Zander-Schiebenhöfer et al. (2016) mention that re-calibration of the subsidence model was performed for the long-term prediction:

„The subsidence model itself has been slightly adjusted in order to show a more conservative approach for the long-term prediction of subsidence. The calibration procedure has once again been run through and passed. This procedure had been necessary, because the previous assumption of the decrease of the angle of draw, which led to successful validation with respect to the observation period until 2010, in the long-term showed a subsidence development due to the gas storage caverns that has been considered as too slow. Thus, a more conservative approach has been chosen.”

Schäfer, Zander-Schiebenhöfer et al. (2016) calculate maximum subsidence due to cavern operation of 193 mm for the end of 2050. A maximum subsidence of 159 mm is attributed to brine caverns, while a maximum of 36 mm is calculated for gas storage caverns. These maxima occur in different locations of the subsidence trough so that the maximum subsidence due to cavern operation differs slightly from the sum of both maximum values. The calculated laterally spread of the subsidence trough is about 6.3 km in relation to the 10 mm line of equal subsidence. The predicted subsidence rate increases from 3.7 mm/a at the end of 2020 to 4.6 mm/a at the end of 2050.

4.1 Comments

On the basis of texts, figures and tables contained in SCHÄFER, ZANDER-SCHIEBENHÖFER et al. (2016) it is expected that the prognosis performed by DEEP / KBB UT is able to provide conservative future subsidence values if future operation conditions do not vary widely from the assumptions underlying the model.

The specification of model and input parameters before and after the re-calibration would facilitate to distinguish between the original and the updated “more conservative” approach.

5 Conclusions

DEEP / KBB UT screened relevant documents, which provided a reliable data base to set up the subsidence model. They applied a commonly used subsidence model (shape and convergence model) for subsidence predictions above cavern fields, which can be considered as state of the art. The overall approach taken by DEEP / KBB UT is considered applicable to the Zuidwending cavern field.

Based on the available documentation it can be expected that the subsidence prognosis conducted by DEEP / KBB UT is capable to conservatively predict the subsidence values for the assumed operation conditions.

The present subsidence prognosis should be checked against updated surface levelling measurements after a time span of approximately five years. If significant deviations between the measured and predicted values occur, an update of the subsidence prognosis is recommended. This includes the adjustment of the model assumptions based on real cavern operation.

References

BÉREST, P., BERGUES, J., BROUARD, B., DURUP, J. G. & GUERBER, B. (2001): A salt cavern abandonment test. -- International Journal of Rock Mechanics & Mining Sciences, **38**, 357-368; Oxford (Pergamon Pr.).-- ISSN 1365-1609.

EICKEMEIER, R. & WALLNER, M. (2000): Diameter Enlargement of Brine Wells in the Heiligerlee Brine Field for a Field Expansion.-- BGR, Hannover.

EICKEMEIER, R. & WALLNER, M. (2002): Future Development and Optimization of the Zuidwending Brine Field.-- BGR, Hannover.

EICKEMEIER, R. (2005): Senkungsprognosen über Kavernenfeldern - Ein neues Modell. Tagungsband des 34. Geomechanik-Kolloquiums (nur auf CD).-- IfG Leipzig, TU Bergakademie Freiberg - Institut für Geotechnik, 18 S.,7 Abb., 4 Tab., Leipzig.

EICKEMEIER, R. & HEUSERMANN, S. (2006): Kavernenfelder Winschoten/Heiligerlee und Zuidwending: Senkungsprognosen für die Kavernenfelder Winschoten / Heiligerlee und Zuidwending. 1 Text- und 1 Anlagenband.-- BGR, Hannover.

EICKEMEIER, R. & HEUSERMANN, S. (2007): Kavernenfelder Winschoten/Heiligerlee und Zuidwending : Senkungsprognosen für die Kavernenfelder Winschoten/Heiligerlee und Zuidwending (Datenbasis 2005). 1 Text- und 1 Anlagenband.-- BGR, Hannover.

EICKEMEIER, R. & HEUSERMANN, S. (2008a): Kavernenfelder Winschoten/Heiligerlee und Zuidwending: Senkungsprognosen für die Produktionserweiterung im Jahr 2010 (Datenbasis 2005). 1 Text- und 1 Anlagenband.-- BGR, Hannover.

EICKEMEIER, R. & HEUSERMANN, S. (2008b): Senkungsprognosen für den Erdgasspeicher Zuidwending: Revision 1, vier Gaskavernen mit jeweils 1.0 Mio. m³ Volumen (Datenbasis 2005), Abschlussbericht.-- BGR, Hannover.

EICKEMEIER, R. & HEUSERMANN, S. (2008c): Senkungsprognosen für den Erdgasspeicher Zuidwending (Datenbasis 2005): Abschlussbericht. - 1 Text- und 1 Anlagenband.-- BGR, Hannover.

EICKEMEIER, R. & HEUSERMANN, S. (2010): Senkungsprognose für den Erdgasspeicher Zuidwending Soprano-ZW2 (Datenbasis 2005): Abschlussbericht. - 1 Text- und 1 Anlagenband.-- BGR, Hannover.

HOENTJEN, K. H. & DAM, J. (2011): Rapport: Geodetische analyse deformatiemeting 2010; Bepaling van de zoutwinning veroozaakte bedemdaling, Winningvergunningen Uitbreiding Adolf van Nassau II en III Opslagvergunning Zuidwending, Winningvergunningen Adolf van Nassau II en III Opslagvergunning Winschoten II an III.-- oranjewoud.

HOENTJEN, K. H. (2014): Rapport: Geodetisch onderzoek, Aardgasbuffer Zuidwending, Studie naar de historische bodemweging, periode 2003 – 2014, d.m.v. radarinterferometrie.-- antea group.

HOENTJEN, K. H. & DAM, J. (2014): Rapportage: GPS monitoring Aardgasbuffer, Resultaten monitoring bodemweging, Aardgasbuffer Zuidwending, 1 oktober - 31 juli 2014.-- antea group.

OLDENZIEL, C. E. (1999): History matching of surface subsidence due to solution mining operations in the Zuidwending and Heiligerlee brinefields.-- Hengelo (Akzo Nobel). - Document: 9911501.doc.

OLDENZIEL, C. E. & ZANDER-SCHIEBENHÖFER, D. (2000): Confidence Building in Relation of the Optimization and extension of the Hvornum Brine Filed in Mariager, Denmark. 8th World salt symposium.-- The Hague, Netherlands.

ORANJEWOUD (2006): Rapport Frequentiemodellering deformatiemetingen 2005 Winningvergunningen Adolf van Nassau en Adolf van Nassau Uitbreiding.

PINKSE, T. (2014): Bodemdaling door zoutwinning in de boorterreinen Heiligerlee en Zuidwending.

SCHÄFER, R. & ZANDER-SCHIEBENHÖFER, D. (2014): Prediction of Subsidence above Caverns at Zuidwending, The Netherlands - Operation Phase - Report on WP1: Review of Documentation.-- Bad Zwischenahn (DEEP).

SCHÄFER, R. & ZANDER-SCHIEBENHÖFER, D. (2015): Prediction of Subsidence above Caverns at Zuidwending, The Netherlands - Operation Phase - Report on WP2: Applied Subsidence Model.-- Bad Zwischenahn (DEEP).

SCHÄFER, R., ZANDER-SCHIEBENHÖFER, D. & HORVÁTH, B. (2016): Prediction of Subsidence above Caverns at Zuidwending, The Netherlands - Operation Phase - Report on WP3: Subsidence Prediction.-- Bad Zwischenahn (DEEP).

SCHOBER, F., SROKA, A. & HARTMANN, A. (1987): Ein Konzept zur Senkungsvorausberechnung über Kavernenfeldern. -- Kali und Steinsalz, **9**, 11: 374-379.-- ISSN 0022-7951.

SROKA, A. & SCHOBER, F. (1982): Die Berechnung der maximalen Bodenbewegungen über kavernenartigen Hohlräumen unter Berücksichtigung der Hohlraumgeometrie.-- Kali und Steinsalz, **8**, 8: 273-277.