

**Prediction of Subsidence above
Caverns at Zuidwending, The Netherlands
Operation Phase
Report on WP1: Review of Documentation**

for

[Redacted]
[Redacted]
[Redacted]
[Redacted]
[Redacted]

Client Inquiry No.: 5200020748

Client Project No.: PR90694

DEEP. Project No.: 5222-880965

Author(s): Dipl-Geol. Raphael Schäfer, DEEP.
Dr.-Ing. Dirk Zander-Schiebenhöfer, KBB UT

Checked: Sf Approved: DZ

Date: 24.11.2014 Revision: 00a

[Redacted]
[Redacted]

Table of Contents

1 Introduction	3
2 Scope of Work – WP1	4
3 Compilation of Findings from Selected Documentation	5
3.1 Levelling campaigns	5
3.2 GPS measurements.....	6
3.3 Radarinterferrometrie.....	6
3.4 Subsidence prediction studies	6
4 Conclusions	8

List of Tables

Table 3.1 Predicted increase of subsidence and subsidence rate according BGR (2007) with reference to 1990..... 7

1 Introduction

Since 1968 AkzoNobel is 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 were 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. It is intended to incorporate both caverns after 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 via the overburden layers to the surface, where they form a subsidence bowl. 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 for respecting limitations on maximum subsidence during cavern operation. Operators therefore 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 check this limitation, levelling campaigns are mandatory after specified periods of time. At Zuidwending however, different sources – such as gas production, salt production, gas storage, ground compaction, and erosion – contribute to surface subsidence. Therefore, theoretical modelling is required, if the individual contributions have to be checked against their individual limitations.

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

Prior to modelling the existing documentation on surface subsidence measurement, evaluation and modelling had to be compiled according to **Workpackage 1 (WP1) – Screening of Documentation**. This information provides basic knowledge about the field development and subsidence observations, which will be used for confidence building and validating of the applied subsidence model.

The present report summarizes findings and conclusions of the work according to WP1.

2 Scope of Work – WP1

When establishing a new subsidence model the continuity with the existing studies and observations has to be assured. This refers to modelling assumptions in principle and to measurement and aims at a reliable history matching of modelled versus observed surface subsidence values.

Provided documentation, studies and measurements reports have been screened with focus on information about field and subsidence development. Given evaluations with respect to the individual contribution of the salt caverns were also searched for. The essential results, observations and findings as presented in the documents form the basis for building and setting-up of the new subsidence model. In this report these essential findings are summarized in short.

The present report focusses on the provided documentation about subsidence measurements, their interpretation and subsidence prediction. Besides this kind of documentation a considerable documentation on cavern development was delivered by AkzoNobel and Gasunie. This set of data is essentially required for the set-up of the subsidence prediction model. They were taken as facts or conclusions from studies without further interpretation. How these data have been integrated in the subsidence model is shown in the report on WP 2 where it is described how the subsidence model is built-up and validated.

3 Compilation of Key Findings from Selected Documentation

By screening the provided information a set of reports has been identified that contains key information about the development of surface subsidence above the Zuidwending caverns. These reports are following:

- History Matching of subsidence
by OLDENZIEL, AKZONOBEL (1999) [1]
- Subsidence Prognosis study
by EICKEMEIER and HEUSERMANN, BGR (2007) [4] and [5]
- Evaluation of Levelling Data
by ORANJEWOUD (2006) [2]
- Evaluation of Levelling Data
by HOENTJEN and DAM, ORANJEWOUD (2011) [3]
- Evaluation of Radarinterferiometrie
by HOENTJEN, ANTEA GROUP (2014) [6]
- Evaluation of GPS monitoring
by HOENTJEN and DAM, ANTEA GROUP (2014) [7]
- Comment on the results of the levelling campaign 2010
by PINKSE, AKZONOBEL (2014) [8]

The general findings and conclusions are discussed subsequently.

3.1 Levelling campaigns

Levelling campaigns were carried out almost every 5 years. Provided documentation describes, evaluates and partly comments/interprets the measurements of 1998, 2005 and 2010.

The report of OLDENZIEL (1999) makes use of the levelling data from 1998 for selected benchmarks. Individual contributions to subsidence by gas production were estimated by using global subsidence maps of Nederlandse Aardolie Maatschappij (NAM), which show values of 50 to 70 mm of total subsidence above the Zuidwending cavern area with reference to the beginning of 1969 shortly after starting cavern operations. By subtracting individual contributions due to gas production (between 27.4 and 48.1 mm) and due to natural sources (constantly 10 mm) and by an additional independently checking of the individual contributions of the brine production caverns (gas storage caverns were not existing at that point in time) a maximum subsidence of 29.9 mm is anticipated. This amount of subsidence was generated during the period from 1969 to 1998.

Further reports on levelling campaigns with interpretation of the measurement results were prepared by ORANJEWOUD for the campaign of 2005 [2] and of 2010 [3]. Therein the raw data were filtered in a sequence of

- stability analysis (correction through assessment of the reliability of the benchmarks),
- object point analysis (subtraction of contributions by ground compaction and gas production), and

- deformation analysis (checking of time dependent continuity of measurements per for each benchmark).

Maximum values of subsidence due to cavern convergence were identified with 39 mm for the period between 1969 and 2005 and nearly the same value for the period 1969 to 2010.

3.2 GPS measurements

Gasunie installed GPS antennas on the wellpads close to the wellheads of its gas storage caverns in 2013. Measurement results were evaluated for the period October 1st, 2013 to September 30th, 2014 by ANTEA GROUP in 2014. Moving average values across 8 weeks were calculated from the fluctuating measurement values. These average values show a trend of about 3 mm of total subsidence at the end of the observation period of one year. Values do not vary essentially between antennas and they are in good agreement with levelling data from 2005 and 2010.

3.3 Radar Interferometry

Gasunie launched a study on determining surface subsidence above the Zuidwending cavern area by evaluation of radar interferometry images which were available from different satellites (Envisat, Radarsat-2 and TerraSAR-X).

Images from Envisat were analysed for the period December 2003 to September 2013 and compared with the results of the levelling campaigns of October 2005 and January 2011 in terms of subsidence rate and observed total subsidence. Calculated subsidence rates based on levelling data were in between 2.1 to 3.2 mm/a and slightly higher than those from evaluation of radar images (1.5 to 3.0 mm/a).

The analysis of images from Radarsat-2 and TerraSAR-X produced similar values for the subsidence rate. About 2.5 mm/a were calculated for the time period June 2010 to April 2014 based on Radarsat-2 data and 3.2 mm/a according to TerraSAR-X data for the period December 2011 to February 2014. Cumulative values are given with 9.7 (Radarsat-2) and 6.8 mm (TerraSAR-X).

3.4 Subsidence prediction studies

EICKEMEIER and HEUSERMANN (2007) performed a subsidence prediction study based on the 2005 levelling campaign data. The applied subsidence model considers the brine production data and takes into account the individual convergence behaviour of the caverns by calculation of convergence rates from numerical cavern models. Calculated subsidence was compared to measured values at selected reliable benchmarks and matched by adjusting the creep behaviour of the salt. At the end of this history matching process a reliable basis was found in order to give predictions of the future subsidence development while assuming different production/operation scenarios. Thereby brine production and gas storage caverns were taken into account.

According to the investigated scenario for brine production with subsequent abandonment of the caverns (scenario ZW01) coupled with the gas storage cavern scenario at average pressure of 145 bar (scenario ZW03-145) the resulting increase in subsidence as well as related subsidence rates were calculated for different points in time as listed in Table 3.1. In the last line of Table 3.1 a calculated initial subsidence of 7.7 mm in the beginning of 1990 is considered.

Table 3.1 Predicted increase of subsidence and subsidence rate according BGR (2007) with reference to 1990

reference year	2000	2007	2018	2050
maximum subsidence rate at the beginning of the reference year [mm/a]	1.08	1.35	1.78	0.77
maximum increase of subsidence between 1990 and the reference year [mm]	9.0	17.4	35.7	84.8
total subsidence since 1969 [mm]	16.7	25.1	43.4	92.5

3.5 Comment on Prediction 2007 vs Levelling Data 2010

PINKSE (2014) compared prediction by EICKEMEIER and HEUSERMANN (2007) with the interpreted results of the levelling campaign of 2010 (HOENTJEN and DAM (2011)). A comparison of predicted versus observed values by using rough calculations indicates that observed subsidence is slightly greater than the predicted for 2014.

4 Conclusions

The existing documents provide a reliable data base for setting up the subsidence model for the intended updated predictions.

Nevertheless some items for clarification shall be addressed in order to consider these during the built-up of the new subsidence prediction model.

- GPS measurements are relative newly implemented, but the trends calculated from the fluctuating GPS measurements are in good agreement with subsidence rates calculated from benchmarks in the centre of the cavern areas between levelling campaigns 2005 and 2010.
- Interpretations of images from radar interferometry show a range of subsidence rates between 1.5 and 3.2 mm/a (different periods as well as satellites). Compared to values calculated from levelling data subsidence rates due radar interferometry are lower.
- Interpretation of the levelling data from 2005 and 2010 at some benchmarks lead to merely no increase in subsidence generate by cavern operation. This seems to be a contradiction to the fact that cavern convergence is on-going due to cavern pressures below the lithostatic pressure.
- A quick comparison of latest predictions and observations show that observed subsidence develops slightly faster than the predicted. This difference may result from the assumption that gas storage operations were considered by presuming an average cavern pressures. Additionally the actually extracted volumes differ. Also cavern ZW A7 was not considered at that point in time.

References

- [1] OLDENZIEL, C.:
'History matching of surface subsidence due to solution mining operations in the Zuidwending and Heiligerlee brinefields',
AkzoNobel, Minerals Department, 1999.
- [2] ORANJEWOUD:
'Rapport Frequentiemodellering deformatiemetingen 2005 Winningvergunningen Adolf van Nassau en Adolf van Nassau Uitbreiding',
projectnr. 15575-61467-16, revisie 00, oranjewoud, 28 juni 2006.
- [3] HOENTJEN, K. H., DAM, J.:
'Rapport Geodetische analyse deformatiemeting 2010; Bepaling van de zoutwinning veroorzaakte bedemdaling, Winningvergunningen Uitbreiding Adolf van Nassau II en III Opslagvergunning Zuidwending, Winningvergunningen Adolf van Nassau II en III Opslagvergunning Winschoten II en III',
projectnr. 242314, revisie 02, oranjewoud, 31 oktober 2011.
- [4] EICKEMEIER, R., HEUSERMANN, S.:
'Kavernenfelder Winschoten / Heiligerlee und Zuidwending Senkungsprognosen für die Kavernenfelder Winschoten / Heiligerlee und Zuidwending (Datenbasis 2005)
Abschlussbericht – Textband, Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), Hannover, Juni 2007
- [5] EICKEMEIER, R., HEUSERMANN, S.:
'Kavernenfelder Winschoten / Heiligerlee und Zuidwending Senkungsprognosen für die Kavernenfelder Winschoten / Heiligerlee und Zuidwending (Datenbasis 2005)
Abschlussbericht – Anlagenband, Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), Hannover, Juni 2007.
- [6] HOENTJEN, K. H.:
'Rapport: Geodetisch onderzoek, Aardgasbuffer Zuidwending, Studie naar de historische bodemweging, periode 2003 – 2014, d.m.v. radarinterferometrie',
antea group, 2014.
- [7] HOENTJEN, K. H., DAM, J.:
'Rapportage: GPS monitoring Aardgasbuffer, Resultaten monitoring bodemweging, Aardgasbuffer Zuidwending, 1 oktober - 31 juli 2014',
antea group, 2014.
- [8] PINKSE, T.:
'Bodemdaling door zoutwinning in de boorterreinen Heiligerlee en Zuidwending'
Memorandum, AkzoNobel, 12 september, 2014.