MEMO
Questions of SodM about Zuidwending Subsidence Modelling

Project No:	PN52	**Date:**	10.10.2017
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Introduction

SodM compared the results of the DEEP/KBB UT subsidence prediction for the Zuidwending cavern field with the predictions results of BGR and TNO-AGE. With regard to subsidence produced by the gas storage caverns until 2050 BGR (2010) predicted a maximum value of 10.5 cm and TNO-AGE 20.1 cm. Both values are substantially higher than the value of 3.6 cm as given by the DEEP/KBB UT study in 2016.

In order to clarify the reasons of this difference, SodM asked Gasunie to provide answers to the following questions:

1. *Explain the differences between the outcome of the new DEEP/KBB prediction and the outcome of the BGR prediction from 2010, is the only difference the number of caverns and the total storage volume?*
2. *What is the uncertainty factor for the outcome of new subsidence prediction model?*
3. *What are the convergence rates (%/year) per cavern?*
    a. *In the IfG report from 2011 values of 0.3-0.4%/year are given. Is this also the case in the new model? If not, why not?*
4. *How realistic is the pressure scenario (WP3, fig. 8) that is used in the DEEP/KBB model?*
    - *Please show us the 2016 pressure plots for caverns A3 and A7.*

Answer to SodM Question (1) – Differences between BGR and DEEP/KBB UT model

The general approach of modelling is the same with the BGR and the DEEP/KBB UT subsidence model. Both models basically rely on the Sroka/Schober concept. However, there are some details that differ:

- The BGR model assumes a fixed value of 45° for the angle of draw, which is constant over time. The DEEP/KBB UT model assumes a time dependent value of the angle of draw that starts with a value of 30° and decreases of the years to 20°. It has been observed above other cavern sites that the angle of draw can be 30° and less. Furthermore, due to history matching of levelling data of these sites it can be assumed that the angle of draw decreases over time.
  With lower values of the angle of draw the maximum value of the predicted subsidence becomes smaller. Therefore, it can be expected that with the DEEP/KBB UT model lower values of subsidence will be predicted. However, the DEEP/KBB UT model has been verified by history matching at benchmarks. This history match revealed a good agreement with values at benchmarks, which are located above the center of the cavern field, and a moderate accordance with benchmarks that are more distant from the caverns.

- The volume of the gas storage caverns has been considered with the actually values due to sonar surveys in the DEEP/KBB UT model. The assumptions made by BGR (2010) are different. With regard to caverns of the first phase (ZW-A2, ZW-A3, ZW-A4, ZW-A6) and ZW-A7 the assumed cavern volumes are slightly smaller compared to the DEEP/KBB UT study. However, the number of caverns and the overall gas storage volume as assumed in the BGR (2010) study is greater: 10 cavern instead of 7 and an overall gas storage volume of about 9.9 million m³ instead of 5.3 million m³. Both assumptions lead to higher subsidence until 2050. Thus, slightly higher subsidence is expected to be predicted by the BGR study.
- In the DEEP/KBB UT model the operated daily pressures during the storage year from 2012 to 2013 for the gas storage caverns have been taken into account as representative for all years until 2050. This modelling approach leads to varying values of convergence during the storage years. The convergence rates for example for cavern ZW-A3 range between 0.07 and 0.36%/a for cavern ZW-A7 between 0.14 and 0.67 %/a. Corresponding average values are 0.19%/a for cavern ZW-A3 and 0.17%/a for cavern ZW-A7. These values are in the range of calculated convergence rates resulting from studies of IfG (2011) and (2012) focusing on cyclic operation of the Zuidwending gas storage caverns. The BGR model assumes an average annual cavern pressure of 145 barg, which produces a convergence rate of 0.49‰/a. The assumed convergence rate as assumed in the BGR prediction is much lower and therefore a substantially lower prediction for the maximum subsidence would be expected from this model.

The predicted values of the maximum subsidence until 2050 as produced by the gas storage caverns are compiled in Table **1** due to the different assumed scenarios of BGR and DEEÜ/KBB UT.

Subsidence Model	Assumed storage history	Assumed Profile of Annual Cavern Pressure	Number of gas storage caverns	Predicted Maximum Subsidence [mm]
BGR (2007)	ZW04	145 bar	4	102
BGR (2010)	V1	minimum	7	70
BGR (2010)	V2	normal	7	51
BGR (2010)	V3	minimum	10	99
BGR (2010)	V4	normal	10	75
BGR (2010)	V5	minimum with existing caverns, normal with additional caverns	10	89
DEEP/KBB UT (2015)	-	representative storage year 2012/2013	7	36

Table 1 Comparison of predicted maximum subsidence due gas storage cavern for different scenarios and based on different models

In order to conclude the above, it can be stated that the predicted lower maximum subsidence until 2050 due to the DEEP/KBB UT model results from the assumption of a greater extent of the subsidence bowl, a slightly smaller overall gas storage volume and a higher average annual cavern pressure.

Answer to SodM Question (2) – Factor of Uncertainty

Different aspects have to be taken into account in order to answer this question:

> Firstly, the cavern volume development depends on the assumed creep ability of the rock salt surrounding the caverns. This creep ability has been tested in the laboratory by IfG.
> Secondly, the potential range of the creep ability in order to fit the cavern volume development is relatively wide, because the convergence volume is substantially smaller compared to the cavern volume.
> And, in the third place calculated subsidence has to math with levelling data that contain not only subsidence contributions from the gas storage caverns.

Thus, the factor of uncertainty cannot be determined precisely, i.e. a discrete value cannot be given. In order to give a range of uncertainty the reliability of the DEEP/KBB UT subsidence model can be described by a comprehensive evaluation of the three different steps of verification:

1. At subsurface the volume development of the cavern has been checked against the sonar measurements.
2. The assumed creep ability of the salt has been checked against laboratory results.
3. On surface the calculated subsidence values have been compared to benchmark values, which have been interpreted by an independent third party with regard to subsidence induced by the salt caverns.

With regard to the subsurface check the uncertainty in the assumed creep rate may theoretically be more than a factor of 2. Above this value the resulting convergence rates start to deviate from the lab-test values of IfG (Figure 1). The average convergence rate will then be about 0.4 %/a for cavern ZW-A7, and about 0.3%/a for cavern ZW-A3. These values range within boundaries as predicted by IfG as mentioned above by SodM.

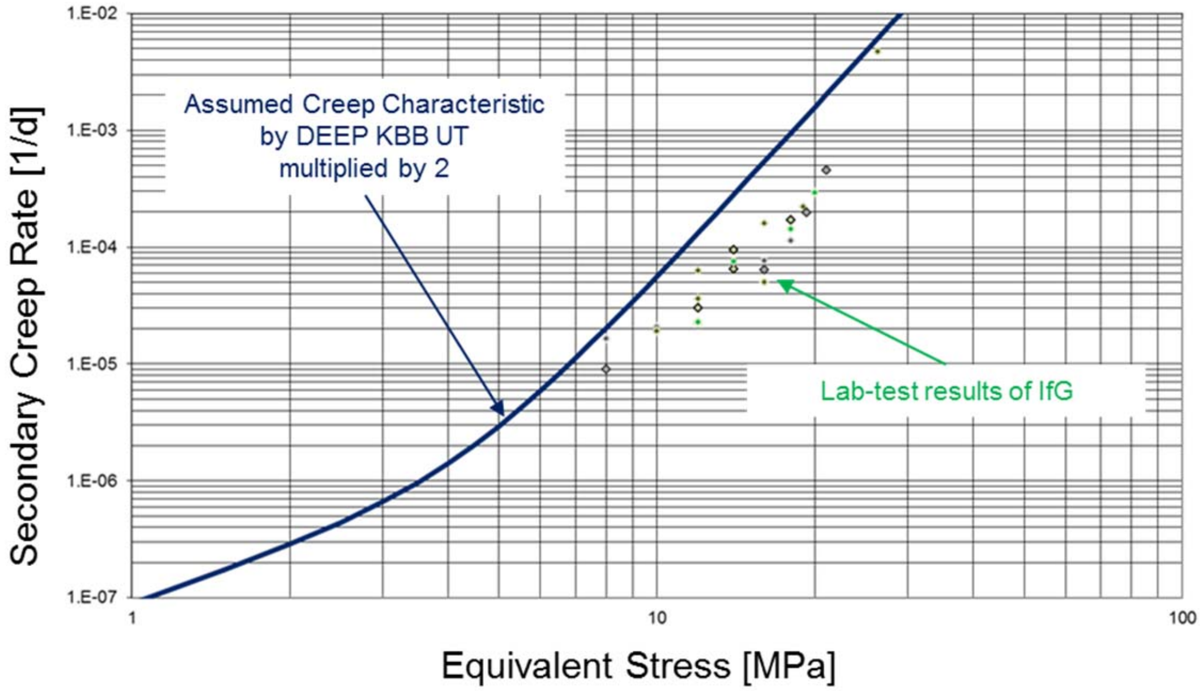

Figure 1 Creep characteristic for an factor of uncertainty of 2 compared to lab-test results of IfG

The check on surface however shows that the uncertainty factor can be assumed to be lower than 2, because calculated values for cavern induced subsidence nearly reach the levelling data, which still include the shares by gas production, ground compaction and other sources (compare Figure 2 and Figure 3). As far as only interpreted levelling data (red diamonds in Figure 2 and Figure 3) would have been used for history matching, the question about uncertainty of the model would have to be related to the uncertainty of the interpretation of the third party, but the additional superposition with the NAM prediction data (2013 and 2016 interpolated) enables a more direct comparison of calculated and measured values.

In conclusion, it is estimated that the factor of uncertainty is below 2.

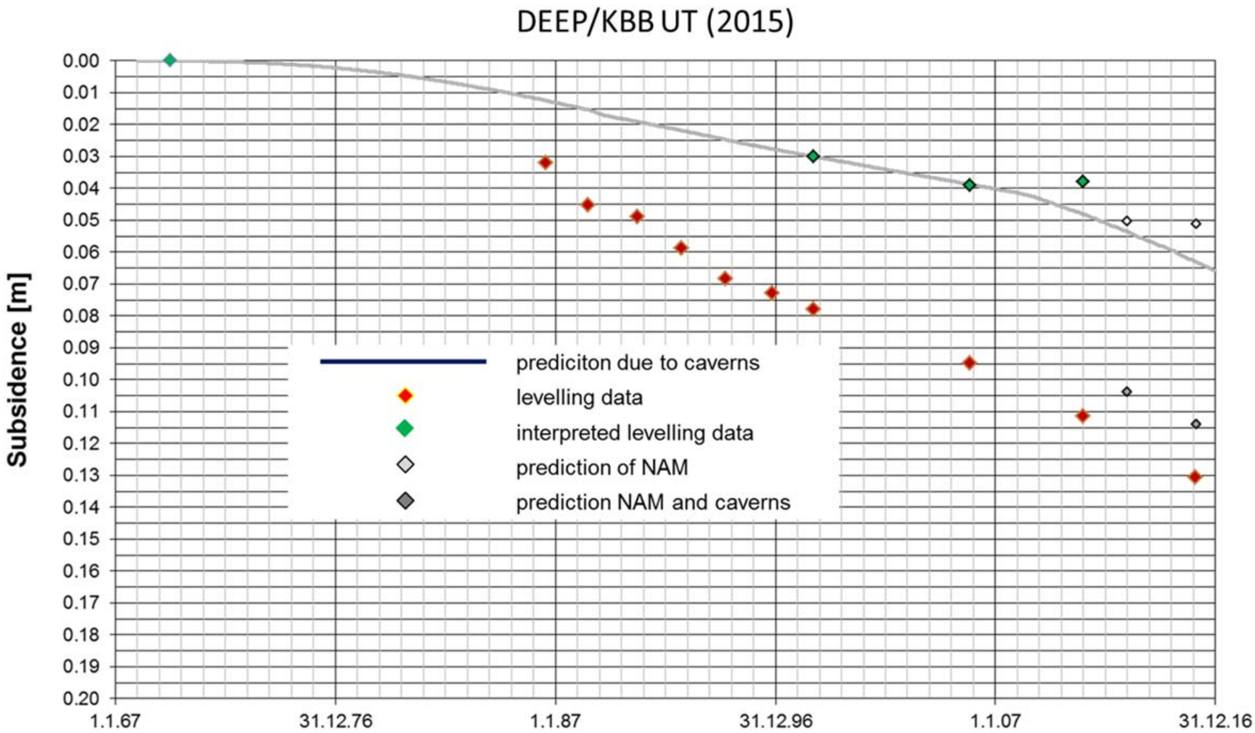

Figure 2 **Prediction 2015/6 compared to measured values at benchmark 012F3600**

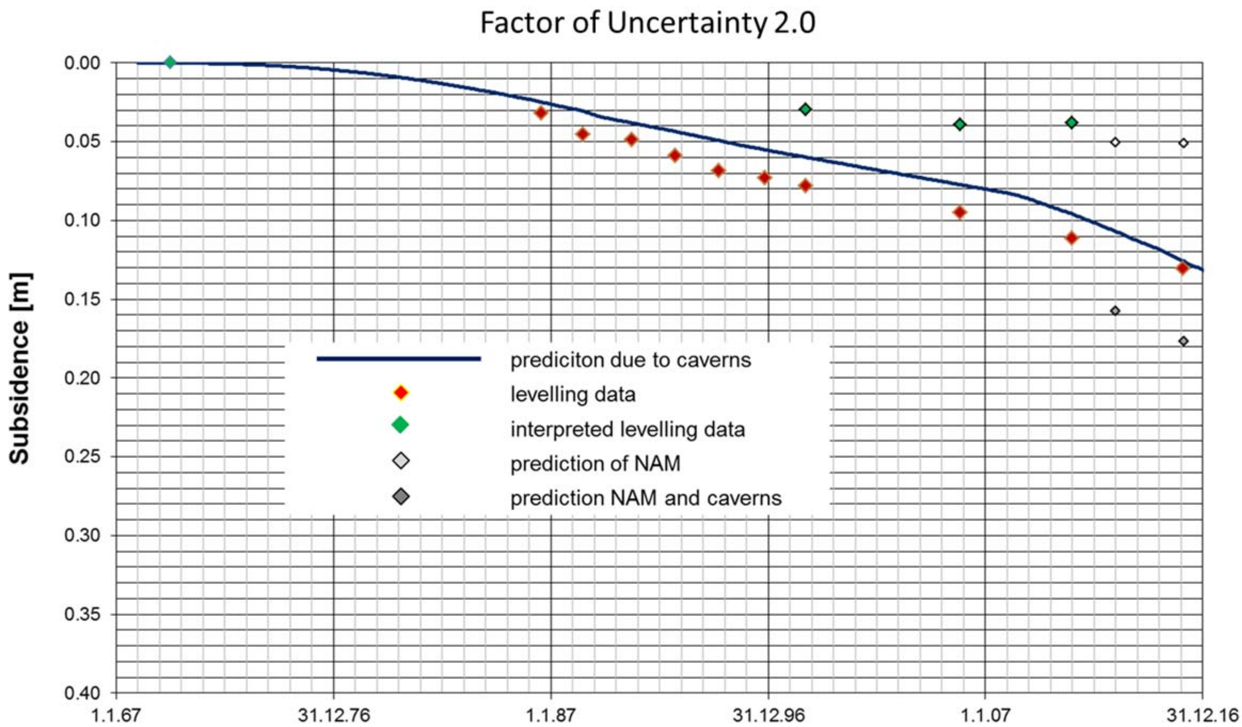

Figure 3 **Prediction 2015/6 assuming the uncertainty factor of 2 compared to measured values at benchmark 012F3600**

Answer to SodM Question (3) – Convergence Rates resulting from the DEEP/KBB UT model

As already mentioned above the calculated convergence rate for the assumed representative annual storage cycle is 0.19%/a for cavern ZW-A3 and 0.17%/a for cavern ZW-A7.

These values are about two to three times higher than the assumed value of 0.49 ‰/a BGR (2007). This does not explain the difference between the subsidence predictions due to gas cavern storage between 51 and 99 mm until 2050 as given by BGR (2010) and 3.6 cm due to by DEEP/KBB UT.

The explanation about how lower convergence rates lead to lower subsidence has been given above. This is mainly due to the larger extent of the subsidence bowl that can be justified by the history match at benchmarks.

Assuming higher values for the convergence rate in the DEEP/KBB UT will not explain the observed values of subsidence as mentioned above. The assumed values in the DEEP/KBB UT model are in very good agreement with the predicted values of IfG (2011) and (2012) for cyclic storage.

Answer to SodM Question (3) – 2016 pressure plots for caverns A3 and A7

The operated wellhead pressures according to years 2011 to 2017 are shown for cavern ZW-A3 in Figure 4 and years 2013 to 2017 for cavern ZW-A7 in Figure 5. The black line represents the assumed annual cycle as used in the DEEP/KBB UT prediction.

It can be stated that in the first half of the year, when cavern pressures were relatively low, the curve as assumed for the subsidence prediction, represents a conservative approach with regard to convergence/subsidence behavior. In the second half more or less the average of all so far operated years is represented by the assumed pressure cycle for the subsidence prediction.

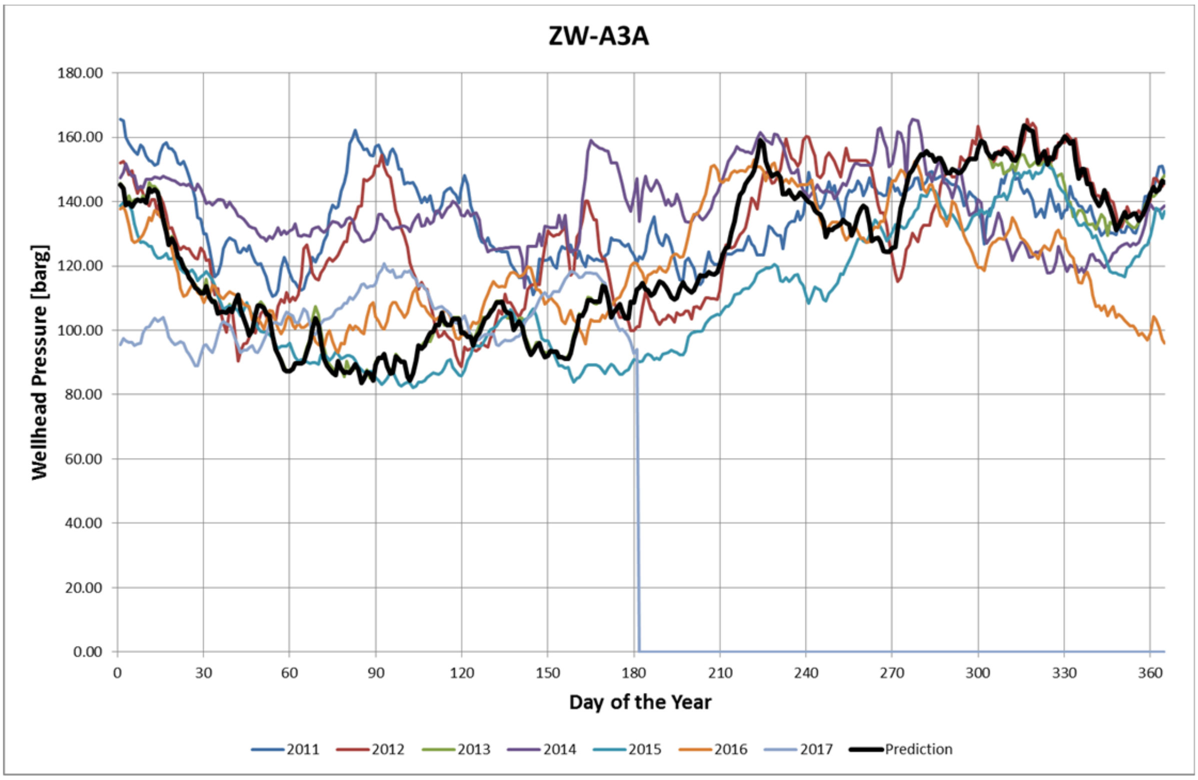

Figure 4 **Wellhead pressure records for cavern ZW-A3A from 2011 to 2017 compared with the representative annual pressure cycle as assumed in the DEEP/KBB UT study.**

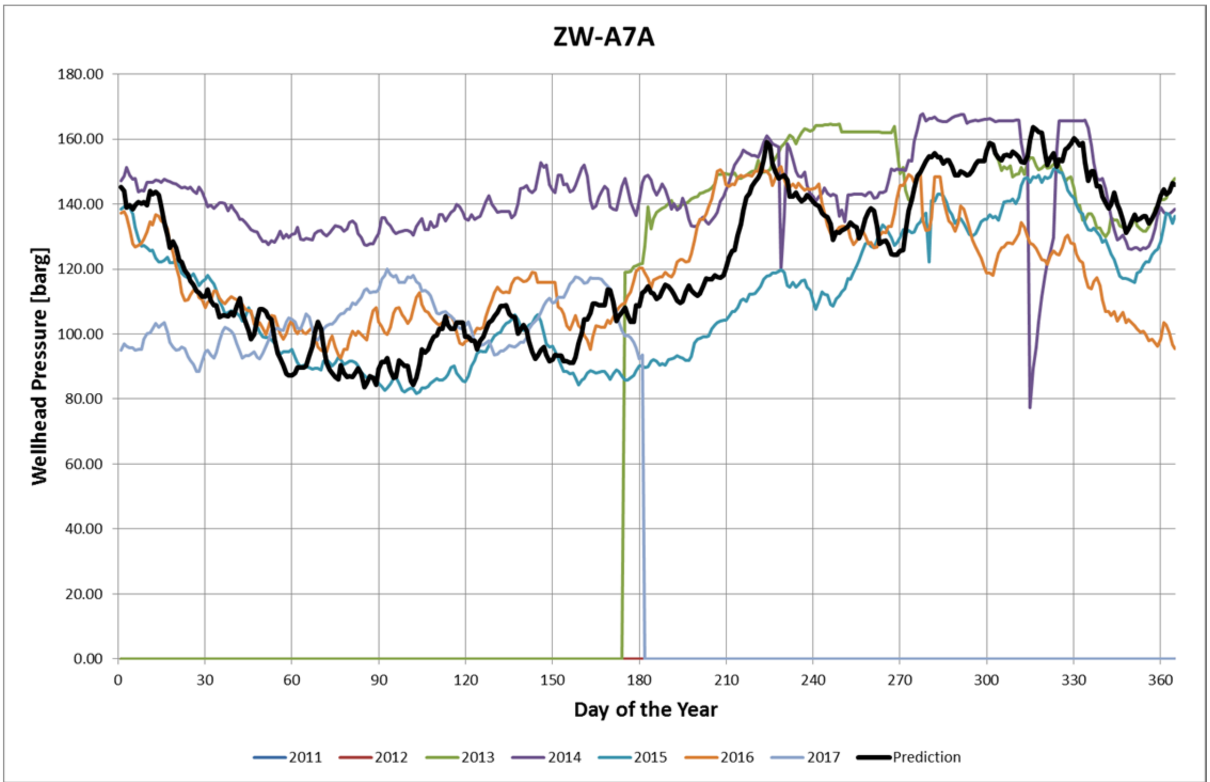

Figure 5 **Wellhead pressure records for cavern ZW-A7A from 2013 to 2017 compared with the representative annual pressure cycle as assumed in the DEEP/KBB UT study.**

General Conclusion

Several influencing factors contribute the difference in the predicted maximum subsidence until 2050 due to the operation of gas storage caverns at Zuidwending as calculated by BGR and DEEP/KBB UT.

Comparing only the assumed convergence rates, it could be expected that the DEEP/KBB UT prediction must give the highest values. But, mainly due to the assumed greater extent of the subsidence bowl it turns out to be the opposite. Further, the assumed overall subsurface volume differs. The majority of the BGR scenarios consider more caverns and/or a greater overall volume.

By applying the levelling data at benchmarks in the center of the subsidence bowl as well as at some more distant points it can be shown that subsidence as predicted by the DEEP/KBB UT model match relatively good with the measured data. This becomes especially evident, when also the predicted values due to the gas production of the NAM will be taken into account. This coincidence indicates a certain degree of reliability.

A factor of uncertainty cannot be determined directly, because three different references for verification have to be considered:

(1) the lab-test results of creep tests,
(2) the sonar survey of the caverns, and
(3) the leveling data including their interpretation.

However, a certain range of reliability can be given by a comprehensive evaluation of all three steps of verification. Due to the threefold checking process the factor of uncertainty of the DEEP/KBB UT model (and based in the assumptions made) can be assumed to be below 2.

Additional Remark

Gasunie has appointed BGR to review the subsidence modelling approach of DEEP/KBB UT. This review has been delivered 15. August 2017 (BGR report B3.5/B50221-01/2017-0006/0001, Gasunie Reference 05-1016-10 d.d. August 2017). In the abstract of the report the following statements are given:

> *"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."*

It is further mentioned in the Conclusions of Chapter 5 that

> *“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.”*

In this context we are convinced to have a reliable subsidence prediction model that will be improved step by step based by history matching of future measurements.

Signed (Dirk Zander-Schiebenhöfer)
(DZ)