SGS

Nedmag B.V.

Modelling of subsidence induced by salt squeeze mining from the Veendam concession: History match 1993 – 2016 and forecast including two new wells

April 2018

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EXECUTIVE SUMMARY

Nedmag B.V. (Nedmag) induces surface subsidence by salt squeeze mining from their Veendam concession in Groningen, north-east Netherlands. SGS Subsurface Consultancy (SGS) has executed a subsidence modelling study consisting of a history match over the period 1993-2016 and a forecast for subsidence beyond 2016 as a result of production from existing wells and two new wells, VE-5 and VE-6.

In accordance with the scope of the study, subsidence modelling was carried out using the Geertsma-Van Opstal model with a variable rigid basement. Main input data to the model were cavern depths and locations and squeeze volumes. Observed subsidence data were used to calibrate the model (i.e. to history match against). All data were delivered to SGS by Nedmag.

The history match of a simplified subsidence model resulted in a reasonable fit of the modelled subsidence bowl to the observed subsidence values at benchmark locations. A detailed history match, which included allocation of production volumes to individual well locations, resulted in a subsidence model that was deemed appropriate for future subsidence forecasting.

A subsidence forecast was performed for three squeeze production scenarios provided by Nedmag. The first scenario is based on the existing wells only, whereby all future squeeze volume is assigned to the TR-1 cavern. The two other scenarios include production from two new wells, VE-5 and VE-6, which are envisaged to be drilled to the west of the existing wells. In the second and third scenario 40% and 20% of the total squeeze volume will be produced by the new wells respectively.

In the production scenario with a squeeze contribution from current wells only, the maximum permitted subsidence of 65 cm will be reached near the TR-1 well location by 2031.

Two to five years of delay in reaching the maximum permitted subsidence can be achieved in case of drilling the VE-5 and VE-6 wells and assigning 20 to 40% of the total squeeze contribution to these wells. This would allow production of 0.44 to 1.1 million m^3 additional squeeze volume compared to the scenario with squeeze contribution from current wells only.

This study is considered a deterministic approach and thus represents one possible development of subsidence due to salt squeeze mining from the Veendam area. The scope of this study did not include uncertainty modelling and/or assessment of uncertainty ranges related to the input data, subsurface simplifications, modelling assumptions and methodological constraints.

TABLE OF CONTENTS

1 INTRODUCTION

Nedmag B.V. (Nedmag) is mining magnesium salt from its Veendam concession located in the province of Groningen, north-east Netherlands (Figure 1-1). Originally, conventional solution mining was used, whereby caverns were created that were kept close to lithostatic pressure. Since 1993, a squeeze mining technique is applied, whereby the pressure in the caverns formed by conventional solution mining is gradually lowered to 60-80 bar below the lithostatic pressure, which allows creep (squeeze) of the magnesium salts into the caverns. Squeeze mining results in gradual thinning of the salt layer and, subsequently, leads to surface subsidence. The subsidence resulting from salt mining is monitored by (bi)annual measurement surveys at benchmark points. All subsidence measurements are relative to the 1993 level. Nedmag has a permit to induce, with salt mining, up to a maximum of 65 cm surface subsidence at benchmark point locations compared to the 1993 reference level. By April 2016, the maximum observed subsidence was 37.7 cm.

Magnesium rich salt minerals, especially bischofite ($MgCl_2{\cdot}6H_2O$), are produced from Permian Zechstein deposits which are located between 1500 and 2000 m depth in the Veendam area. The bischofite layer within the Zechstein deposits shows significant thickness variations, from several metres up to 21 m thick. Nedmag has modelled historical subsidence from 1993 onward with the Geertsma-Van Opstal method. The observed widening of the subsidence bowl with time was accommodated for in this model by an increasing reservoir radius. A TNO publication on subsidence related to gas extraction (Muntendam et al., 2012 [1]) suggests that the behaviour of the subsidence bowl with time could be more realistically captured by assuming a variable rigid basement in the Geertsma-Van Opstal model. Based on this experience Nedmag, wants to model the existing and future subsidence resulting from squeeze mining with the Geertsma-Van Opstal model applying a variable rigid basement.

Nedmag is planning to drill new wells to the west of the existing salt wells and requires prediction of expected subsidence due to future salt mining from both the existing wells and the planned wells. Nedmag has requested SGS Subsurface Consultancy (SGS) to perform a subsidence modelling study using the Geertsma-Van Opstal model with a variable rigid basement, the results of which are reported here.

1.1 SUBSIDENCE MODELLING

At Nedmag's request, subsidence due to Nedmag's salt production was modelled using the Geertsma – Van Opstal model (Van Opstal, 1974 [4] and Geertsma, 1966 [3]) with a variable rigid basement depth parameter. This method has been successfully applied to model gas production induced subsidence, e.g. by Muntendam et al. (2012) [1].

The analytical Geertsma – van Opstal model assumes linear and uniform elastic behaviour of the formations in which the reservoir (or salt cavern, in this case) is embedded. The model further assumes a rigid basement below the reservoir, at or below which displacement is zero for all rock. The implication of these assumptions is that any effect of a non-planar or laterally varying overburden geometry will not be considered. The analytical approach used in this model is a simplified representation of the real subsurface. The depth of the rigid basement determines the shape of the subsidence bowl and as such mimics the elastic behaviour of the overlying layers. Contrary to what the name may suggest, it is not a physical parameter that represents the geological basement. A schematic illustration of the rigid basement depth affecting the subsidence bowl shape is included in Appendix A. In this study, a variable rigid basement depth is used to describe the subsidence bowl shape development through time. Subsidence can be calculated at any specified point at surface or on a dense grid of surface locations.

The measured surface subsidence in the Veendam concession area is not only the result of salt mining activities, but is also partly due to nearby gas production (the Groningen, Annerveen and Kiel-Windeweer gas fields are surrounding the Veendam salt mining location). The observed subsidence may also include an autonomous subsidence component (i.e. subsidence originating from movements in the shallow subsurface). This study only models the salt mining induced subsidence.

1.2 INPUT DATA

The following data were provided to SGS by Nedmag and were used as input to the study:

- Cavern (well) locations and depths
- Squeeze volumes (per individual well until cavern connection, from then on volume per cluster)
- Cavern connection times
- Subsidence at benchmark locations due to squeeze mining in the period from 1993 to 2016 (processed from the original data by *'objectpunt'* analysis)

The study covers the production from 13 existing wells (VE-1 to 4 and TR-1 to 9) and two planned wells (VE-5 and VE-6). The historic squeeze volumes were provided by Nedmag, who established these squeeze volumes by mass balance calculations based on injected water volumes, understanding of the nature of the salt layers, salt solution processes and on extracted brine volumes. Input into the modelling study consisted of a single deterministic set of squeeze volumes. Over time, salt caverns of different wells have become connected, possibly through preferential dissolution paths or due to mobilisation of the Bischofite crystal water as a result of pressure differences between the caverns, to form clusters from which the salt is produced. When producing from a cluster, the production figures per individual well cannot be accurately established. Therefore, Nedmag only provided total cluster squeeze production volumes. Cavern (well) locations, production figures and cavern connection times are available in Appendix A.

The subsidence data from benchmark measurements available for this study were processed from the original data by the Antea Group and by Nedmag. The original subsidence measurements have undergone 'objectpunt' analysis to separate contributions from various sources, notably to separate the gas-extraction induced subsidence from the salt-mining induced subsidence. For this study, only the part of the measured subsidence allocated to salt-mining was used as input data into the model and is referred to in this report as 'subsidence' or 'observed subsidence'. Input into the modelling study consisted of a single set of benchmark data without measurement and processing error bars. The Veendam benchmark network contains 258 benchmark points. 119 of these have monitored subsidence since the start of the studied period (1993) and have been used in this study (Appendix C). Figure 1-1 shows the subsidence bowl as observed from benchmark measurements in April 2016, the last benchmark measurement survey available for this study. By April 2016, the maximum observed salt induced subsidence was 37.7 cm close to well TR-1. All measurements together reveal the presence of a symmetric, circular subsidence bowl around this point.

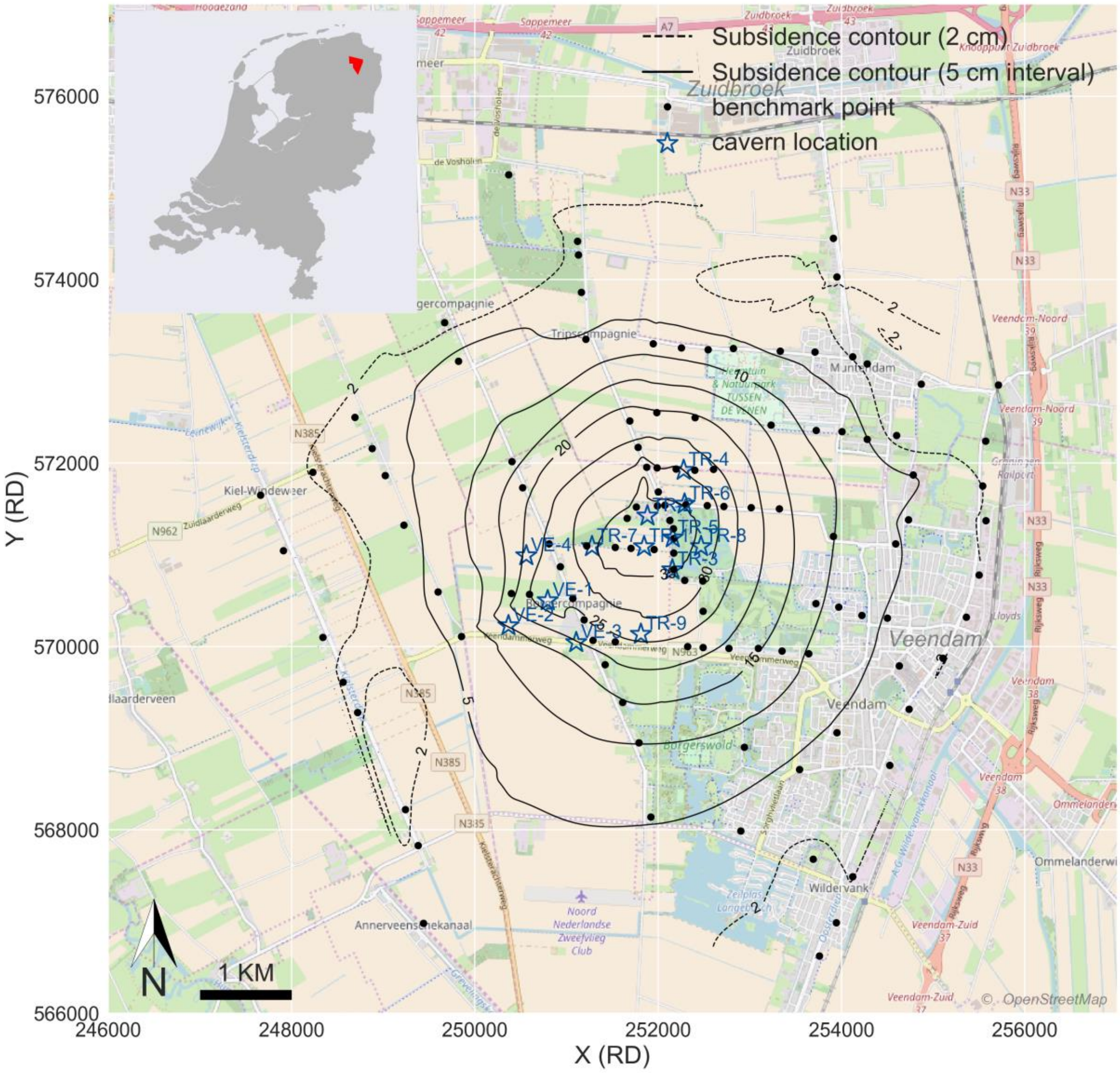

Figure 1-1 Cumulative observed subsidence (in cm) at benchmark locations by April 2016 (cubic interpolation). Due to the sparsity of the benchmark points the outermost contours become unreliable. The data are only interpolated (i.e. no extrapolation) and the contours therefore stop at the outer edge of the data. Inset shows location of Veendam concession.

1.3 STUDY OUTLINE

The study consisted of two phases: a history matching phase and a forecasting phase. First, the observed subsidence over the period 1993-2016 was history matched, from which several subsidence modelling parameters were determined. These derived parameters were employed in the following phase of subsidence predictions for various potential future well and production scenarios. These scenarios were based on existing wells and two new wells: VE-5 and VE-6. All modelling was carried out in Python.

2 HISTORY MATCH OF HISTORICAL SUBSIDENCE

The main objective of the history match phase was to create a mathematical model calibrated to available subsidence data and to prepare the model for subsidence forecast. In addition, squeeze volumes from cluster production were allocated to specific wells.

The model calibration was carried out in two steps:

- **Simplified history match**
  To verify consistency between the calculated squeeze volumes and subsidence data, a simplified subsidence model was developed. In this exercise, the squeeze volume from all wells and clusters was assigned to a single location: the TR-1 cavern. For each time step, rigid basement depth and cumulative squeeze volume were calculated via optimisation. Optimisation aimed at finding the smallest mismatch between modelled and observed subsidence at all benchmark points.

- **Detailed history match**
  In the detailed history match, a varying rigid basement formula was applied, for which the function parameters were determined through an optimisation exercise. The optimisation again aimed at finding the smallest mismatch between the model and the observed subsidence values. Additionally, the cluster squeeze volumes as provided by Nedmag were used and mathematically allocated between various wells to improve the match between modelled and observed subsidence.

The history matching exercise optimised the model based on cumulative subsidence from 1993. Therefore, only those 119 benchmark points where subsidence has been monitored since that year were used in this study (Appendix C). Points that were later added to the network have not been used for the optimisation of the modelling parameters. The method summaries and main findings from both the simple and detailed history match are presented below.

2.1 SIMPLIFIED HISTORY MATCH

In the simplified history match, the entire historic squeeze volume was assigned to a single well – the TR-1 well. This well location corresponds with the approximate centre of the observed subsidence bowl (Figure 1-1). The model aimed at matching the cumulative subsidence in each benchmark point by minimizing the root-mean-square error (RMSE). The RMSE is the root of the mean squared difference between modelled and observed subsidence and is based on all available benchmark points (listed in Appendix C). Two parameters were used to optimise the model: cumulative squeeze volume and rigid basement depth. Optimisation was performed for every subsidence measurement survey from January 1999 to March 2016. Earlier surveys, from February 1995 to January 1998, were not used in the simplified history match, because the subsidence measurements from this period contained too much scatter to find a meaningful optimum. The maximum subsidence in this initial period is less than 10 mm, therefore excluding these data does not significantly impact the conclusions from the simplified history match. For each combination of optimisation parameters (squeeze volume and rigid basement depth) the RMSE was computed and the parameters that led to the smallest error were selected as the optimum. This was done for every benchmark survey. The results from this optimisation can be visualized in an error density map, an example of which is presented in Figure 2-1. The combination of parameters which resulted in the minimum error is labelled as “local minimum”.

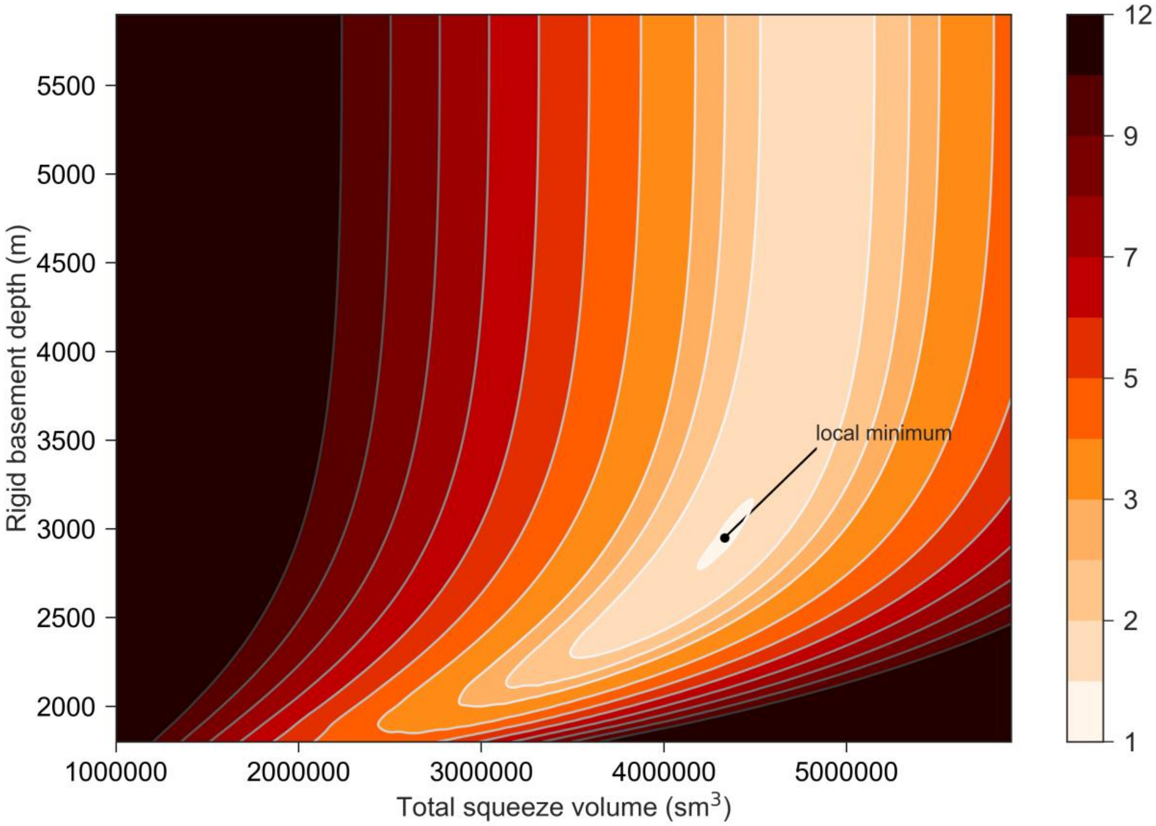

Figure 2-1 Error density map illustrating the model error (RMSE in cm, based on the difference between modelled and observed subsidence at all benchmark locations) for varying combinations of rigid basement depth and cumulative squeeze volume for the April 2016 survey.

The optimum parameters for each benchmark survey date are summarized in Table 2-1. As can be seen in the second column, the rigid basement parameter is varying between 2834 and 3774 m depth. The modelled optimum squeeze volumes (column 3,

Table 2-1) are compared to the cumulative volumes reported by Nedmag in columns 4 and 5. The differences between modelled and reported squeeze volumes are relatively small (<13%), which is considered acceptable to continue with a detailed history match. In the simplified history match, the modelled volumes are consistently less than the volumes reported by Nedmag. This is probably the result of the simplified modelling approach where all production is assigned to one location producing a single subsidence bowl. By allocating the total squeeze volume to the TR-1 location, the model is forced to focus on matching the main subsidence bowl and to ignore the contributions from other production locations.

Table 2-1 Results from the simplified history match with the two optimisation parameters rigid basement depth and squeeze volume. In the rightmost two columns, the modelled squeeze volume is compared to the volumes reported by Nedmag.

Benchmark survey date	Rigid basement depth (m)	Squeeze volume modelled (m^3)	*Squeeze volume reported (m^3)*	*Modelled / reported (%)*
Jan 1999	3626	1194395	*1237705*	*97%*
Jan 2000	3774	1443921	*1456876*	*99%*
Jan 2002	3000	1667802	*1853106*	*90%*
Jan 2004	3429	2156421	*2297674*	*94%*
Jan 2006	2834	2353722	*2724744*	*86%*
Jan 2008	3178	2848164	*3122759*	*91%*
Jan 2010	2853	3038207	*3505141*	*87%*
Mar 2012	3031	3639670	*4095653*	*89%*
Feb 2014	3005	3989265	*4503023*	*89%*
Apr 2016	2950	4331444	*4925577*	*88%*

In Figure 2-2, the subsidence model for April 2016 is compared to the observed subsidence in a stacked cross plot of distance from the TR-1 well (approximate centre of the subsidence bowl) versus subsidence for all benchmark points. The figure illustrates that the model is able to match the maximum observed values as well as the overall shape of the subsidence bowl, even with the simplified modelling approach. Despite this overall shape agreement, the figure also shows that improvements can be made: the model exceeds observations in the deepest part (<500 m from the centre) while it falls behind on the flanks between ~1000 and 2000 m from the centre. Achieving an even better fit to the data is the main objective of the detailed history match discussed below.

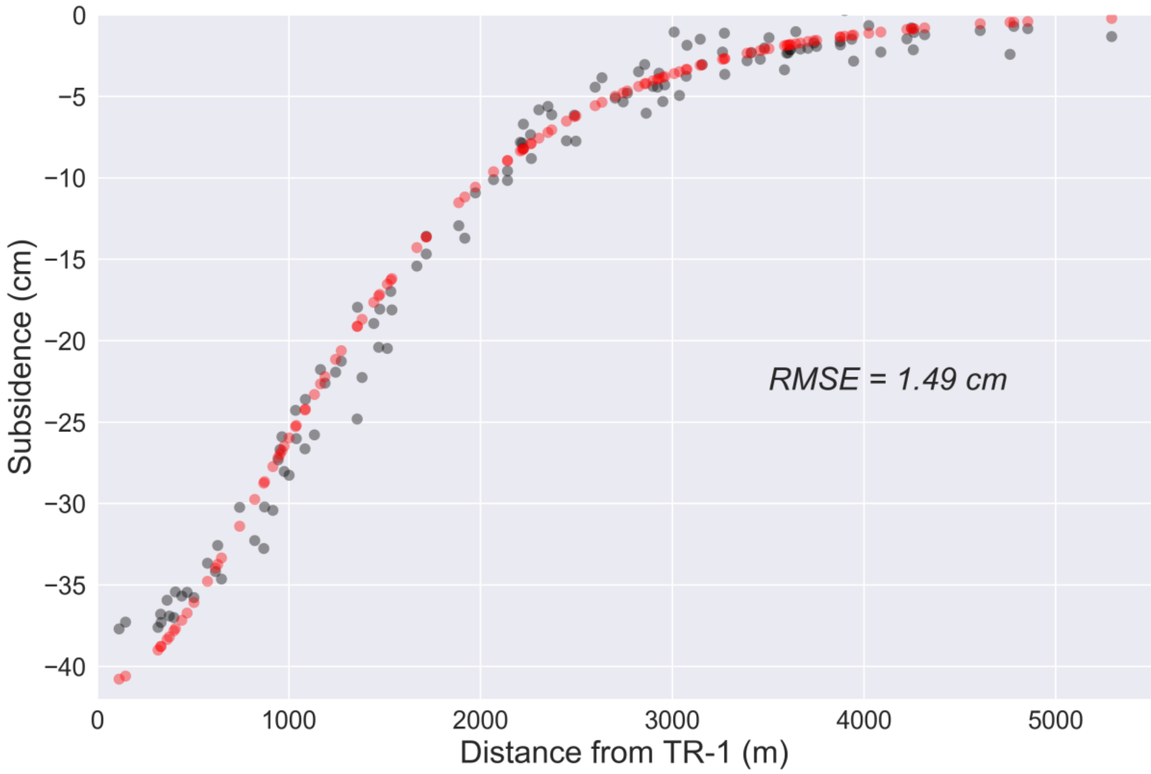

Figure 2-2 Modelled (red dots) and observed (black dots) subsidence (April 2016) vs. distance to TR-1 well location. Modelled cumulative squeeze volume = 4331444 m^3, modelled rigid basement depth = 2950 m. The modelling error (RMSE) is 1.49 cm.

2.2 Detailed History Match

The detailed history match focused on further improvement of the subsidence model to better match the observed subsidence. A second objective was to allocate the squeeze volumes that were provided per cluster (Appendix A) to individual wells. Guided by Nedmag's request to SGS the following assumptions were implemented in the detailed history match:

- Reported squeeze volumes were used as input into the model
- All subsidence surveys from May 1993 to March 2016 were used for model calibration
- Rigid basement depth was modelled using a formula adapted from Muntendam et al. (2012) [1]:

$$c/k(t) = c/k(0) - d(c/k)\left(1 - e^{\frac{-(t-t_0)}{\tau_{zout}}}\right)$$

where c is the reservoir depth, k the rigid basement depth and c/k(t) the ratio of these two over time. The original formula had a plus (+) sign after the first term (c/k(0)) and described a reducing rigid basement depth with time. The gas induced subsidence bowl that was subject of the study by Muntendam et al. (2012) was narrowing and steepening because of salt creep in the overburden [1] of the reservoir and this effect was simulated by a shallowing rigid basement depth. In the Veendam situation, the 'reservoir' lies within the salt and the subsidence bowl widens. To accurately describe such a widening bowl, the formula was to be adapted for this study. The depth increases from a starting position c/k(0) with a rate that is defined by a rate parameter d(c/k) and by the relaxation time of the salt (τ_{zout}). These three parameters were subjected to the optimisation exercise in this history match.

Volume allocation to individual wells and optimisation of this allocation involved a large number of parameters, namely a volume allocation fraction for each well at each benchmark survey date. Together with the rigid basement parameters described above, this resulted in more than 100 parameters to optimise for. As a result, there existed a high probability to find a local minimum and hence to find a sub-optimal solution for the optimisation objective function. To overcome this problem and to increase the probability of finding a true global minimum, the optimisation algorithm was initialized multiple times (25 runs), using random initial values for each parameter in each run. From the 25 runs two minima were found, which are summarized in Table 2-2 (individual results for each of the optimisation runs are presented in Appendix D). Within each of these minima the total model error is relatively constant, but between the two there is a significant error difference. All runs that ended up in the minimum with the larger error have a similar rigid basement behaviour: a minimally varying basement depth (small d(c/k)), which starts at 1000 times the reservoir depth (c/k(0) = 0.001). During the optimisation, the c/k(0) parameter was allowed to vary between 1 (rigid basement equal to reservoir depth) and 0.001 (rigid basement ‘infinitely’ deep) and so the optimisation process got ‘stuck’ at the bounding value. Because of this, and because of its larger modelling error, this minimum is considered a local minimum, while the other is considered to represent the global minimum: a true optimal solution of the optimisation function.

Table 2-2 Summary of the optimisation results as part of the detailed history match: rigid basement depth parameters and modelling error for the two minima identified (details see text). The modelling error is presented as the root-mean-square error for all benchmark point at all survey dates available.

minimum	# runs	Mean rigid basement parameters (± stdev)			Average RMSE (cm)
		c/k(0)	d(c/k)	τ_{zout}	
global	16	0.704 (0.002)	0.695 (0.155)	50.1 (13.6)	0.7154
local	9	0.001 (0)	0.005 (0.002)	53.8 (22.5)	0.9723

For the detailed history match, cluster production volumes were allocated to individual wells and these allocation fractions were part of the optimisation exercise whereby the total error between modelled and observed subsidence was minimised (a typical example of the individual well allocation fractions is presented in Appendix E). In all simulation runs the optimisation algorithm found a similar optimal result where the maximum volumes are allocated to wells TR-1 and TR-2. This result is in line with visual inspection of the reported subsidence data which show a circular bowl centred around these wells (see Figure 1-1).

The modelled subsidence is compared to the observed subsidence at all benchmark locations for April 2016 in Figure 2-3. Comparing Figure 2-3A and Figure 2-2 shows that the detailed history match has addressed the shortcomings of the simple history match in the deepest point and on the flanks of the subsidence bowl (as described above) and resulted in a smaller modelling error (RMSE has reduced from 1.49 to 1.33 cm). In the shallower parts of the bowl however, between ~2 and 10 cm subsidence, the model often exceeds the observations. The map in Figure 2-3B shows for each benchmark point whether the modelled subsidence is exceeding the observations (red dots) or whether it falls behind (blue). The larger the circle, the larger the relative mismatch between modelled and observed subsidence. The model is both under- and overestimating the amount of subsidence, both near the centre of the subsidence bowl (i.e. near the TR-1 cavern centre) and on the flanks. Note that because the size of the bubbles is proportional to the mismatch this display under-exposes points where the model matches well with the observations.

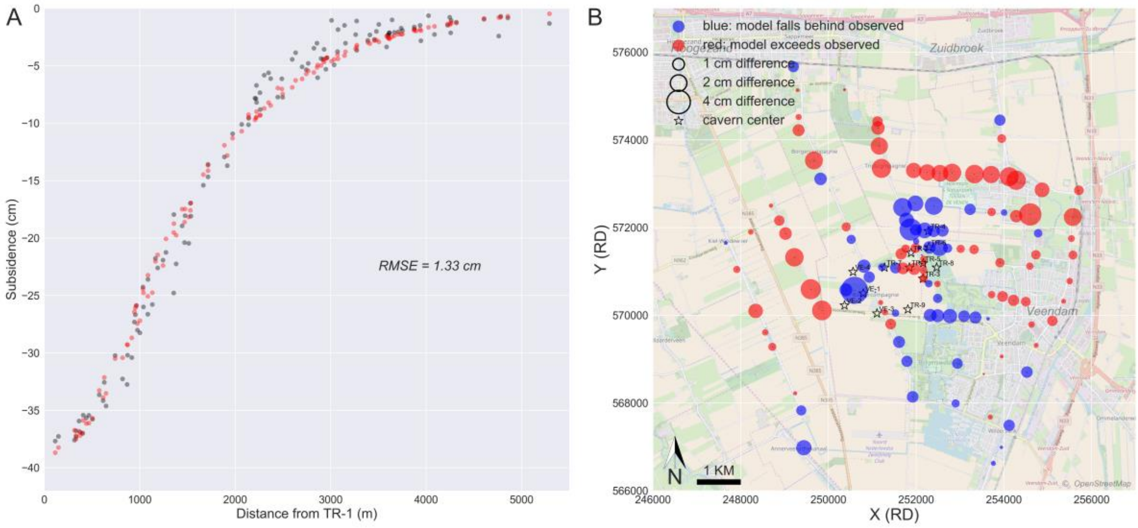

Figure 2-3 Detailed history match QC (April 2016, based on the best optimisation run). A: Modelled (red) and observed (black) subsidence vs. distance to well TR-1 well (compare to Figure 2-2). The root-mean-square error for the April 2016 survey alone is 1.33 cm. B: bubble plot of difference between modelled and observed subsidence (size proportional to amount of mismatch, colour indicates over- or underperformance)

The mismatches between modelled and observed subsidence as shown in Figure 2-3B could, amongst others, result from simplifications in the model and/or uncertainties in the allocation of subsidence contributions during objectpunt analysis. For example, the Geertsma-Van Opstal model assumes the reservoir is embedded in a uniform medium and therefore cannot account for overburden geometry variations that may affect the symmetry of the subsidence bowl. Besides this, the subsidence measurements may contain contributions that are not accounted for in the model, e.g. locally varying compaction of the shallow subsurface (autonomous subsidence) or the split between salt induced and gas induced subsidenc contributions may not have been fully accurate. Despite the observed differences, the model is clearly capable of matching the deepest part and the overall shape of the observed subsidence bowl (Figure 2-3A). Matching the deepest part of the subsidence is most important because salt mining induced subsidence is not allowed to exceed 65 cm at any benchmark point within the Veendam concession. Based on this consideration, the subsidence model using the optimised parameters from the detailed history match is considered acceptable and is used for forecast calculations.

For all 16 optimisation runs that ended in the global minimum (Appendix D) the differences in rigid basement behaviour for the history matched period are minimal. The initial rigid basement depth, defined by the c/k(0) parameter, is very similar, and despite variations in the rate parameter d(c/k) and salt relaxation time (τ_{zout}) the rigid basement depth curves are almost indistinguishable for the period until April 2016. This is illustrated in Figure 2-4. However, when the parameters are used to forecast rigid basement depths the differences become larger (Figure 2-4) which will result in different subsidence forecasts. A clear trend can be observed between the modelling error and the future basement depth.

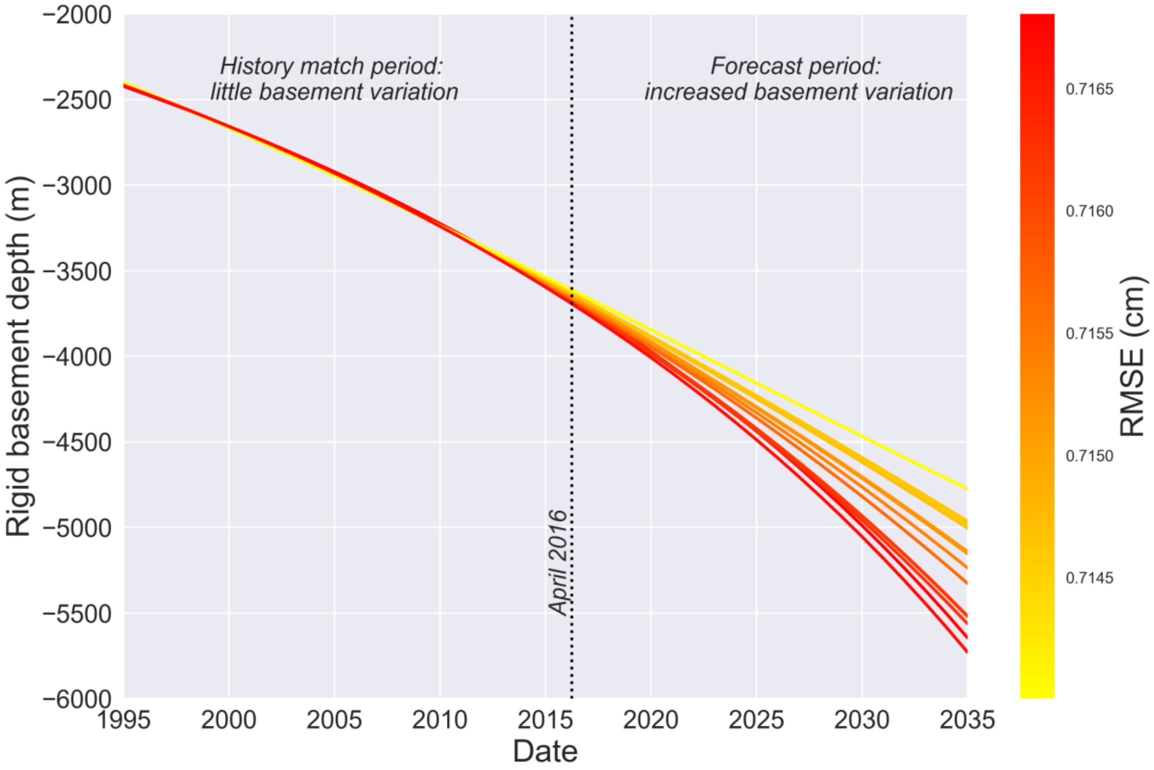

Figure 2-4 Rigid basement depth behaviour for all 16 global minimum runs assuming a reservoir depth of 1700 m and coloured according to the RMSE modelling error.

3 PREDICTION OF FUTURE SUBSIDENCE

For future salt production from the Veendam concession, Nedmag is planning to allow a yearly squeeze contribution of 220,000 m^3 until the permitted maximum subsidence is reached. Nedmag is also considering drilling two additional wells (VE-5 and VE-6) at ~ 2700 m west of the TR-1 well location (see Figure 3-1). The VE-5 and VE-6 planned well locations are situated near the western edge of the current subsidence bowl (see Figure 3-1A). Nedmag has requested SGS to forward model the impact these new wells would have on the future subsidence development in the area.

It should be noted that the current benchmark network in the area is not dense enough to effectively monitor the future subsidence in the VE-5 and VE-6 area, even if the additional benchmark points are considered that have been added to the network after 1993 (Figure 3-1B).

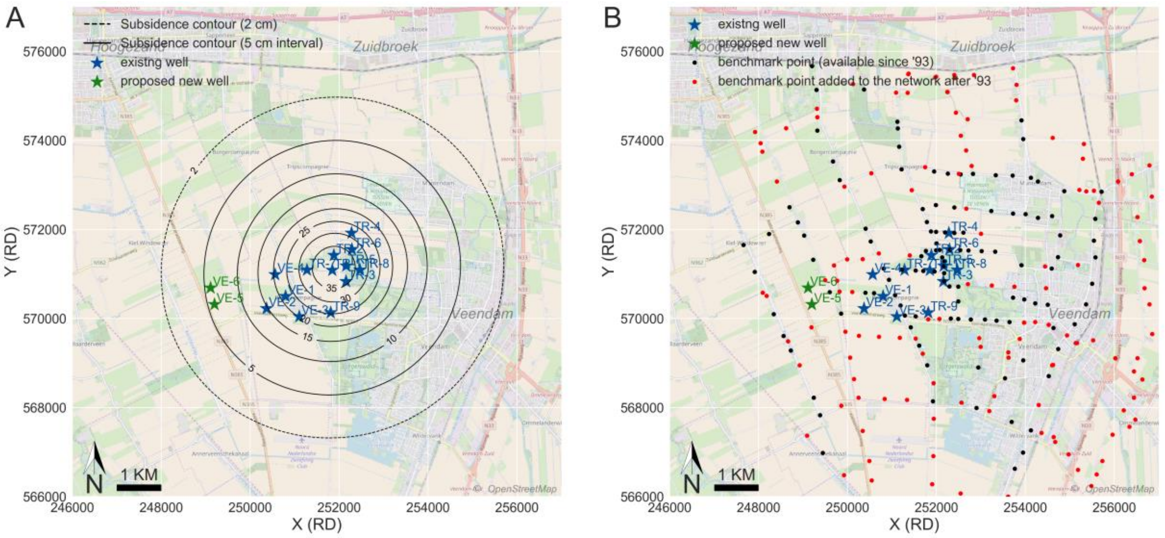

Figure 3-1 A: Modelled subsidence (in cm) for April 2016 with the proposed VE-5 and VE-6 well locations (in green). B: Benchmark network coverage of the existing and new well locations.

The subsidence forecasts are based on the subsidence model from the detailed history match described in Chapter 2. The parameters associated to the run with the smallest error (RMSE = 0.7140 cm, Appendix D) are carried forward into a single deterministic subsidence model. Despite the fact that modelling uncertainties are not addressed in this study, the subsidence model's sensitivity to the rigid basement definition is illustrated by executing all forecast scenarios a second time using the parameters associated with the largest error (RMSE = 0.7168 cm, Appendix D). These results are available in Appendix E.

A subsidence forecast was performed for three squeeze production scenarios that were provided by Nedmag. The first scenario is based on the existing wells only: all planned squeeze production is assigned to the TR-1 cavern. Two other scenarios include production from the VE-5 and VE-6 wells where either 40% (scenario 2) or 20% (scenario 3) of the total squeeze volume will be produced by the new wells. A summary of all modelling input parameters is shown in Table 3-1.

Table 3-1 Model input for the subsidence forecast scenarios

Scenario	Annual squeeze volume allocation (220,000 m^3)	Total squeeze volume fraction		Rigid basement depth parameters		
		TR-1	VE-5&6	c/k(0)	D(c/k)	τ_{zout}
1	All new squeeze volume will be assigned to cavern TR-1	1	0			
2	Squeeze volume allocation: TR1 (60%) + VE-5&6 (40%)	0.6	0.4	0.707	0.502	33.3
3	Squeeze volume allocation: TR1 (80%) + VE-5&6 (20%)	0.8	0.2			

For each scenario, the forecasted subsidence is displayed twice: once for 2023, when a maximum subsidence of approximately 50 cm is reached, and once for the year in which the modelled subsidence reaches the maximum permitted subsidence of 65 cm at a benchmark location. This moment varies for the different scenarios as can be observed in the resulting subsidence maps in Figure 3-2 to Figure 3-4.

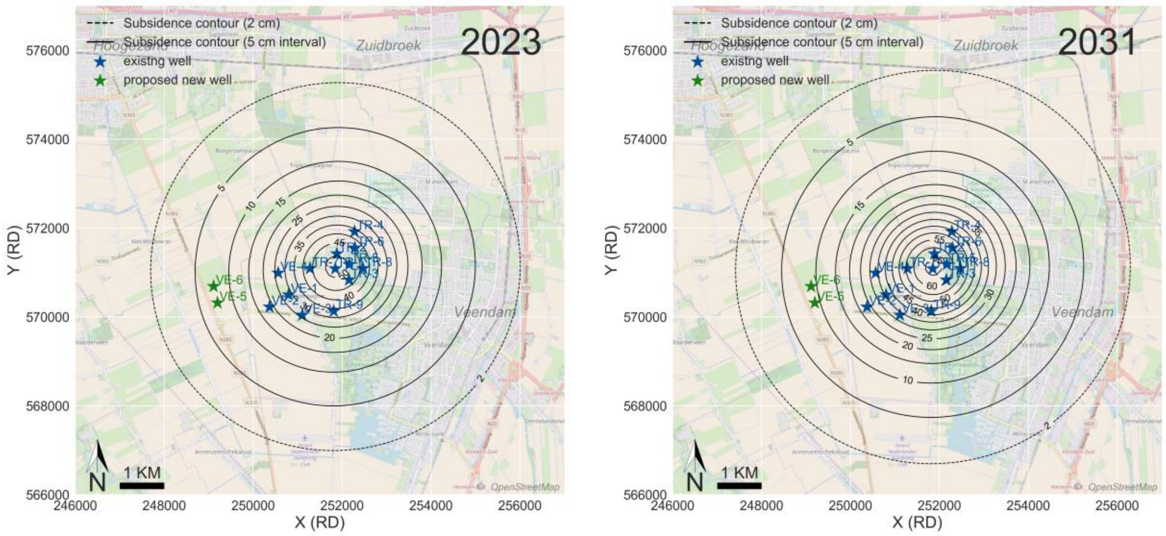

Figure 3-2 Subsidence forecast (in cm) for 2023 (left) and 2031 (right) based on production scenario 1.

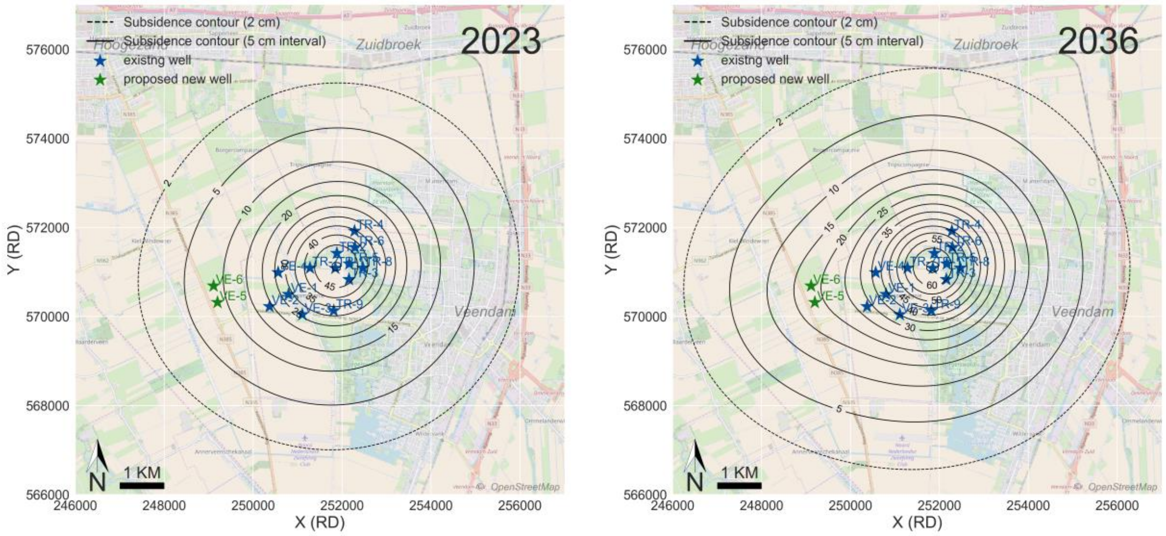

Figure 3-3 Subsidence forecast (in cm) for 2023 (left) and 2036 (right) based on production scenario 2.

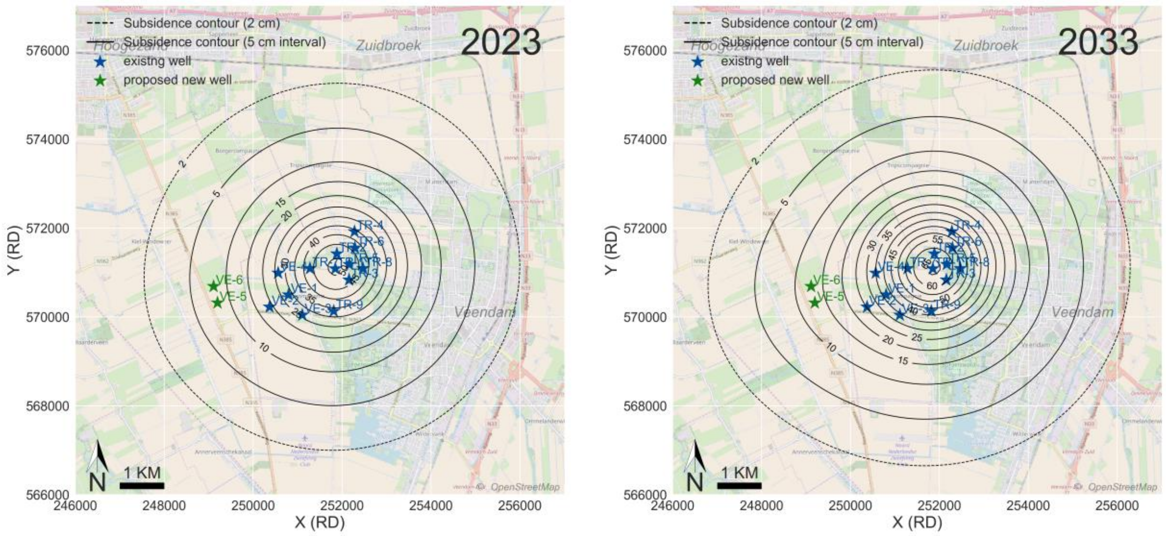

Figure 3-4 Subsidence forecast (in cm) for 2023 (left) and 2033 (right) based on production scenario 3.

The forecast results are summarized in Table 3-2, which shows the year in which the maximum permitted 65 cm of salt mining induced subsidence is reached at a benchmark location, as well as the cumulative squeeze volume at that time. According to these results, assigning part of the planned production to two additional wells (VE-5 and VE-6) has a clear impact on the development of the subsidence bowl (Figure 3-2 to Figure 3-4). By distributing the squeeze volume extraction across the area through production from additional wells, the time when the maximum permitted subsidence is reached can be delayed. When production is only from the existing wells, the maximum permitted subsidence will be reached in 2031, at which time a total cumulative squeeze volume of 8.22 million m^3 would be realised. In scenario 2, the year in which the maximum permitted subsidence is reached is delayed by 5 years until 2036. By this time, the cumulative squeeze volume will be 9.32 million m^3, 1.1 million m^3 more than in scenario 1 where all new squeeze volume is assigned to the existing

TR-1 well. In scenario 3, a smaller part of the planned production is assigned to the new wells, which results in a delay of 2 years before reaching the maximum permitted subsidence and an increased cumulative production of 0.44 million m^3 compared to scenario 1.

Table 3-2 Summary of forecast results

Scenario	Squeeze volume production allocation	Permitted subsidence (65 cm) reached at	
		Year	Cumulative squeeze volume million m^3
1	100% from TR-1	2031	8.22
2	60% from TR-1 40% from VE-5&6	2036	9.32
3	80% from TR-1 20% from VE-5&6	2033	8.66

4 DISCUSSION OF MODELLING LIMITATIONS

The subsidence model described above represents a possible development of subsidence due to salt squeeze mining by Nedmag from the Veendam area. The scope of this study did not include uncertainty modelling and/or assessment of uncertainty ranges related to the input data, subsurface simplifications, modelling assumptions and methodological constraints. The only uncertainty that has been evaluated during this study is the model’s sensitivity to the rigid basement depth parameters, which is illustrated by the alternative scenario in Appendix E. Since only one parameter variation has been included in the forecast (with a statistically insufficient number of runs to reliably capture the full solution space), the results of this study should be regarded as a single, deterministic case providing an indication of possible subsidence due to future salt squeeze mining.

Input data considered to have a potentially significant uncertainty range that could generate a broader range of forecast outcomes are the calculated squeeze volumes and the subsidence measurements. For instance, significant uncertainties are attached to the squeeze volume calculations. The subsidence measurements carry both measurement uncertainties and uncertainties due to objectpunt analysis.

Other potential contributors to model uncertainty and resulting forecast are related to the methodological choices and constraints. An example of this is, for instance, the simplified geomechanical behaviour of the reservoir and overburden. The Geertsma-Van Opstal model assumes a homogeneous half-space in which the reservoir resides which results in an intrinsically symmetric subsidence bowl at surface. In reality, the overburden may contain dipping layers with varying geomechanical properties which would influence the shape of the subsidence bowl.

Post production creep effects such as continued subsidence or rebound (as suggested by Fokker, 2011 [2]) were also outside the scope of this study.

5 CONCLUSIONS

The existing and future subsidence as a result of salt squeeze mining in the Veendam concession were modelled using the Geertsma-Van Opstal method with a variable rigid basement. The history match of a simplified subsidence model resulted in a reasonable fit of the modelled subsidence bowl to the observed subsidence values at benchmark locations.

The detailed history match, which included allocation of production volumes to individual well locations, resulted in a subsidence model that was deemed appropriate for future subsidence forecasting. Rigid basement parameter variation was included as an uncertainty in the forecast. As further uncertainty modelling was outside the scope of this study, the forecast result can essentially be considered a deterministic case that gives an indication of the possible subsidence due to future salt squeeze mining.

In the production scenario with a squeeze contribution from current wells only, the maximum permitted subsidence of 65 cm will be reached near well TR-1 by 2031.

Two to five years of delay in reaching the maximum permitted subsidence can be achieved in case of drilling the VE-5 and VE-6 wells and assigning 20 to 40% of the total squeeze contribution to these wells. This would allow production of 0.44 to 1.1 million m^3 additional squeeze volume compared to the scenario with squeeze contribution from current wells only.

The main driver is the productivity of the new wells (maximum squeeze rate) in these scenarios. The larger the production rate in the new wells, the smaller the squeeze rates in the current wells, and hence the later the permitted subsidence will be reached.

The current benchmark point network is not dense enough to the west of VE-5 and VE-6 to adequately monitor potential future subsidence from these new wells.

6 GLOSSARY

Nedmag	Nedmag B.V.
SGS	SGS Subsurface Consultancy / SGS Nederland B.V.
TNO-AGE	TNO Advisory Group for Economic affairs
Antea	Antea Group Nederland
WHC	well head centre
NAM	Nederlandse Aardolie Maatschappij
m	metre (unit of length)
cm	centimetre (unit of length)
m^3	cubic metre
(k)ton	(kilo)ton = $(10^3*)10^3$ kg (unit of weight)
RMSE	root-mean-square error

7 REFERENCES

[1] Muntendam-Bos, A. et al., 2012. Toetsing van de belasting op de gebruiksruimte in de kombergingsgebieden Pinkegat en Zoutkamperlaag door bodemdaling ten gevolge van gaswinning onder de Waddenzee. TNO-060-UT-2011-02035/C I Eindrapport. 106 pp.

[2] Fokker, P.A., 2011. Nedmag Veendam Studie Inversie van bodemdalingmetingen. TNO-060-UT-2011-00687. 39 pp.

[3] Geertsma, J., 1966. Problems of Rock Mechanics in Petroleum Production Engineering. Proceedings 1st Congress of the International Society of Rock Mechanics, Lisbon, I, 585.

[4] Van Opstal, G.H.C., 1974. The effect of base-rock rigidity on subsidence due to reservoir compaction. Proc. 3rd Congress of the Int. Soc. of Rock Mech., Denver, II, Part B, p.1102-1111.

APPENDIX A RIGID BASEMENT ILLUSTRATION

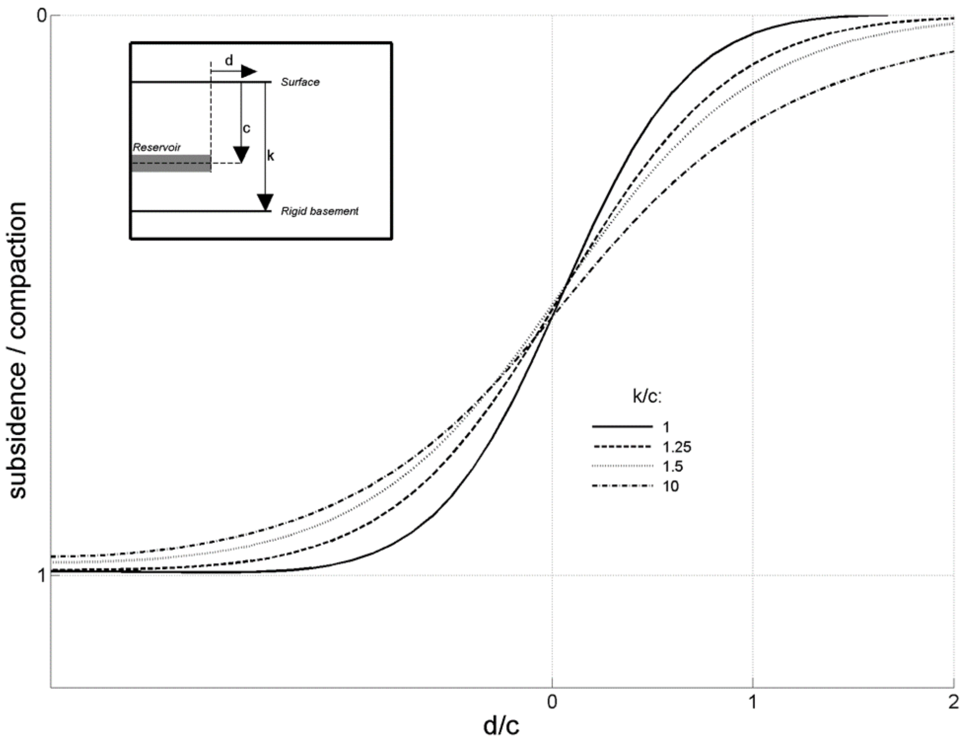

Figure 7-1 Rigid basement effect on shape of subsidence bowl for a simple model (geometry illustrated in inset)

The depth of the rigid basement influences the shape of the subsidence bowl, which is illustrated in the figure above. Subsidence is shown along a line across a rectangular reservoir with uniform compaction. The vertical axis shows the amount of subsidence relative to the amount of compaction in the reservoir. The horizontal axis highlights the extent of the bowl beyond the edge of the reservoir (d) as a factor of the reservoir depth (c). The deepest and steepest bowl is obtained with a rigid basement depth (k) equal to the reservoir depth (k/c = 1).

APPENDIX B PRODUCTION DATA

Table 7-1 Cavern (well) list and coordinates (RD)

Well	X	Y
VE-1	250795.00	570500.00
VE-2	250366.95	570226.79
VE-3	251106.26	570042.89
VE-4	250561.51	570990.30
VE-5	249195.00	570319.00
VE-6	249109.00	570691.00
TR-1	251846.61	571088.29
TR-2	251882.99	571423.42
TR-3	252154.63	570836.10
TR-4	252278.26	571920.98
TR-5	252159.32	571185.27
TR-6	252287.92	571553.39
TR-7	251278.28	571089.19
TR-8	252467.39	571089.43
TR-9	251811.62	570133.51

Table 7-2 Cavern connection times: wells that share the same colour form a cluster and are producing from the same cavern

Well	VE-1	VE-2	VE-3	VE-4	TR-1	TR-2	TR-3	TR-4	TR-5	TR-6	TR-7	TR-8	TR-9
Oct-82													
Nov-96													
Jul-97													
Jan-98													
Jul-99													
Nov-99													
Mar-01													
Oct-02													
Nov-06													
Sep-09													

Table 7-3 Cumulative squeeze volumes from separate wells and clusters at the time of subsidence measurement

Status at	TR-1 & -2	TR-3	TR-4	TR-5	TR-6	TR-7	TR-8	TR-9	VE-1	VE-2	VE-3	VE-4	Total (wells)	Cluster contribution		Total
	m^3	m^3	m^3	m^3	m^3	m^3	m^3	m^3	m^3	m^3	m^3	m^3	m^3	m^3	from wells	m^3
May-93	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0
Feb-95	5,970	1,036	163,041	11,214	31,286	10,542	9,794	0	0	3,302	-9,567	1,594	228,211	0		228,211
Jul-95	9,439	1,549	189,917	17,265	80,786	14,142	11,912	0	0	4,458	-8,275	2,815	324,007	0		324,007
Jan-96	36,716	17,643	199,577	41,413	98,361	38,781	29,290	0	0	8,813	-6,430	1,253	465,417	0		465,417
Jan-97	52,863	29,229	223,822	100,950	104,965	73,708	76,852	0	0	19,554	-2,954	4,233	683,221	17,423	TR-1, 2 & 5	700,644
Jan-98	52,863	48,241	241,578	100,950	121,979	121,269	113,322	0	0	52,481	1,514	11,053	865,250	96,322	TR-1, 2 & 5	961,571
Jan-99	52,863	65,567	241,578	100,950	121,979	129,661	147,682	0	0	104,317	3,623	29,910	998,130	239,574	TR-1, 2, 5 & 4 & 6	1,237,705
Jan-00	52,863	108,941	241,578	100,950	121,979	122,033	181,362	0	0	104,317	39,140	34,816	1,107,979	348,897	TR-1, 2, 3, 5, 7 & 4 & 6	1,456,876
Jan-02	52,863	108,941	241,578	100,950	121,979	122,033	212,084	0	12,597	104,317	73,845	42,219	1,193,405	659,700	TR-1, 2, 3, 5, 7, 8 & 4 & 6	1,853,106
Jan-04	52,863	108,941	241,578	100,950	121,979	122,033	212,084	0	12,597	104,317	78,467	53,122	1,208,931	1,088,743	TR-1, 2, 3, 4, 5, 6, 7, 8	2,297,674
Jan-06	52,863	108,941	241,578	100,950	121,979	122,033	212,084	0	12,597	104,317	80,856	70,524	1,228,721	1,496,023	TR-1, 2, 3, 4, 5, 6, 7, 8	2,724,744
Jan-08	52,863	108,941	241,578	100,950	121,979	122,033	212,084	0	12,597	104,317	84,983	86,242	1,248,566	1,874,192	TR-1, 2, 3, 4, 5, 6, 7, 8 & VE-2 & 3	3,122,759
Jan-10	52,863	108,941	241,578	100,950	121,979	122,033	212,084	0	12,597	104,317	84,983	86,107	1,248,431	2,256,710	TR-1, 2, 3, 4, 5, 6, 7, 8, VE-4 & VE-2 & 3	3,505,141
Mar-12	52,863	108,941	241,578	100,950	121,979	122,033	212,084	0	12,597	104,317	84,983	86,107	1,248,431	2,847,222	TR-1, 2, 3, 4, 5, 6, 7, 8, VE-4 & VE-2 & 3	4,095,653
Feb-14	52,863	108,941	241,578	100,950	121,979	122,033	212,084	8,367	12,597	104,317	84,983	86,107	1,256,798	3,246,225	TR-1, 2, 3, 4, 5, 6, 7, 8, VE-4 & VE-2 & 3	4,503,023
Apr-16	52,863	108,941	241,578	100,950	121,979	122,033	212,084	52,147	12,597	104,317	84,983	86,107	1,300,578	3,624,999	TR-1, 2, 3, 4, 5, 6, 7, 8, VE-4 & VE-2 & 3	4,925,577

APPENDIX C BENCHMARK SUBSIDENCE DATA

Table 7-4 The following tables show the benchmark data available for this study: point number, coordinates and salt induced subsidence between 1993 and 2016

Point	X	Y	1-May-93	1-Feb-95	1-Jul-95	1-Jan-96	1-Jan-97	1-Jan-98	1-Jan-99	1-Jan-00	1-Jan-02	1-Jan-04	1-Jan-06	1-Jan-08	1-Jan-10	1-Mar-12	1-Feb-14	1-Apr-16
1	251,988	571,949	0.000	-0.022	-0.026	-0.038	-0.057	-0.069	-0.081	-0.094	-0.110	-0.135	-0.162	-0.187	-0.213	-0.250	-0.277	-0.302
3	252,194	571,936	0.000	-0.024	-0.028	-0.044	-0.062	-0.074	-0.085	-0.099	-0.113	-0.138	-0.168	-0.192	-0.218	-0.254	-0.280	-0.304
5	252,398	571,923	0.000	-0.024	-0.027	-0.040	-0.058	-0.069	-0.079	-0.092	-0.105	-0.128	-0.155	-0.178	-0.201	-0.236	-0.260	-0.282
7	252,602	571,931	0.000	-0.024	-0.027	-0.037	-0.054	-0.063	-0.076	-0.088	-0.099	-0.119	-0.143	-0.163	-0.185	-0.216	-0.237	-0.258
10	252,302	571,548	0.000	-0.023	-0.028	-0.044	-0.069	-0.082	-0.098	-0.112	-0.132	-0.168	-0.199	-0.226	-0.253	-0.292	-0.319	-0.346
12	252,533	571,537	0.000	-0.035	-0.040	-0.055	-0.074	-0.089	-0.103	-0.117	-0.135	-0.162	-0.190	-0.213	-0.238	-0.274	-0.298	-0.323
14	252,717	571,528	0.000	-0.021	-0.026	-0.038	-0.055	-0.069	-0.081	-0.094	-0.112	-0.136	-0.161	-0.181	-0.205	-0.236	-0.258	-0.280
15	252,126	571,374	0.000	-0.019	-0.024	-0.042	-0.071	-0.086	-0.103	-0.119	-0.144	-0.178	-0.211	-0.240	-0.268	-0.310	-0.340	-0.370
16	252,166	571,285	0.000	-0.017	-0.023	-0.040	-0.067	-0.084	-0.102	-0.118	-0.144	-0.177	-0.210	-0.239	-0.267	-0.309	-0.339	-0.369
17	252,167	571,178	0.000	-0.016	-0.022	-0.040	-0.070	-0.085	-0.102	-0.120	-0.148	-0.181	-0.214	-0.243	-0.271	-0.312	-0.342	-0.373
19	252,169	571,019	0.000	-0.015	-0.020	-0.037	-0.062	-0.082	-0.099	-0.117	-0.146	-0.179	-0.212	-0.240	-0.267	-0.307	-0.336	-0.368
28	252,169	570,839	0.000	-0.012	-0.016	-0.032	-0.055	-0.076	-0.091	-0.110	-0.139	-0.173	-0.203	-0.230	-0.256	-0.295	-0.323	-0.354
34	252,288	570,720	0.000	-0.010	-0.013	-0.028	-0.049	-0.067	-0.083	-0.101	-0.132	-0.162	-0.190	-0.215	-0.240	-0.275	-0.306	-0.336
36	252,487	570,714	0.000	-0.010	-0.013	-0.027	-0.045	-0.063	-0.077	-0.094	-0.119	-0.145	-0.172	-0.195	-0.218	-0.251	-0.274	-0.302
44	251,780	572,170	0.000	-0.018	-0.022	-0.032	-0.049	-0.058	-0.067	-0.078	-0.092	-0.114	-0.138	-0.161	-0.185	-0.219	-0.243	-0.266
54	251,989	571,533	0.000	-0.019	-0.024	-0.041	-0.058	-0.082	-0.098	-0.113	-0.135	-0.166	-0.199	-0.228	-0.255	-0.297	-0.325	-0.354
69	251,760	571,520	0.000	-0.015	-0.019	-0.036	-0.058	-0.078	-0.093	-0.109	-0.133	-0.164	-0.197	-0.227	-0.254	-0.296	-0.327	-0.357
79	252,000	571,685	0.000	-0.022	-0.027	-0.043	-0.064	-0.080	-0.094	-0.109	-0.128	-0.159	-0.190	-0.217	-0.246	-0.286	-0.314	-0.342
81	251,874	571,955	0.000	-0.023	-0.027	-0.041	-0.059	-0.074	-0.087	-0.100	-0.118	-0.144	-0.174	-0.200	-0.236	-0.274	-0.301	-0.327
87	251,984	572,550	0.000	-0.018	-0.020	-0.027	-0.037	-0.045	-0.049	-0.061	-0.069	-0.085	-0.103	-0.121	-0.140	-0.166	-0.186	-0.204
89	252,402	572,496	0.000	-0.029	-0.032	-0.038	-0.046	-0.053	-0.058	-0.069	-0.076	-0.092	-0.109	-0.126	-0.144	-0.169	-0.188	-0.205
93	253,229	572,416	0.000	-0.016	-0.019	-0.023	-0.030	-0.035	-0.037	-0.046	-0.052	-0.062	-0.073	-0.086	-0.097	-0.114	-0.126	-0.137
95	253,721	572,356	0.000	-0.008	-0.010	-0.013	-0.018	-0.022	-0.021	-0.030	-0.034	-0.042	-0.048	-0.054	-0.061	-0.072	-0.081	-0.088
96	254,004	572,344	0.000	-0.009	-0.011	-0.014	-0.018	-0.021	-0.020	-0.027	-0.032	-0.038	-0.043	-0.050	-0.057	-0.064	-0.072	-0.077
97	253,911	571,199	0.000	-0.007	-0.010	-0.012	-0.019	-0.023	-0.027	-0.033	-0.041	-0.048	-0.056	-0.063	-0.072	-0.084	-0.093	-0.101
100	253,320	571,500	0.000	-0.012	-0.015	-0.021	-0.032	-0.039	-0.046	-0.055	-0.066	-0.079	-0.094	-0.106	-0.122	-0.142	-0.156	-0.170
102	253,015	571,514	0.000	-0.016	-0.020	-0.029	-0.043	-0.052	-0.061	-0.073	-0.085	-0.104	-0.123	-0.139	-0.158	-0.184	-0.202	-0.219
108	252,490	569,990	0.000	-0.004	-0.006	-0.013	-0.024	-0.035	-0.047	-0.059	-0.079	-0.098	-0.116	-0.133	-0.150	-0.172	-0.190	-0.212
110	252,489	570,385	0.000	-0.007	-0.010	-0.020	-0.035	-0.051	-0.064	-0.080	-0.104	-0.127	-0.150	-0.171	-0.192	-0.219	-0.241	-0.267
113	251,220	571,097	0.000	-0.007	-0.008	-0.023	-0.045	-0.062	-0.076	-0.093	-0.124	-0.151	-0.180	-0.206	-0.231	-0.269	-0.296	-0.326

Point	X	Y	1-May-93	1-Feb-95	1-Jul-95	1-Jan-96	1-Jan-97	1-Jan-98	1-Jan-99	1-Jan-00	1-Jan-02	1-Jan-04	1-Jan-06	1-Jan-08	1-Jan-10	1-Mar-12	1-Feb-14	1-Apr-16
115	251,532	571,080	0.000	-0.021	-0.024	-0.041	-0.065	-0.086	-0.102	-0.120	-0.152	-0.185	-0.216	-0.246	-0.272	-0.314	-0.343	-0.376
116	251,659	571,399	0.000	-0.011	-0.015	-0.032	-0.056	-0.077	-0.092	-0.108	-0.136	-0.167	-0.199	-0.230	-0.257	-0.299	-0.328	-0.359
118	251,701	571,070	0.000	-0.006	-0.009	-0.028	-0.053	-0.075	-0.091	-0.110	-0.143	-0.176	-0.209	-0.239	-0.267	-0.309	-0.339	-0.373
121	251,955	571,057	0.000	-0.009	-0.013	-0.032	-0.060	-0.079	-0.095	-0.115	-0.146	-0.180	-0.213	-0.243	-0.271	-0.313	-0.344	-0.377
136	253,350	569,950	0.000	-0.002	-0.003	-0.007	-0.014	-0.021	-0.028	-0.036	-0.049	-0.059	-0.072	-0.086	-0.093	-0.106	-0.116	-0.129
137	252,770	569,980	0.000	-0.002	-0.004	-0.011	-0.020	-0.030	-0.041	-0.052	-0.069	-0.087	-0.103	-0.118	-0.134	-0.154	-0.170	-0.189
140	251,530	570,050	0.000	-0.001	-0.004	-0.010	-0.021	-0.035	-0.048	-0.063	-0.088	-0.109	-0.128	-0.145	-0.165	-0.190	-0.210	-0.236
141	251,420	569,800	0.000	-0.001	-0.003	-0.007	-0.013	-0.026	-0.036	-0.048	-0.068	-0.082	-0.096	-0.110	-0.124	-0.143	-0.159	-0.179
143	255,360	570,320	0.000	-0.002	-0.003	-0.004	-0.006	-0.008	-0.009	-0.011	-0.014	-0.016	-0.018	-0.019	-0.022	-0.023	-0.023	-0.023
144	254,500	570,310	0.000	-0.003	-0.004	-0.006	-0.009	-0.012	-0.015	-0.018	-0.021	-0.026	-0.029	-0.033	-0.037	-0.042	-0.046	-0.048
145	254,220	570,340	0.000	-0.002	-0.004	-0.005	-0.009	-0.014	-0.017	-0.021	-0.025	-0.030	-0.036	-0.040	-0.046	-0.052	-0.058	-0.061
146	253,970	570,430	0.000	-0.001	-0.003	-0.006	-0.009	-0.015	-0.020	-0.025	-0.031	-0.038	-0.045	-0.051	-0.059	-0.068	-0.076	-0.082
147	253,720	570,470	0.000	-0.002	-0.004	-0.008	-0.014	-0.021	-0.026	-0.033	-0.042	-0.050	-0.060	-0.068	-0.078	-0.091	-0.101	-0.109
156	255,574	571,373	0.000	-0.003	-0.003	-0.004	-0.005	-0.007	-0.008	-0.009	-0.010	-0.012	-0.013	-0.014	-0.015	-0.017	-0.018	-0.017
160	254,780	571,870	0.000	-0.002	-0.003	-0.004	-0.007	-0.013	-0.014	-0.017	-0.020	-0.023	-0.026	-0.030	-0.034	-0.041	-0.046	-0.049
161	254,280	572,260	0.000	-0.002	-0.003	-0.005	-0.009	-0.013	-0.013	-0.015	-0.019	-0.023	-0.027	-0.032	-0.035	-0.042	-0.047	-0.051
175	250,405	572,016	0.000	-0.001	-0.003	-0.005	-0.012	-0.018	-0.024	-0.031	-0.040	-0.050	-0.063	-0.075	-0.089	-0.106	-0.121	-0.136
176	250,520	571,730	0.000	-0.002	-0.004	-0.009	-0.017	-0.026	-0.034	-0.043	-0.057	-0.070	-0.087	-0.103	-0.120	-0.143	-0.162	-0.180
177	250,810	571,120	0.000	-0.002	-0.004	-0.013	-0.026	-0.042	-0.055	-0.068	-0.094	-0.116	-0.139	-0.160	-0.180	-0.213	-0.235	-0.260
187	249,021	571,864	0.000	0.000	0.000	-0.002	-0.003	-0.005	-0.007	-0.010	-0.011	-0.014	-0.017	-0.020	-0.023	-0.026	-0.031	-0.036
188	249,224	571,322	0.000	-0.001	0.001	-0.001	-0.003	-0.006	-0.008	-0.012	-0.014	-0.016	-0.019	-0.022	-0.025	-0.029	-0.034	-0.039
190	249,597	570,594	0.000	-0.001	0.000	-0.004	-0.005	-0.010	-0.015	-0.020	-0.025	-0.028	-0.032	-0.035	-0.039	-0.046	-0.052	-0.058
194	248,880	572,160	0.000	-0.002	-0.002	-0.004	-0.005	-0.007	-0.009	-0.012	-0.014	-0.014	-0.016	-0.018	-0.020	-0.023	-0.026	-0.030
199	249,852	570,110	0.000	0.000	0.001	-0.002	-0.004	-0.012	-0.018	-0.024	-0.031	-0.033	-0.037	-0.042	-0.046	-0.054	-0.059	-0.067
211	250,595	570,570	0.000	-0.003	-0.003	-0.011	-0.020	-0.045	-0.059	-0.072	-0.102	-0.120	-0.135	-0.151	-0.168	-0.196	-0.221	-0.248
306	251,190	570,290	0.000	-0.003	-0.005	-0.012	-0.023	-0.039	-0.053	-0.066	-0.094	-0.114	-0.132	-0.152	-0.170	-0.197	-0.217	-0.243
308	250,930	570,870	0.000	-0.003	-0.005	-0.015	-0.028	-0.045	-0.059	-0.073	-0.102	-0.125	-0.148	-0.170	-0.191	-0.224	-0.246	-0.273
1215	250,398	570,580	0.000	-0.002	-0.002	-0.008	-0.014	-0.028	-0.041	-0.053	-0.073	-0.086	-0.100	-0.111	-0.126	-0.146	-0.161	-0.181
1219	251,287	570,067	0.000	-0.002	-0.005	-0.009	-0.019	-0.034	-0.046	-0.059	-0.083	-0.102	-0.119	-0.135	-0.152	-0.176	-0.194	-0.218
1220	251,066	570,525	0.000	-0.003	-0.005	-0.014	-0.026	-0.043	-0.057	-0.071	-0.100	-0.122	-0.142	-0.162	-0.182	-0.211	-0.233	-0.259

Point	X	Y	1-May-93	1-Feb-95	1-Jul-95	1-Jan-96	1-Jan-97	1-Jan-98	1-Jan-99	1-Jan-00	1-Jan-02	1-Jan-04	1-Jan-06	1-Jan-08	1-Jan-10	1-Mar-12	1-Feb-14	1-Apr-16
12E038	249,820	573,110	0.000	-0.001	-0.002	-0.004	-0.007	-0.010	-0.011	-0.016	-0.019	-0.023	-0.028	-0.033	-0.039	-0.046	-0.054	-0.060
12E147	248,690	572,500	0.000	-0.001	-0.001	-0.002	-0.004	-0.006	-0.007	-0.009	-0.011	-0.013	-0.015	-0.017	-0.018	-0.020	-0.023	-0.027
12E149	248,230	571,900	0.000	-0.001	-0.001	-0.002	-0.003	-0.005	-0.006	-0.008	-0.009	-0.010	-0.011	-0.013	-0.014	-0.017	-0.018	-0.020
12E171	247,911	571,045	0.000	0.000	0.000	-0.001	-0.002	-0.004	-0.005	-0.006	-0.008	-0.009	-0.011	-0.012	-0.013	-0.013	-0.014	-0.015
12E183	248,340	570,100	0.000	-0.001	-0.001	-0.002	-0.001	-0.004	-0.004	-0.006	-0.008	-0.009	-0.009	-0.010	-0.010	-0.010	-0.010	-0.010
12E196	247,660	571,650	0.000	-0.002	-0.002	-0.003	-0.005	-0.006	-0.007	-0.008	-0.010	-0.010	-0.010	-0.011	-0.012	-0.012	-0.013	-0.015
12F042	255,106	569,872	0.000	-0.002	-0.003	-0.004	-0.006	-0.007	-0.008	-0.010	-0.011	-0.013	-0.015	-0.017	-0.018	-0.019	-0.020	-0.020
12F051	255,500	570,780	0.000	-0.003	-0.004	-0.005	-0.006	-0.009	-0.010	-0.012	-0.013	-0.015	-0.017	-0.018	-0.019	-0.020	-0.021	-0.021
12F055	252,070	571,540	0.000	-0.022	-0.027	-0.044	-0.067	-0.085	-0.100	-0.115	-0.137	-0.169	-0.201	-0.230	-0.258	-0.300	-0.329	-0.358
12F058	254,590	571,120	0.000	-0.004	-0.007	-0.007	-0.011	-0.014	-0.016	-0.019	-0.023	-0.027	-0.031	-0.036	-0.040	-0.046	-0.050	-0.053
12F059	255,540	571,750	0.000	-0.002	-0.003	-0.003	-0.005	-0.006	-0.008	-0.009	-0.010	-0.012	-0.014	-0.015	-0.016	-0.017	-0.020	-0.019
12F089	254,630	569,790	0.000	-0.002	-0.002	-0.004	-0.006	-0.009	-0.012	-0.014	-0.018	-0.021	-0.024	-0.027	-0.030	-0.034	-0.035	-0.038
12F090	253,640	569,920	0.000	-0.002	-0.003	-0.006	-0.011	-0.016	-0.022	-0.028	-0.037	-0.044	-0.052	-0.060	-0.069	-0.078	-0.087	-0.096
12F091	252,320	570,000	0.000	-0.004	-0.006	-0.014	-0.025	-0.037	-0.049	-0.063	-0.084	-0.104	-0.123	-0.141	-0.159	-0.182	-0.201	-0.226
12F100	253,090	569,980	0.000	-0.002	-0.004	-0.009	-0.017	-0.026	-0.034	-0.044	-0.057	-0.070	-0.083	-0.096	-0.109	-0.125	-0.138	-0.154
12F113	251,690	572,460	0.000	-0.016	-0.019	-0.026	-0.038	-0.047	-0.053	-0.062	-0.074	-0.091	-0.112	-0.132	-0.152	-0.181	-0.203	-0.223
12F116	254,735	569,315	0.000	-0.002	-0.003	-0.005	-0.006	-0.009	-0.011	-0.013	-0.015	-0.017	-0.019	-0.022	-0.024	-0.026	-0.026	-0.028
12F180	254,730	571,380	0.000	-0.004	-0.006	-0.006	-0.009	-0.012	-0.013	-0.016	-0.020	-0.023	-0.026	-0.030	-0.033	-0.038	-0.042	-0.044
105	251,944	573,302	0.000	-0.012	-0.015	-0.017	-0.022	-0.022	-0.024	-0.029	-0.031	-0.038	-0.043	-0.050	-0.059	-0.068	-0.074	-0.079
106	252,252	573,256	0.000	-0.013	-0.016	-0.017	-0.023	-0.023	-0.025	-0.029	-0.032	-0.038	-0.043	-0.050	-0.059	-0.068	-0.074	-0.078
107	252,543	573,238	0.000	-0.009	-0.012	-0.014	-0.019	-0.020	-0.021	-0.026	-0.029	-0.035	-0.040	-0.047	-0.055	-0.063	-0.070	-0.073
157	255,570	572,240	0.000	-0.003	-0.004	-0.004	-0.004	-0.003	-0.005	-0.007	-0.006	-0.006	-0.005	-0.005	-0.004	-0.004	-0.002	0.003
162	253,330	573,220	0.000	-0.004	-0.008	-0.009	-0.013	-0.012	-0.013	-0.017	-0.018	-0.024	-0.026	-0.030	-0.035	-0.040	-0.043	-0.044
164	253,910	574,450	0.000	-0.004	-0.004	-0.005	-0.007	-0.009	-0.011	-0.012	-0.013	-0.015	-0.019	-0.022	-0.024	-0.026	-0.028	-0.028
169	251,160	573,860	0.000	-0.002	-0.004	-0.004	-0.007	-0.007	-0.007	-0.008	-0.010	-0.014	-0.015	-0.018	-0.022	-0.026	-0.028	-0.030
170	251,130	574,270	0.000	-0.002	-0.004	-0.003	-0.005	-0.006	-0.006	-0.007	-0.008	-0.012	-0.012	-0.014	-0.016	-0.021	-0.021	-0.023
178	249,670	573,530	0.000	-0.002	-0.005	-0.005	-0.007	-0.007	-0.008	-0.007	-0.008	-0.009	-0.009	-0.011	-0.012	-0.013	-0.013	-0.011
193	254,120	573,160	0.000	-0.003	-0.005	-0.005	-0.008	-0.008	-0.010	-0.010	-0.011	-0.014	-0.013	-0.016	-0.018	-0.019	-0.019	-0.018
311	249,320	574,520	0.000	-0.001	-0.001	-0.002	-0.003	-0.004	-0.005	-0.005	-0.006	-0.007	-0.008	-0.009	-0.010	-0.011	-0.011	-0.011
382	254,870	572,860	0.000	-0.004	-0.004	-0.007	-0.007	-0.008	-0.009	-0.011	-0.012	-0.014	-0.014	-0.015	-0.016	-0.018	-0.016	-0.014

Point	X	Y	1-May-93	1-Feb-95	1-Jul-95	1-Jan-96	1-Jan-97	1-Jan-98	1-Jan-99	1-Jan-00	1-Jan-02	1-Jan-04	1-Jan-06	1-Jan-08	1-Jan-10	1-Mar-12	1-Feb-14	1-Apr-16
12E157	249,320	574,220	0.000	-0.001	-0.003	-0.002	-0.003	-0.004	-0.004	-0.004	-0.005	-0.006	-0.007	-0.008	-0.008	-0.009	-0.008	-0.006
12F080	253,950	574,030	0.000	-0.004	-0.005	-0.006	-0.008	-0.009	-0.010	-0.011	-0.012	-0.014	-0.016	-0.018	-0.019	-0.020	-0.022	-0.021
12F103	255,710	572,850	0.000	-0.003	-0.004	-0.004	-0.005	-0.006	-0.007	-0.008	-0.009	-0.010	-0.011	-0.012	-0.012	-0.013	-0.012	-0.008
12F129	254,600	572,300	0.000	-0.004	-0.004	-0.006	-0.006	-0.007	-0.008	-0.009	-0.010	-0.011	-0.011	-0.014	-0.013	-0.014	-0.014	-0.010
12F130	251,120	574,420	0.000	-0.002	-0.003	-0.002	-0.006	-0.007	-0.007	-0.007	-0.009	-0.011	-0.013	-0.014	-0.017	-0.020	-0.022	-0.023
12F131	252,820	573,250	0.000	-0.007	-0.010	-0.012	-0.016	-0.016	-0.018	-0.022	-0.023	-0.030	-0.034	-0.039	-0.045	-0.052	-0.058	-0.061
12F133	253,710	573,210	0.000	-0.005	-0.007	-0.009	-0.012	-0.012	-0.013	-0.015	-0.016	-0.021	-0.022	-0.025	-0.029	-0.032	-0.034	-0.035
12F186	254,280	573,080	0.000	-0.004	-0.005	-0.007	-0.008	-0.008	-0.009	-0.010	-0.010	-0.013	-0.013	-0.015	-0.016	-0.017	-0.017	-0.015
12F191	251,210	573,350	0.000	-0.004	-0.007	-0.007	-0.011	-0.012	-0.013	-0.015	-0.019	-0.024	-0.028	-0.033	-0.039	-0.048	-0.053	-0.056
7G191	249,200	575,670	0.000	-0.002	-0.002	-0.005	-0.005	-0.004	-0.005	-0.008	-0.008	-0.009	-0.009	-0.012	-0.013	-0.013	-0.013	-0.013
7G221	249,299	575,135	0.000	-0.001	-0.002	-0.002	-0.003	-0.003	-0.003	-0.004	-0.006	-0.006	-0.006	-0.008	-0.008	-0.008	-0.007	-0.007
7H223	250,367	575,144	0.000	-0.002	-0.002	-0.003	-0.004	-0.005	-0.006	-0.006	-0.007	-0.008	-0.009	-0.010	-0.011	-0.011	-0.011	-0.012
132	253,943	566,988	0.000	-0.002	-0.001	-0.002	-0.003	-0.005	-0.003	-0.008	-0.002	-0.008	-0.002	-0.009	-0.001	-0.009	-0.009	-0.009
133	254,120	567,490	0.000	-0.002	-0.002	-0.005	-0.004	-0.007	-0.004	-0.011	-0.005	-0.014	-0.007	-0.017	-0.007	-0.019	-0.020	-0.021
142	251,610	569,390	0.000	-0.001	-0.002	-0.004	-0.008	-0.019	-0.022	-0.036	-0.042	-0.064	-0.065	-0.089	-0.086	-0.115	-0.129	-0.147
12E020	249,380	567,830	0.000	-0.001	0.000	-0.001	-0.001	-0.006	-0.001	-0.009	-0.002	-0.013	-0.004	-0.017	-0.004	-0.019	-0.021	-0.023
12E026	248,560	569,610	0.000	0.000	-0.001	-0.002	-0.004	-0.006	0.001	-0.009	0.001	-0.014	-0.015	-0.017	-0.018	-0.020	-0.022	-0.023
12E160	249,440	566,980	0.000	-0.001	-0.001	-0.001	-0.001	-0.006	-0.002	-0.010	-0.004	-0.014	-0.005	-0.018	-0.019	-0.020	-0.023	-0.024
12E172	248,720	569,280	0.000	-0.001	-0.001	-0.002	-0.004	-0.006	-0.008	-0.010	0.000	-0.014	-0.015	-0.016	-0.018	-0.019	-0.020	-0.021
12E173	249,240	568,220	0.000	-0.001	-0.001	-0.002	-0.003	-0.005	0.000	-0.008	0.000	-0.011	-0.012	-0.013	-0.014	-0.015	-0.017	-0.018
12F016	253,759	566,626	0.000	-0.001	-0.001	-0.002	-0.001	-0.004	-0.001	-0.005	-0.001	-0.007	-0.007	-0.008	-0.001	-0.008	-0.009	-0.008
12F028	251,920	568,140	0.000	-0.001	-0.001	-0.003	-0.002	-0.009	-0.007	-0.015	-0.014	-0.024	-0.022	-0.035	-0.028	-0.044	-0.048	-0.053
12F030	254,525	568,705	0.000	-0.001	-0.002	-0.004	-0.003	-0.007	-0.006	-0.011	-0.006	-0.017	-0.011	-0.024	-0.013	-0.028	-0.030	-0.033
12F127	252,900	567,990	0.000	-0.001	-0.002	-0.003	-0.003	-0.008	-0.005	-0.011	-0.009	-0.020	-0.012	-0.024	-0.015	-0.030	-0.033	-0.036
12F137	251,790	568,950	0.000	-0.001	-0.002	-0.003	-0.005	-0.014	-0.014	-0.024	-0.028	-0.044	-0.043	-0.062	-0.056	-0.079	-0.089	-0.101
12F139	253,690	567,680	0.000	-0.002	-0.001	-0.003	-0.001	-0.005	-0.001	-0.008	-0.001	-0.010	-0.011	-0.012	-0.001	-0.014	-0.015	-0.016
12F167	253,950	569,060	0.000	-0.001	-0.002	-0.004	-0.002	-0.007	-0.006	-0.014	-0.009	-0.021	-0.015	-0.028	-0.019	-0.035	-0.039	-0.044
12F168	253,540	568,660	0.000	-0.001	-0.001	-0.002	-0.002	-0.007	-0.004	-0.011	-0.009	-0.021	-0.014	-0.028	-0.018	-0.034	-0.038	-0.043
12F171	252,940	568,900	0.000	-0.002	-0.002	-0.005	-0.005	-0.012	-0.011	-0.020	-0.018	-0.034	-0.031	-0.048	-0.041	-0.060	-0.068	-0.077

APPENDIX D OPTIMISATION RESULTS

Table 7-5 Summary of the detailed history match results showing the three rigid basement parameters that were subjected to the optimisation procedure and the resulting modelling error. The runs are coloured to illustrate the two minima that were identified.

optimization run	Rigid basement depth parameters			RMSE (cm)	local/global minimum
	c/k(0)	d(c/k)	τ_{zout}		
0	0.704	0.675	48.3	0.7154	*global*
1	0.001	0.003	30.4	0.9723	*local*
2	0.701	1	78.2	0.7168	*global*
3	0.706	0.566	38.8	0.7146	*global*
4	0.001	0.006	59.4	0.9723	*local*
5	0.706	0.565	38.7	0.7146	*global*
6	0.001	0.007	69.1	0.9723	*local*
7	0.705	0.578	39.9	0.7147	*global*
8	0.705	0.632	44.6	0.7151	*global*
9	0.001	0.001	56.3	0.9723	*local*
10	0.001	0.003	26	0.9723	*local*
11	0.703	0.852	63.6	0.7163	*global*
12	0.703	0.826	61.3	0.7162	*global*
13	0.705	0.634	44.7	0.7151	*global*
14	0.703	0.83	61.7	0.7162	*global*
15	0.704	0.72	52.2	0.7157	*global*
16	0.001	0.006	58.8	0.9723	*local*
17	0.001	0.003	22.8	0.9723	*local*
18	0.706	0.569	39.1	0.7146	*global*
19	0.705	0.636	44.8	0.7152	*global*
20	0.001	0.008	84.1	0.9723	*local*
21	0.706	0.568	39	0.7146	*global*
22	0.707	0.502	33.3	0.7140	*global*
23	0.001	0.007	77.6	0.9723	*local*
24	0.702	0.972	74	0.7167	*global*

APPENDIX E EXAMPLE OF THE INDIVIDUAL WELL ALLOCATION FRACTIONS

Table 7-6 A typical example of squeeze volume allocation fractions after optimisation. The numbers are fractions of the total cumulative volume produced to that date.

Date	Allocation well fraction												
	TR-1	TR-2	TR-3	TR-4	TR-5	TR-6	TR-7	TR-8	TR-9	VE-1	VE-2	VE-3	VE-4
Feb-95	-	-	-	-	-	-	-	-	-	-	-	-	-
Jul-95	-	-	-	-	-	-	-	-	-	-	-	-	-
Jan-96	-	-	-	-	-	-	-	-	-	-	-	-	-
Jan-97	0	1	-	-	0	-	-	-	-	-	-	-	-
Jan-98	0	0.19	-	-	0.81	-	-	-	-	-	-	-	-
Jan-99	0	0	-	0	1	0	-	-	-	-	-	-	-
Jan-00	1	0	0	0	0	0	0	-	-	-	-	-	-
Jan-02	0.94	0	0.06	0	0	0	0.01	0	-	-	-	-	-
Jan-04	0.74	0	0.26	0	0	0	0	0	-	-	-	-	-
Jan-06	0.58	0.42	0	0	0	0	0	0	-	-	-	-	-
Jan-08	0.84	0.16	0	0	0	0	0	0	-	-	0	0	-
Jan-10	0.38	0.62	0	0	0	0	0	0	-	-	0	0	0
Mar-12	0.66	0.34	0	0	0	0	0	0	-	-	0	0	0
Feb-14	1	0	0	0	0	0	0	0	-	-	0	0	0
Apr-16	1	0	0	0	0	0	0	0	-	-	0	0	0

APPENDIX F SUBSIDENCE MAPS USING ALTERNATIVE RIGID BASEMENT PARAMETERS

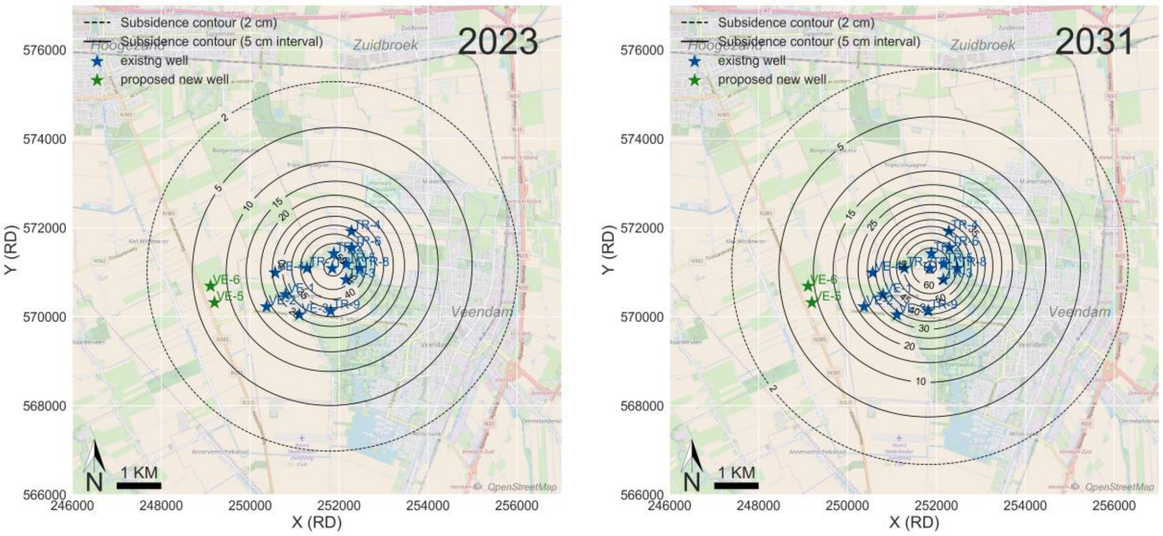

Figure 7-2 Subsidence forecast (in cm) for 2023 (left) and 2031 (right) based on production scenario 1 using the rigid basement parameters from the global minimum that resulted in the largest modelling error, see Appendix D. 2031 is the year when subsidence at a benchmark location reached the maximum permitted 65 cm.

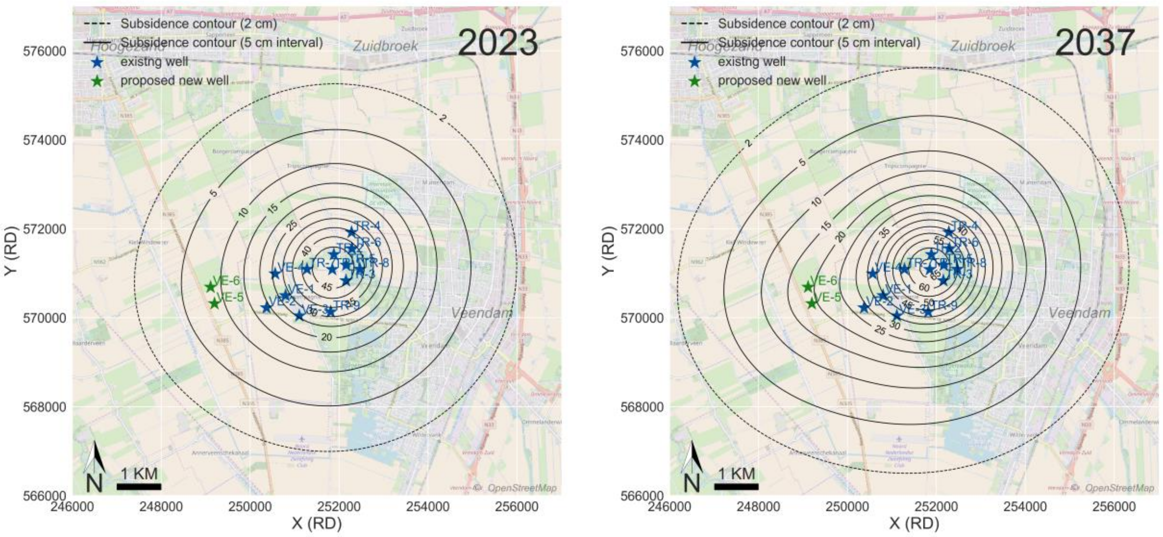

Figure 7-3 Subsidence forecast (in cm) for 2023 (left) and 2037 (right) based on production scenario 2 using the alternative rigid basement parameters. As a result of applying the alternative parameters to scenario 2 the maximum permitted subsidence at a benchmark location is reached in 2037, one year later than in the forecast reported in Chapter 3.

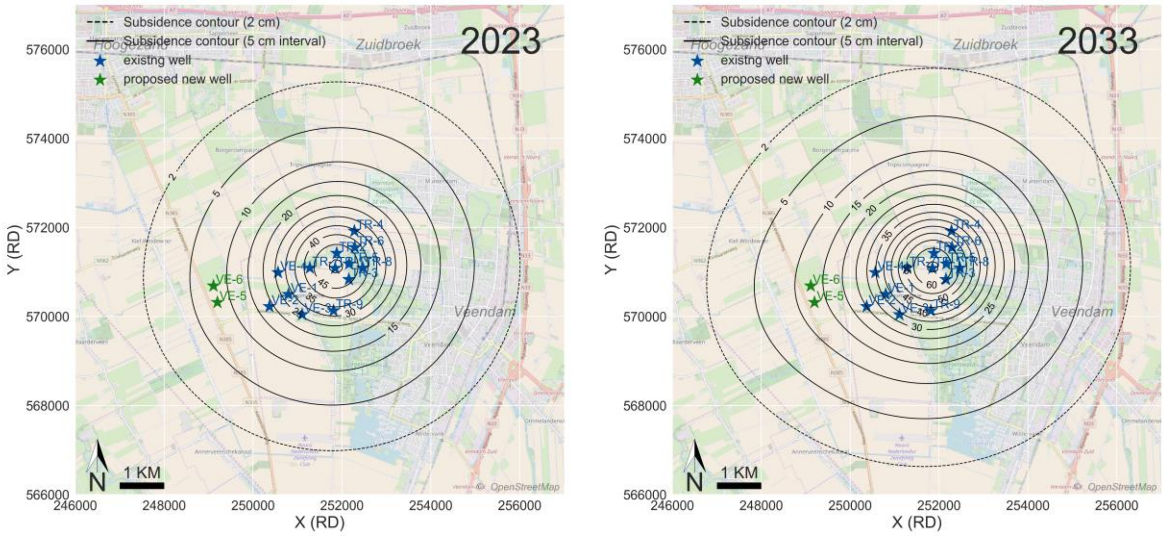

Figure 7-4 Subsidence forecast (in cm) for 2023 (left) and 2033 (right) based on production scenario 3 using the alternative rigid basement parameters.