Proposal subsidence analysis procedure 2017

Prepared by:	Well Engineering Partners, Hoogeveen
Author:	
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Approved:	Frisia Zout B.V.

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Management summary

According to State Supervision of Mines, the growing systematic deviations between benchmark movements, measured by periodic leveling surveys, and Frisia's Gaussian iterative forward modeling of land subsidence need to be addressed.

As follow-up method, Frisia now proposes to (re)start making conventional contourmaps of salt-production induced subsidence, using periodic benchmark height differentials corrected for autonomous movements not caused by salt production. A new element of the method is the 'flexible benchmark inclusion', applied to Kriging interpolation. This procedure enables the successive smooth inclusion of new, secondary benchmarks into the set of original primary benchmarks.

Before contouring the specific salt-extraction caused subsidence, autonomous benchmark movements and gas production impact are removed from the benchmark differentials-lists representing total regional subsidence. Frisia aims at correcting for autonomous benchmark movements on a very local scale and based on dedicated geodetic stability studies.

The on-line monitoring of subsidence by means of GPS measurements at or near the deepest points of the three subsidence-bowls will be continued as usual. However, GPS reporting layout is modified, by entirely removing references to leveling-based subsidence results.

Introduction

According to State Supervision of Mines (SSM), more investigations are needed to explain the growing systematic deviations between benchmark movements, measured by periodic leveling surveys, and Frisia's Gaussian iterative forward modeling of land subsidence (refs.1, 2).

Consequently, Frisia has performed an in-depth analysis of the feasibility of the currently applied modeling method (ref.3). Based on the analysis, Frisia has concluded that the method has gradually become inadequate for reliably deriving the maximum subsidence above salt-producing caverns from benchmark movements.

As follow-up method, Frisia now proposes to (re)start making conventional contourmaps of subsidence, using periodic benchmark height differentials corrected for autonomous movements not caused by salt production (ref.3). Additional analytical modeling is not needed anymore.

In the Technical Attachment of the Monitoring & control protocol (ref.4), the iterative Gaussian subsidence modeling is still assigned as analysis and control method. Now, an alternative method for interpreting benchmark data published in official survey registers must be developed. The new procedure will be submitted to SSM for approval.

1 New approach to benchmark subsidence contouring

Subsidence is periodically measured by means of second order leveling surveys of benchmarks and permanently monitored in or near the deepest bowl points by GPS.

Principally, the new approach applies conventional contouring techniques for mapping benchmark differentials published in the official survey registers. However, the benchmark differentials are partially reprocessed and/or corrected for local autonomous movements in an unconventional manner.

The reprocessing is comparable to the flexible benchmark-inclusion procedure introduced in 2008 for the iterative Gaussian modeling. In addition to the primary benchmarks, it enables to also use the growing secondary set of benchmark data for contouring purposes.

The allocation of land subsidence volumes to either Frisia salt extraction or Vermilion gas production is separately done by presuming that the Frisia subsidence contours above caverns are rather circular in comparison to the irregular subsidence pattern due to gas production.

Subsidence data obtained from permanent GPS monitoring is considered as an independent source of subsidence information. Periodically, GPS data is calibrated using height differentials of nearby benchmarks. The local height differentials are first corrected for autonomous movements. Then, cumulative differentials are determined, taking the start date of GPS measurements as starting point of the cumulation interval. Deviations between GPS subsidence data and corrected benchmark differentials should be minimal.

2 Earlier experience with conventional contouring

Before start of gas production in 1988, an initial benchmark survey was done. Before Frisia salt production started in 1995, another initial survey in the area was performed. Although the two benchmark networks overlapped near the town of Franeker, the benchmark heights were adjusted to different stable NAP reference benchmarks. Also, the networks were enlarged and modified several times after the zero measurement, with changing stable reference benchmarks. This has resulted in published heights related to different reference systems.

At the request of SSM, the height differentials of the primary (initial) set of benchmarks of Vermilion (1988) and Frisia (1995) were consistently re-interpreted over the period 1988-2006 (ref.5). The measured primary data were again adjusted to NAP by means of two stable deeply-founded benchmarks. Benchmark OA2760 (Zweins) was selected as common stable NAP reference for the two networks. The transition of the Frisia primary data set to OA2760 was done using the height of deeply-founded subsurface benchmark OA2748 as bridging reference. Subsequently, the heights of all primary benchmarks were recalculated for the period 1988-2006, applying the geodetic technique known as 'free adjustment' (vrije vereffening) relative to OA2760 only. This procedure yielded a new primary differentials list.

In Attachment 1, a subsidence contour map is shown obtained by Kriging interpolation of total *primary*-benchmark subsidence in the period 1988-2006. In certain areas, contours could not be determined reliably due to lack of benchmark density. This is particularly the case in the northeastern corner of the Frisia salt extraction area, where in October 2003 salt leaching had started in cavern BAS-3. In fact, all over the places of salt production enough benchmark data is available from periodic leveling surveys, but the data belongs to the secondary benchmark set. To obtain more accurate and reliable contours, it is necessary to also include subsidence data from the secondary benchmark set in the Kriging interpolation. In next section, it is explained how this requirement can be fulfilled.

3 Flexible benchmark inclusion applied to Kriging interpolation

The Frisia leveling network has been extended and condensed several times since the initial reference measurement in 1995. The first network consisted of 50 benchmarks, whereas in 2006 in total 208 benchmarks were measured.

A subgroup of 97 benchmarks could be classified as 'primary'. These benchmarks were also not affected by subsidence contributions from gas production. The position of the benchmarks is depicted in the map of Attachment 1. After introduction of the flexible benchmark-inclusion procedure in July 2008, far more benchmarks became useful for subsidence analyses. For example, regarding the 2009 leveling survey, even after exclusion of 50 benchmarks significantly influenced by gas production up to 193 benchmarks were available for subsidence analyses (Gaussian iterative modeling).

Successive inclusion of new benchmarks for subsidence contouring
Flexible benchmark inclusion consists of assigning a 'synthetic' initial reference height to a new secondary benchmark, such that the apparent height differential at the time of first measurement, is exactly equal to the subsidence value of the best-fitting Gaussian bowl at that new benchmark location.

Above procedure is also easily applicable to the mapping of subsidence by Kriging interpolation of benchmark differentials, without the necessity of any form of additional analytical modeling. Refrain from analytical modeling is an explicit goal of the new subsidence analysis procedure.

The method goes as follows. For every survey, in which new benchmarks are introduced in the network, conventional Kriging interpolation of benchmark differentials is performed without taking the measurement results of the new benchmarks into account. The positions of the new benchmarks are projected on the survey contourmap. The subsidence at the spot of a new benchmark is interpreted as an apparent height differential. Then, to the new benchmark, an initial 'synthetic' height at the time of the survey is assigned that exactly produces the subsidence value of the contour map.

The established practice of delivering an official survey register in accordance with NAP instructions remains in place. A new element is the separate production of a dedicated register with synthetic heights and height differentials for new secondary benchmarks, based on contourmaps of differentials of primary and previously included secondary benchmarks.

Reprocessing of all 18 repeat surveys since 1995
The new procedure is meant to first apply in full size after the repeat survey performed in October/November 2017. To this end, Kriging interpolation and assignment of synthetic heights for secondary benchmarks must be reprocessed for all repeat surveys, starting with first repeat survey of August 1996 and ending with repeat survey October 2015.

4 From total subsidence to salt-extraction induced subsidence

The above exercise will deliver contourmaps and differentials lists representative of total regional subsidence, including autonomous benchmark movements and gas production effects.

However, according to official requirements from mining legislation Frisia must accurately specify the contribution of salt extraction to land subsidence. The region of the Barradeel and Barradeel II licences is prone to autonomous soil compaction and subsidence. Furthermore, as shown in Attachment 2, a well-defined exclusion zone exists with significant impact of gas production to land subsidence. Consequently, further processing of benchmark differentials is needed before a representative contourmap of salt-extraction induced land subsidence is achieved that enables a fair review pertinent to the license-related subsidence limits.

Impact of regional Holocene structure on benchmark stability
Recent geodetic findings have been reported regarding autonomous movements of benchmarks near the deepest point of the Frisia subsidence bowls (ref.5). The average autonomous movements are apparently determined by very local circumstances. The amount of autonomous movements varies between -0.7 and -2.8 mm per year.

Also, in the Vermilion gas production area comparable autonomous movements have been found (ref.6). In the Franeker area, the autonomous movements of benchmarks relative to six nearby deeply-founded subsurface benchmarks, including free adjustment reference OA2760, were investigated. The average autonomous movements of the shallow-founded benchmarks varied between -0.1 and -1.6 mm per year, with average of circa -1 mm per year. In a recent extensive subsidence analysis and prognosis publication of Vermilion (ref.7), the regional autonomous benchmark subsidence is fixed to a standard value of 1 mm per year for the whole period between 1988 and 2050. During that period, circa 6 cm of autonomous subsidence on average is expected and accounted for.

When looking at the specific regional Holocene layer structure, the cause of the erratic autonomous movements of superficially-founded benchmarks (coppar bolts in (farm)houses, sheds and small bridges, and short poles and screw anchors in the free field) becomes largely evident. The Holocene layer structure has been investigated for the two Frisia production license areas and the direct surroundings, including the main subsidence area of Vermilion gas production (refs.8, 9). In Attachment 3, the studied area is depicted, including the Frisia license boundaries and the position of two profile lines AA' and BB', for which a structural cross section down to 30 m below surface is made.

In Attachment 4, profile line AA' that crosses the Frisia cavern positions is shown. The Holocene structure is very irregular, with total depth varying between 5 and 20 m below surface. In the Frisia license areas, the Holocene package has maximum thickness of 18 to 22 m, some places mainly sandy or silty, others mainly clayey. In the SW and NE corners of the profile the Holocene is thin, and Pleistocene is rather near to the surface. These Pleistocene heights are old drowned Wadden-islands. Just at the top of the Pleistocene heights, the so called Base Peat is found, being remnants of the island vegetation, with thicknesses of some decimeters. Near Franeker another peat type is locally found at circa 3 m depth, the Hollandveen, consisting of read peat of circa 30 cm thickness. Peat is very susceptible to compaction and oxidation when subjected to lower freatic water levels, as occurs in polders with reduced polder water levels.

Apart from Holocene impact on autonomous benchmark subsidence, other possible external causes could be building modifications, usually an enlargement or improvement with more load on existing foundation, and water management decisions to lower the original free water level, triggering accelerated large-scale soil compaction.

Local corrections for autonomous benchmark subsidence

Contrary to the general Vermilion practice, Frisia aims at correcting for autonomous benchmark movements on a very local scale and based on dedicated geodetic studies (ref.5). For example, along and near the enlarged dike of the Waddensea autonomous benchmark movements are significant. In the 2015 control cycle report (ref.1), eight out of 13 rejected benchmarks of the iterative Gaussian modeling are located at or near the dike. So, before composing representative time-dependent contourmaps of autonomous benchmark subsidence, some additional geodetic analyses should be performed in certain critical benchmark areas. The Frisia maps will exclude the region disturbed by gas-production.

After having constructed the time-dependent autonomous subsidence contourmaps, the local autonomous subsidence is subtracted from the total subsidence to finally obtain the real salt-production related land subsidence.

5 Geodetic reinforcement of benchmark survey network

Commissioned by SSM, Oranjewoud has advised on effective benchmark network-design, in view of mining legislation addressing reliable subsidence monitoring by mining companies (ref.10). A recent industry guideline on geodetic monitoring (ref.11) recommended uniformly.

Looking at the new Frisia approach on subsidence monitoring, the following recommendations in the Oranjewoud report are relevant to keep in mind:

- When using one reference benchmark only for leveling adjustments (‘vrij vereffening’), the probability of keeping a wrong NAP height is considerable (>20% for height error <1 cm).
- Minimally two reference benchmarks should be used for reliably connecting the benchmark heights to NAP. Using more than one reference height implies so called forced adjustment (‘gedwogen vereffening’).
- Benchmark networks dedicated to detecting land subsidence caused by deep underground mining, must include sufficient benchmarks firmly-founded in Pleistoceen sediment. These subsurface benchmarks are constructed according to GeoDelft techniques and marked by OA indication. In Attachment 5, a construction sketch of the GeoDelft type subsurface benchmark is shown.

Need for more stable subsurface reference benchmarks

As published in all Frisia survey registers so far, the standard deviations of the benchmark heights adjusted to the one and only subsurface reference benchmark OA2760 (Zweins) vary from 1.2 mm near reference benchmark Zweins to 2 mm at the outer boundaries of the survey network (ref.3).

The small standard deviations are indicative of high-quality and accurate height measurements in a well-defined network. The primary goal of the surveys is not so much to determine the exact NAP heights of the benchmarks, but rather to obtain reliable benchmark differentials from one survey to the other. To date, no indications of suspicious benchmark rise relative to Zweins have been seen. Also, apart from unstable outliers at or near the Waddenzee dike (exceeding 13 mm criterion in Gaussian modeling), the residual subsidence components of the benchmarks at the outer boundaries do not deviate from those of benchmarks nearer to the reference benchmark Zweins. From these observations it is concluded that in the Frisia case single point reference Zweins is fit for porpose.

To remove any doubt in the outside world, it is worthwhile to perform a pilot investigation, as suggested next, to confirm the robustness of reference benchmark Zweins and Frisia network.

At Harlingen port head, subsurface firmly-founded benchmark OA4020 is available, being the only stable subsurface alternative for Zweins in the whole region of NW-Friesland. In the period 1998-2015, the cumulative differential relative to Zweins amounts to -6 mm. Furthermore, some surface benchmarks in the city of Harlingen show even smaller differentials between -1 mm (5D0004 and 5D0005), +1 mm (5D0037) and +3 mm (5D0007) in the same period. The objects, in which these stable surface benchmarks have been installed, are unknown to the author.

It goes too far to suspect tilt of the city of Harlingen relative to Zweins. On the other hand, choosing a second stable reference benchmark, maybe OA4020 or an intrinsically-stable surface benchmark in Harlingen, offers the opportunity to perform a forced re-adjustment of benchmark heights to two reference points. If the recalculated differentials do not significantly differ from the original free-adjustment data, this strongly validates the choice so far to only refer to subsurface benchmark Zweins.

6 New layout for mapping GPS subsidence data

As pointed out above, Frisia is interested in relative movements. This also holds for the GPS subsidence data that forms an information source independent of leveling survey techniques.

To date, complications with GPS trendline interpretation and application have been regularly met because of the practice to couple the starting value of the trendline to a nearby benchmark height, determined by leveling survey analyses. In hindsight, the following drawbacks are identified:

- Sometimes, the specific subsidence value of the coupled benchmark that determines the start level of the trendline, changes based on results from new iterative Gaussian modeling.
- The extra subsidence to be added to the GPS subsidence value to ‘know’ the amount of subsidence in the deepest point of the bowl must be modified after almost every new leveling survey.
- The red bullits periodically inserted in the GPS graphs as synchronous subsidence results from leveling surveys, detract from the reliability of the permanent GPS observations, because the leveled benchmarks are subjected to non-negligible autonomous subsidence.

The mentioned drawbacks have invoked the need for a different and independent way of reporting the GPS subsidence data, not disturbed by leveling survey results with intrinsic autonomous subsidence components. A preliminary example of the new GPS trendline is shown in Attachment 6 for the Barradeel GPS station. Since start of the permanent GPS monitoring in week 25 of 2004, subsidence at production location Barradeel has increased by circa 2.5 cm at maximum. Although the station is not exactly located in the deepest point of the subsidence bowl, subsidence above caverns BAS-1 and 2 has clearly come to an end since beginning 2010.

After approval of SSM, the GPS data of all three observation stations (BAS-1/2, BAS-3/3O and BAS-4) will be published according to the new layout, not disturbed by autonomous trends from benchmark leveling surveys.

7 References

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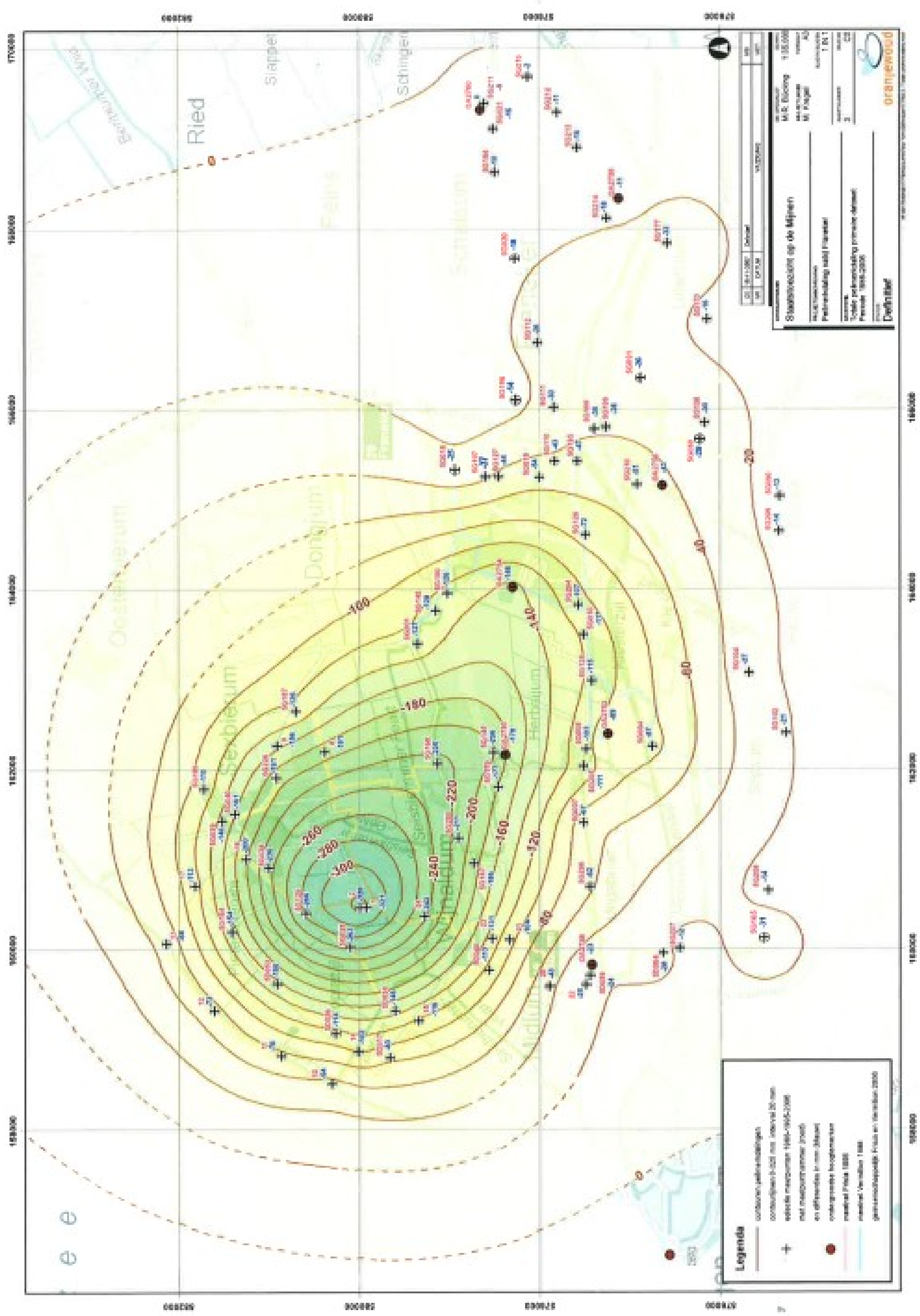
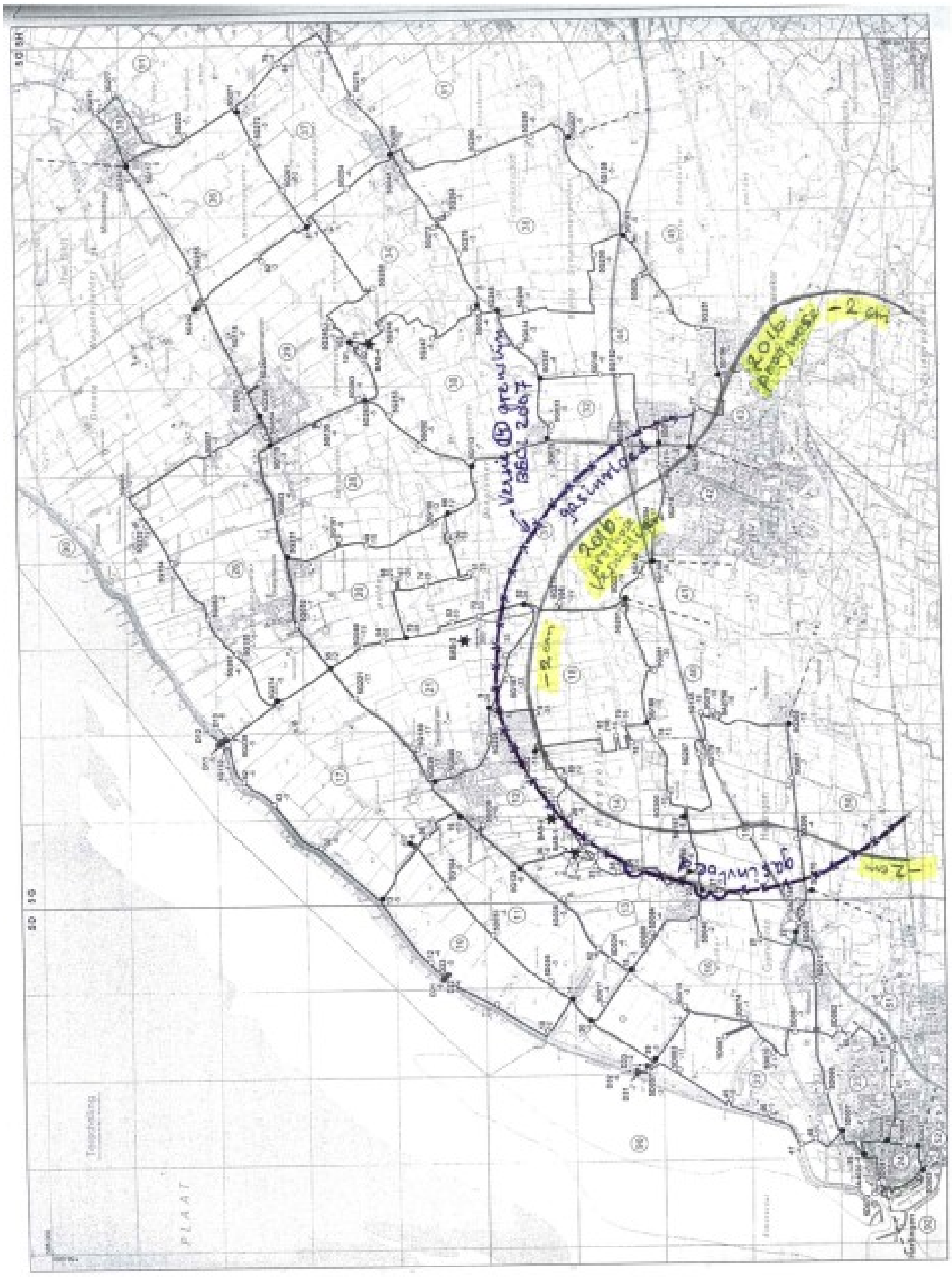
11. Geodetische basis voor Mijnbouw, Industrieleidraad Versie 1.0, Technisch Platform Bodembeweging, mei 2014.

Attachment 1: Primary benchmark subsidence 1988-2006 gas and salt production



Contours solely based on primary dataset of Vermilion (1988) and Frisia (1995) (ref.6).

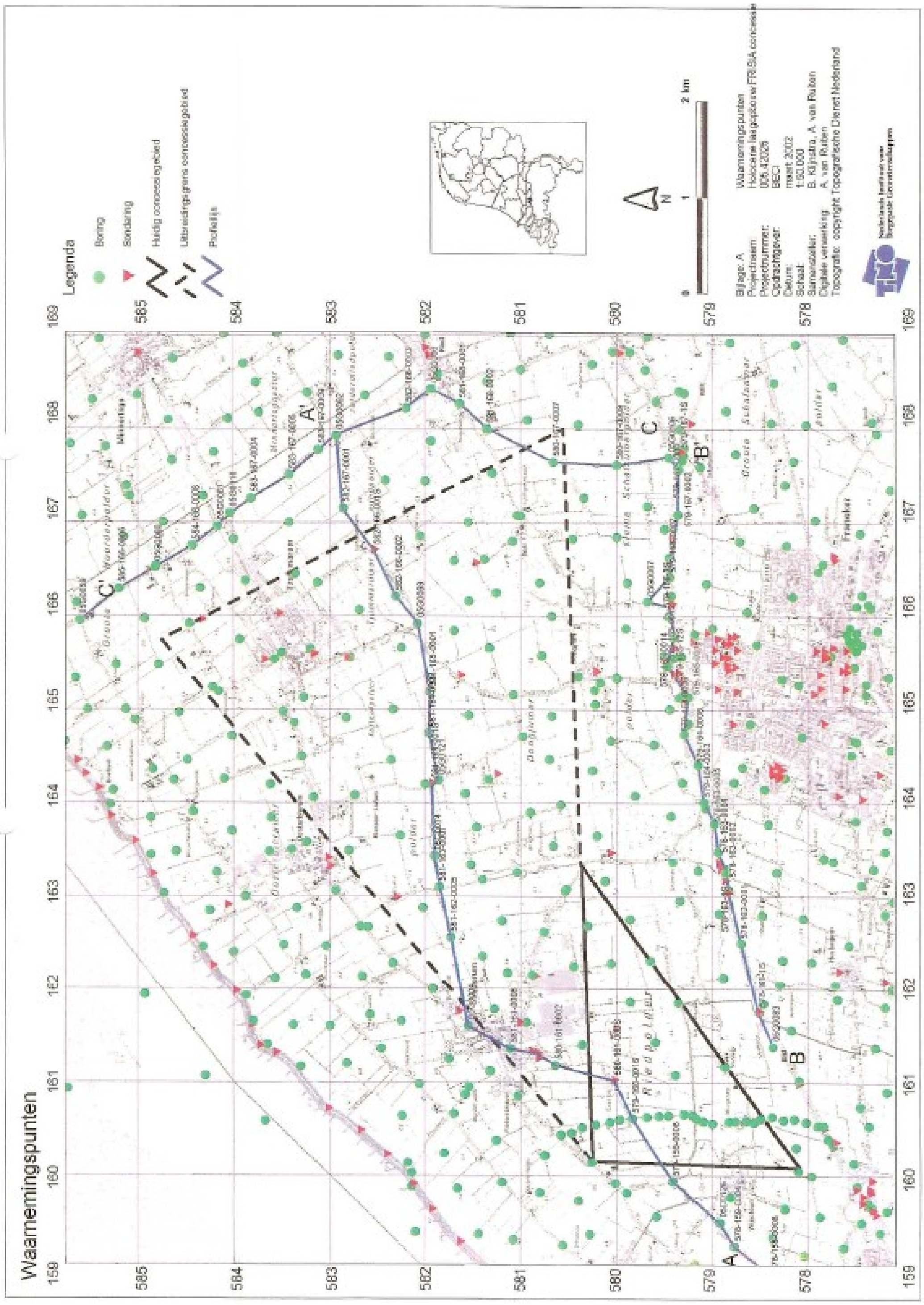
Attachment 2: Vermilion gas production impact zone



Explanation of written text in picture:

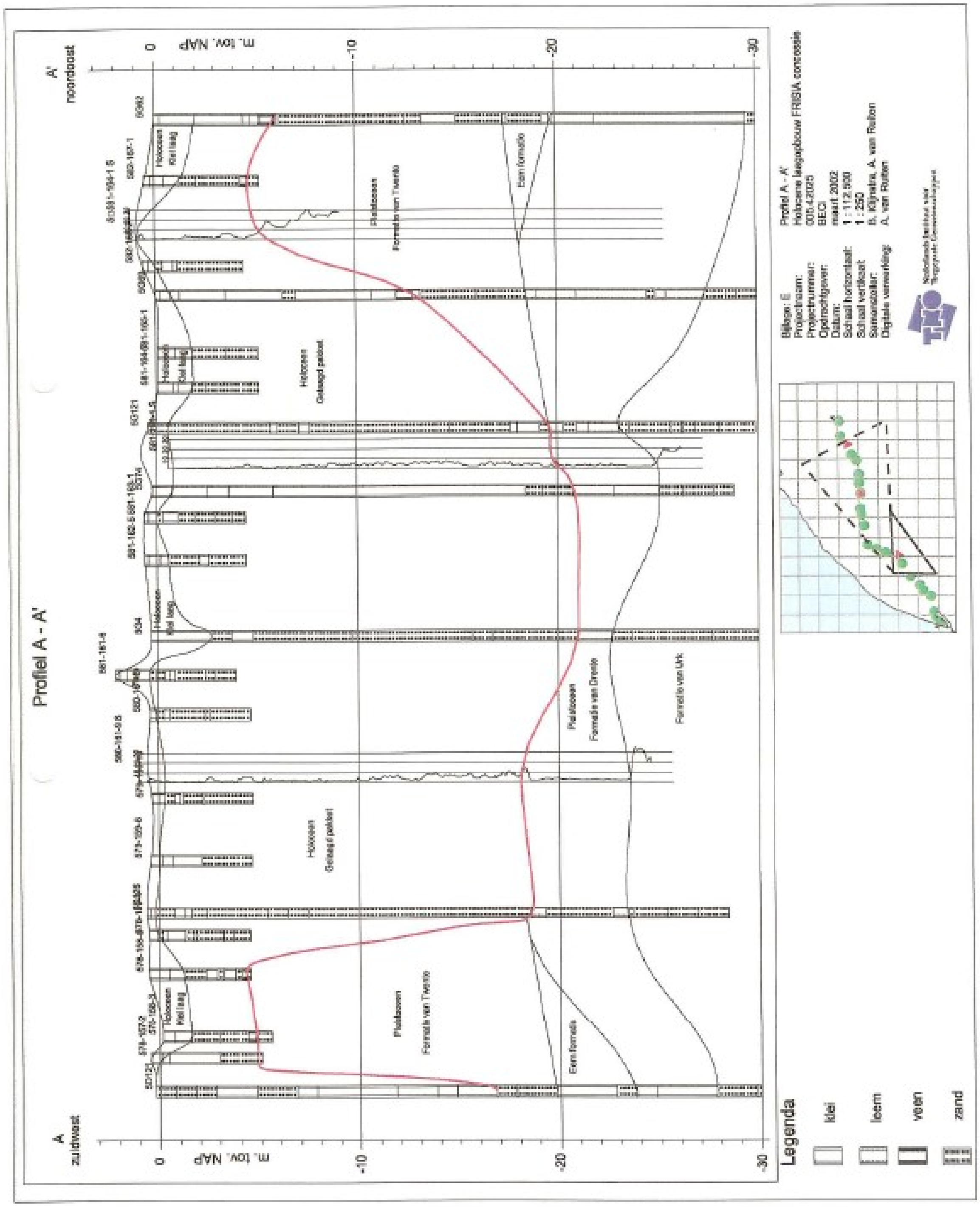
- gasinvloed = gas subsidence impact zone, based on Vermilion 2016 prognosis;
- versie 14 grenslijn BECi 2007 = benchmark exclusion boundary line used in analysis of levelling survey September 2006.

Attachment 3: Holocene structure observation points in and around Frisia license areas



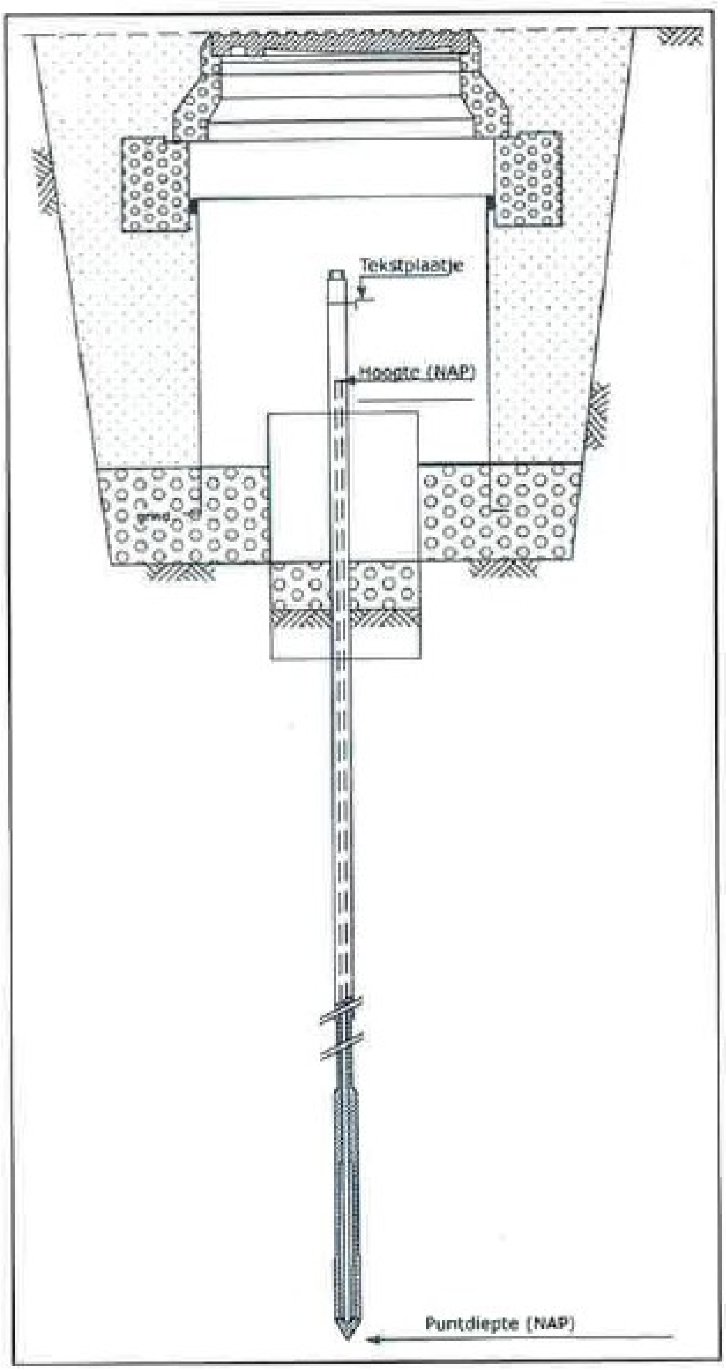
Black line represents Barradeel license area, dotted line Barradeel II area. Blue lines (AA' and BB') show position of Holocene profiles of layer structure down to 30 m depth (ref.9).

Attachment 4: Profile AA' of Holocene layer structure above Frisia caverns



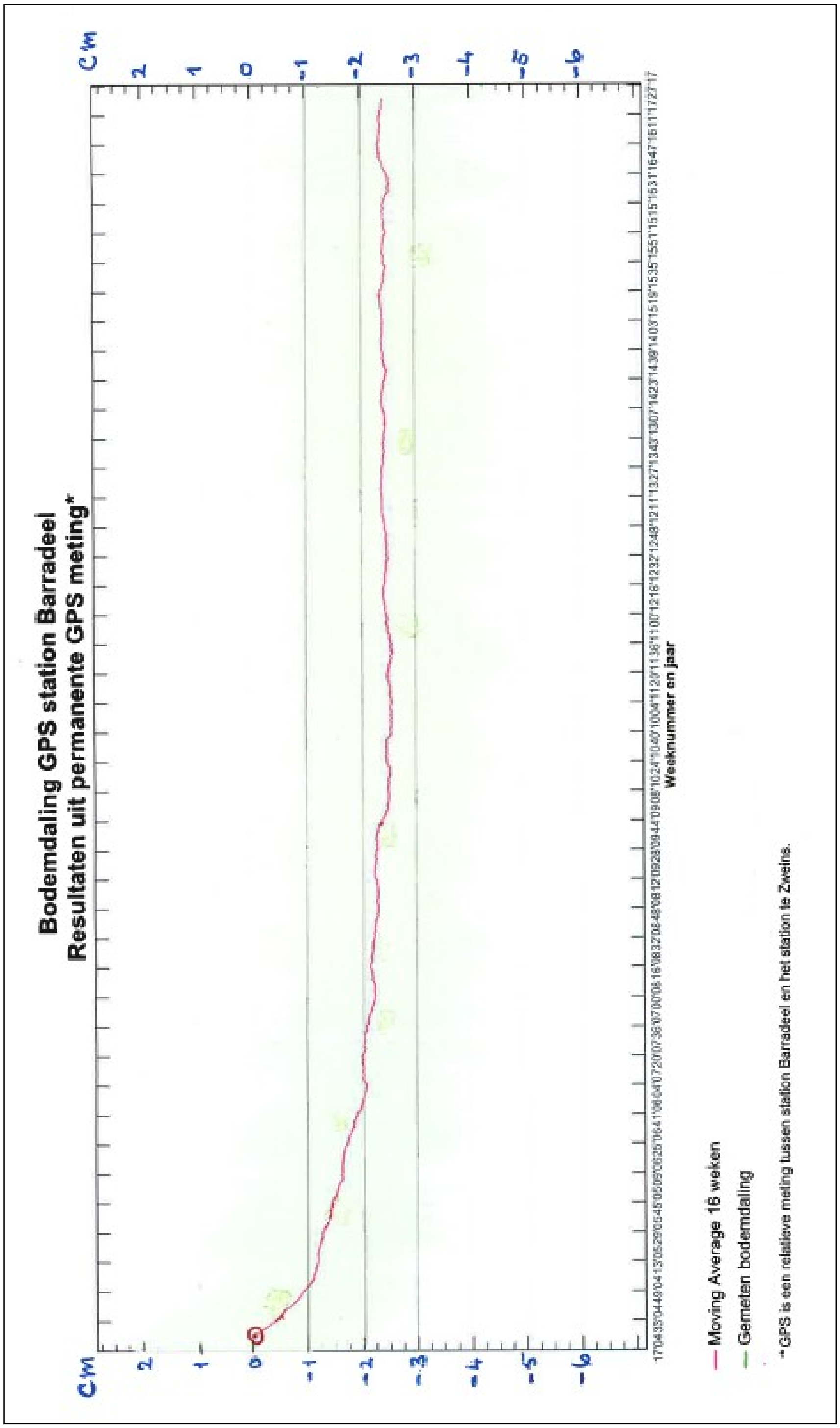
Picture adopted from ref.9.

Attachment 5: Construction sketch of GeoDelft subsurface benchmark



The cone at the end of the inner rod is placed in a stable Pleistocene sand layer with a pressure of 20 to 30 MPa. The inner rod is placed frictionless in an outer rod filled with oil. The top position of the inner rod (Hoogte NAP) is measured by leveling surveys. (refs.10, 11).

Attachment 6: New layout of permanent GPS monitoring data



Example of GPS data trend in time for station Barradeel, relative to non-subsiding reference station Zweins. The start value is set to zero in week 25 of year 2004, being the average value of 16 weeks of observations from week 17 to 33 (period of -8 weeks to +8 weeks).