



Survey data contouring by Kriging

Pilot project Frisia

project number 0432418.00
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July 9, 2018

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1 Summary

Differences between periodically surveyed benchmarks and the Gaussian iterative modelling as proposed by ESCO Frisia and Well Engineering Partners (WEP) are growing systematically, which makes the modelling less representative in certain bowl areas. Therefore alternatives need to be investigated that can replace Frisia's Gaussian iterative geodetic modelling. This report describes the first results of the pilot research project performed on such a method, being 'flexible benchmark inclusion using Kriging interpolation'.

The goal of the pilot project is to investigate the feasibility of the newly proposed geodetic modelling method of creating contour maps. It is performed on data of surveyed benchmarks of 1995, 1997, 1998 and 1999. Antea Group performed the research in collaboration with Well Engineering Partners.

The proposed method is based on Kriging interpolation, which requires a semi-variogram as input. First test runs showed that by using standard parameters and settings during the Kriging interpolation, the results were not sufficient. Therefore more research has been performed on Kriging interpolation and the variogram settings. This resulted among others to the use of a Gaussian variogram model and a shorter range of 1000 meters during the first repeat survey. Using these defined starting points subsidence contour maps were created for the pilot period of 1995 till 1999.

However, the created contour maps are still not satisfying. Outside of the extraction influence zone the subsidence presented on the contour maps is higher than expected (>2cm). This problem need to be solved before we are able to continue this method. However it is at present not certain whether a workable solution will be attained and possibly more research is needed. Furthermore, the choice of using an Gaussian variogram and associated parameters all have direct influence on the end results. While it is aimed to make the most optimal decisions, others may have a different interpretation. This makes this method open for discussion. It is therefore advised to investigate another method which is able to replace or improve the current Frisia's Gaussian iterative modelling.

2 Introduction

There are growing systematic deviations between benchmarks movements measured by periodic levelling surveys and ESCO Frisia's (Frisia) and Well Engineering Partners (WEP) Gaussian iterative forward modelling, as described in the 'Proposal subsidence analysis procedure 2017', esco/Frisia Zout B.V., v.2 (final), 19 February 2018. It was concluded that the previously used method becomes less and less accurate. This leads to the need of a new method which is able to derive the maximum depths and contour maps.

This report focuses on primary results of the pilot research project by using a proposed new method, being 'Flexible benchmark inclusion applied to Kriging interpolation'. Kriging is a widely used interpolation method. An advantage of this method is that there is no need of analytical modelling anymore. The description of the pilot project can be found in 'Pilot project Frisia: Survey data contouring by Kriging'.

Assumptions of the pilot:

- The initial period of interest is 1995-1999, being the years 1995, 1997, 1998 and 1999. In a later phase this can be extended up to and including the most recent surveys;
- Focus is on total subsidence measured. In consultation with Frisia and WEP, influence of autonomous subsidence is neglected for now.

3 Goal of the pilot project

Since the previously used iterative Gaussian modelling has its limitations and seems like becoming less accurate, WEP suggested to investigate alternatives of geodetic modelling. One alternative is the flexible benchmark-inclusion using Kriging interpolation. The goal of the project is to test the feasibility of using this new method.

3.1 Flexible benchmark-inclusion applied to Kriging interpolation

In order to create a contour map using either modelling or interpolation, the surveyed benchmarks are the starting point. When creating a contour map it is important that enough data, or surveyed benchmarks, are used. Next to that should the benchmark heights all be known in the same reference year (null-survey) before taking them into account for a contour map of total subsidence. In case only the primary benchmarks surveyed during the null-survey are taken into account, not enough data is available to create reliable contour maps. Flexible benchmark inclusion deals with this problem.

Important aspect is to assign a synthetic reference height of the null-survey to secondary benchmarks which are first surveyed in periods later than the null-survey of 1995. The principle is as follows:

1. Height differentials from benchmarks which are surveyed in the null-survey (1995) and the first repeat survey (1997) are interpolated using Kriging interpolation, which results in a contour map of subsidence between 1995 and 1997.
2. The interpolated subsidence of 1995 and 1997 is retrieved on locations of benchmarks which are first surveyed during the first repeat survey of 1997.
3. Subtracting the interpolated subsidence from the surveyed height in 1997 results in a synthetic initial reference height in 1995.

So the artificial height of the null-survey (1995) for benchmarks measured first during the first repeat survey of 1997 is the surveyed height of 1997 minus the interpolated subsidence during 1995-1997.

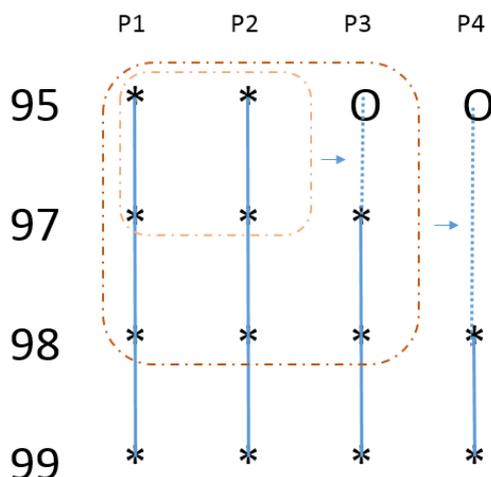


Figure 1 Diagram showing the principle of flexible benchmark inclusion

4 Methods

The procedures are performed using a combination of Surfer and ArcGIS Pro. Surfer is software specialized in (Kriging) interpolation, while ArcGIS is specialized in visualizing spatial data. Many test runs have been performed and progression was made by trial-and-error. Results were thereby discussed periodically with WEP () and in an iterative process improved.

There are different types of Kriging in which the following are the most common:

- Simple Kriging
There is a known constant mean
- Ordinary Kriging
There is an unknown but constant mean
- Universal Kriging
There is an unknown and varying mean

Ordinary Kriging is considered the best Kriging method for our situation. It is the most flexible and best method when there is a stationary constant mean in which a small trend is not a problem. The mean is not known so simple Kriging is not an option and universal Kriging is only used when the data is highly unpredictable.

4.1 Standard settings and parameters

Benchmark heights from the register of 2007 were used as in this year the most recent recalculation took place. During this year the reference benchmark changed to the stable benchmark Zweins (OA2760) which is still used today. Data from 2007 is used instead of the registers 1995 to 1999 because an extension of the pilot period would result in different reference benchmarks.

During the first runs, the processes were performed using standard settings, auto-filled parameters and the linear semi-variogram model for the Kriging interpolation. This leads to unsatisfied results which can be seen in Figures 2, 3 and 4. It is unsatisfying because we do not know the influence on the results of the given settings and the bowl has an oval shape pointed to the south-east, which is likely due to the linear variogram.

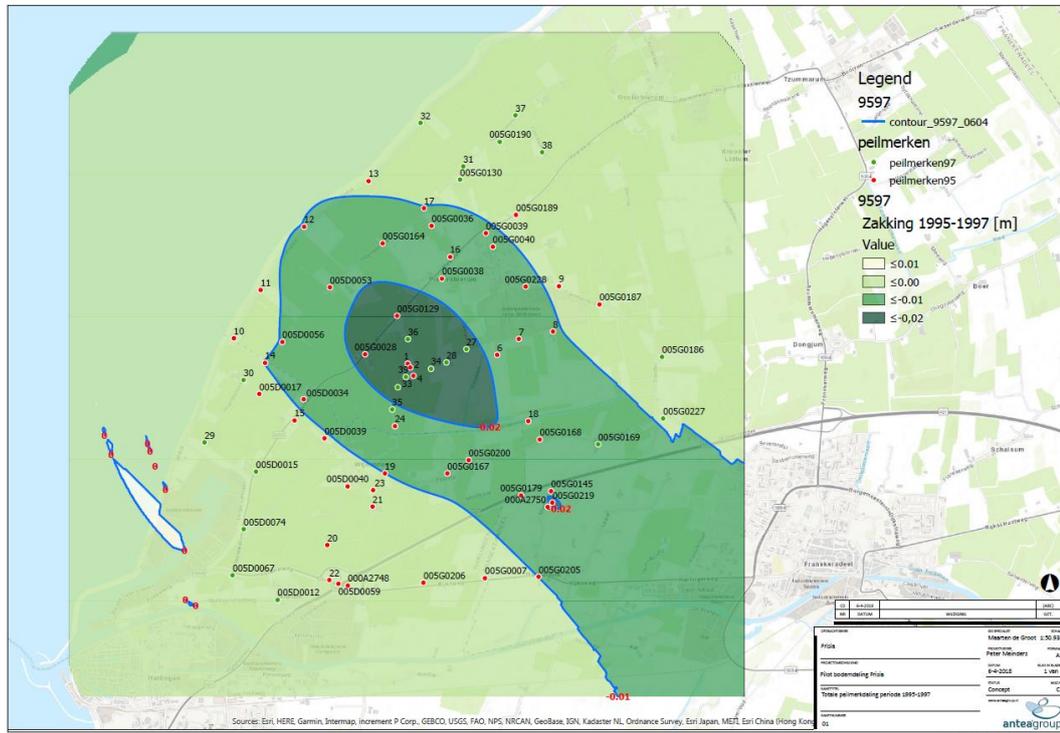


Figure 2 Insufficient contour map of total subsidence during 1995-1997

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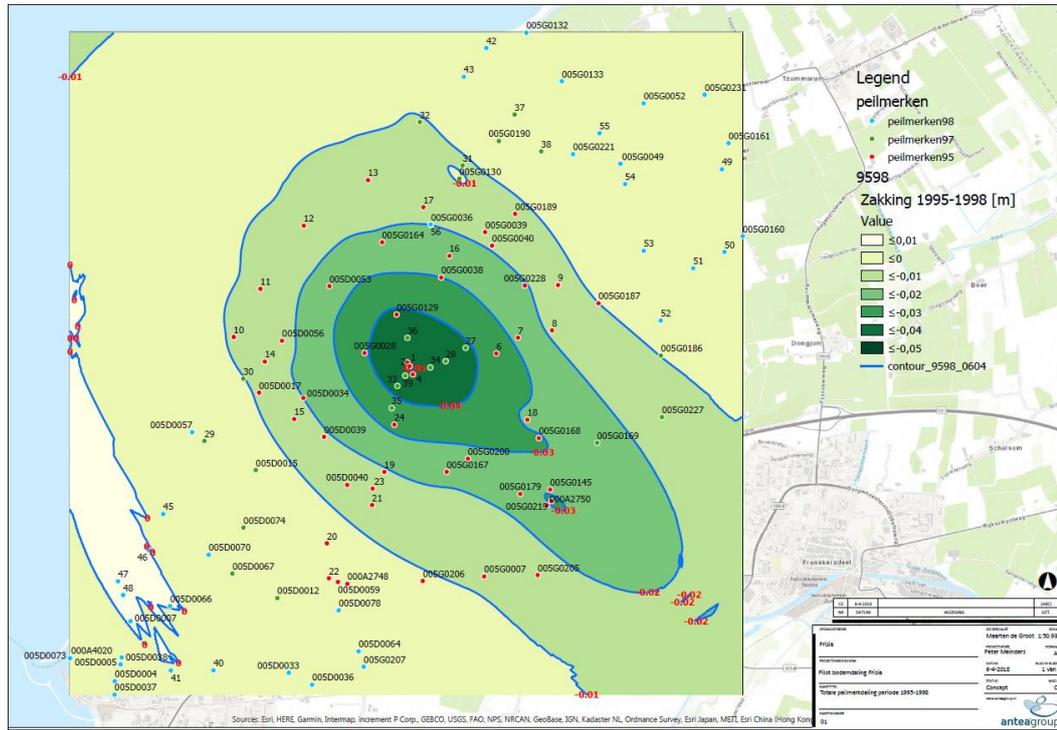


Figure 3 Insufficient contour map of total subsidence during 1995-1998

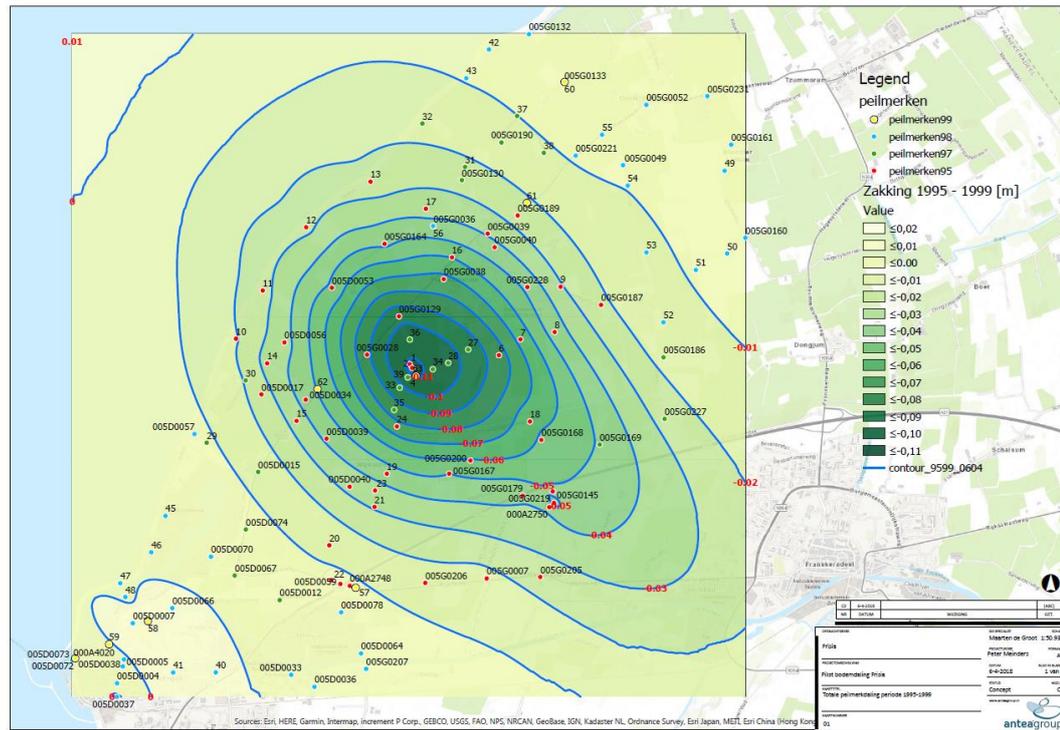


Figure 4 Insufficient contour map of total subsidence during 1995-1999

4.2 The variogram

Since applying the standard and auto-filled settings of the software did not lead to satisfying results, more research was necessary. Simply said, the weights used during Kriging interpolation are defined using the semi-variogram, which describes the spatial variability of the data.

First an experimental variogram is created using the data itself, while subsequently a variogram model is fitted through the experimental variogram. Both can be seen in Figure 5. On the x-axis is the lag distance, or the distance between a pair of points, and on the y-axis the computed variogram value. The greater the variogram value means that there is less correlation between the pair of points. In blue is the variogram model shown. An important aspect of Kriging interpolation is to choose a model and its parameters which fits the data and the situation in the field the best.

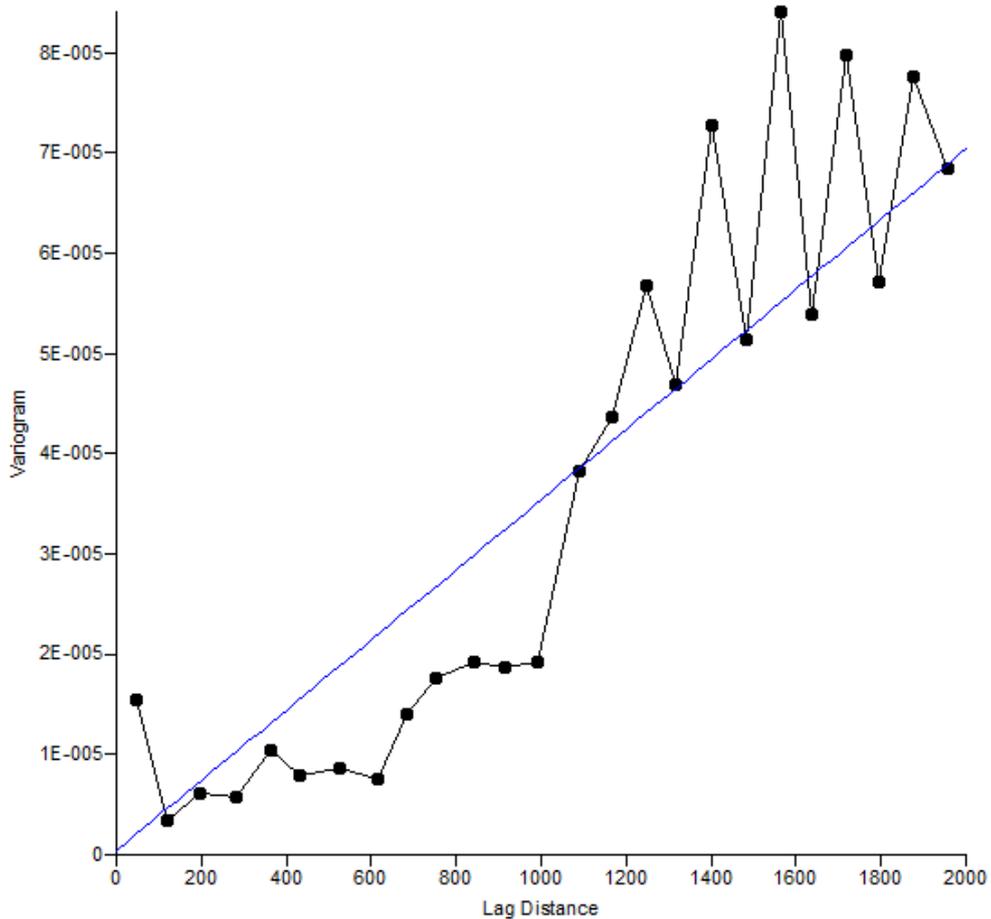


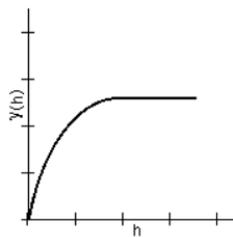
Figure 5 An experimental variogram in black and a (linear)variogram model in blue. This is created using standard parameters and is considered insufficient. It shows the subsidence data of 95-97 and is created using Surfer.

There are several types of variogram models, but the spherical, exponential, Gaussian and linear model are the most common. Each variogram model can be described using the **Nugget**, **Sill** and

Range:

- **Nugget:** offset on the y-axis
- **Sill:** Value on the y-axis in which the model flattens
- **Range:** Value on x-axis in which the sill is attained, points which are more distant than the range are considered uncorrelated

SPHERICAL

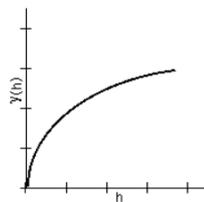


$$\gamma(h) = c_0 + c \left(\frac{3h}{2\alpha} - \frac{1}{2} \left(\frac{h}{\alpha} \right)^3 \right) \quad 0 < h \leq \alpha$$

$$\gamma(h) = c_0 + c \quad h > \alpha$$

$$\gamma(0) = 0$$

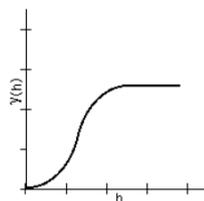
EXPONENTIAL



$$\gamma(h) = c_0 + c \left(1 - \exp\left(-\frac{h}{\tau}\right) \right) \quad h > 0$$

$$\gamma(0) = 0$$

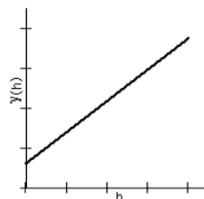
GAUSSIAN



$$\gamma(h) = c_0 + c \left(1 - \exp\left(-\frac{h^2}{\tau^2}\right) \right) \quad h > 0$$

$$\gamma(0) = 0$$

LINEAR



$$\gamma(h) = c_0 + c \left(\frac{h}{\alpha} \right) \quad 0 < h \leq \alpha$$

$$\gamma(h) = c_0 + c \quad h > \alpha$$

$$\gamma(0) = 0$$

Figure 6 Overview of the most common variogram models. Source: http://resources.esri.com/help/9.3/arcgisdesktop/com/gp_toolref/spatial_analyst_tools/how_krige_and_variogram_work.htm

More research into the variogram resulted in the following starting points instead of the standard parameters of the Surfer software, which are used as a basis for the variogram selection. This is necessary as every input parameter and setting has direct influence on the end results.

- Ordinary Kriging is the best suited Kriging type for our situation;
- The Gaussian model is best suited for our situation;
- A (small) nugget effect is necessary;
- A maximum lag distance of 1/3 of the maximum distance is preferred over the auto-filled value;
- The range will likely increase in time.

Using these principles, the variogram model could be defined for every year of surveying. Figure 7 shows the new experimental variogram in black and the Gaussian variogram model in blue for subsidence during 1995-1997. The main settings for this variogram are:

Max Lag Distance	1650
Model type	Gaussian
Sill	7E-5
Range	1000
Nugget	4E-6

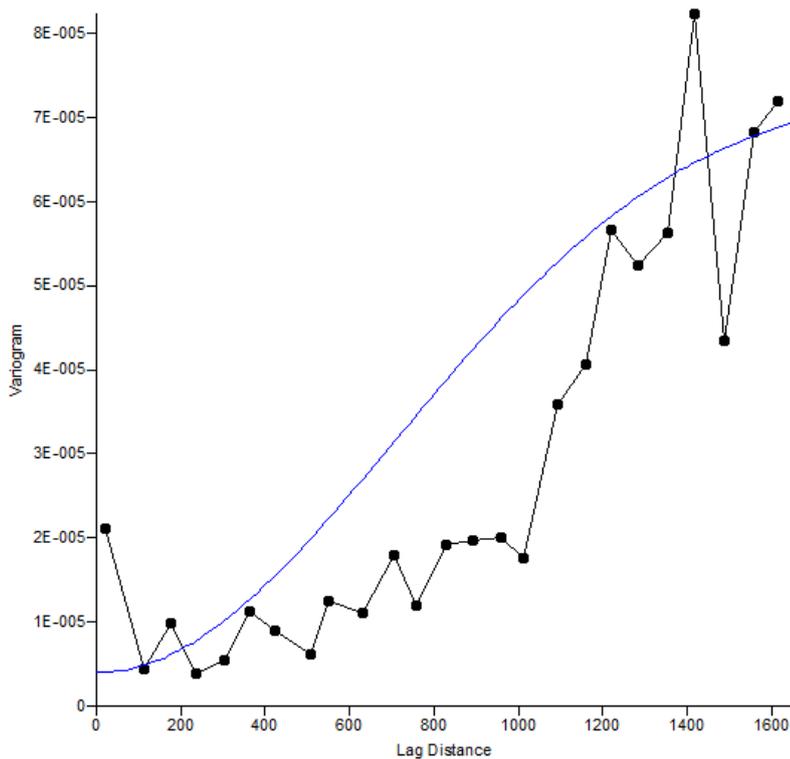


Figure 7 The variogram which is considered sufficient for our purpose. It is created for total subsidence during 1995-1997.

5 Results

5.1 Contour map 1995-1999

The contour map of 1995-1999 which is shown in Figure 9 and Appendix A shows the expected behavior near the bowl. It is thereby noted that the subsidence outside the bowl is much higher (>2cm) than expected. This is likely caused by the used extrapolation instead of interpolation when benchmarks outside the convex hull are added. This is a problem which accumulates over time and needs to be solved before extending the time-period!

One of the goals of the pilot was to identify questionable benchmarks. The reason is that some benchmarks may subside not only due to salt extraction and standard autonomous subsidence, but also due to local circumstances. These benchmarks need to be excluded from the dataset because they can distort the results. However, during previous analysis no questionable benchmarks are present within the period of the pilot, being from 1995 to 1999. Therefore no extensive research has been performed on questionable benchmarks. This is still a point of attention when the pilot will be continued.

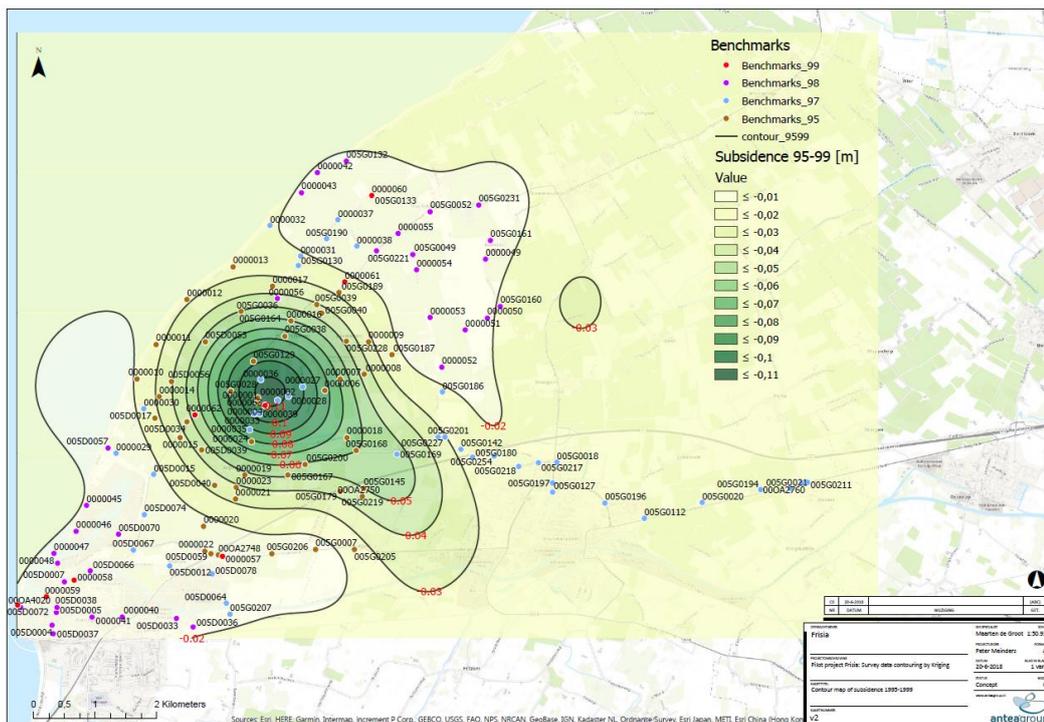


Figure 9 Contour map total subsidence during 1995-1999

5.2 Conclusion

The investigated method, being flexible benchmark inclusions using Kriging interpolation requires in-depth knowledge of both the interpolation method and the situation in the field. The reason is that the standard settings and parameters are not sufficient. Next to that, the method is not straightforward since many settings and parameters need to be chosen in which every decision has impact on the results. It is aimed to select to best settings for our situation, but others may have a different interpretation. This makes it a hard method to apply without discussion.

Furthermore, it is uncertain if the final outcome will be a workable solution. During the pilot project, which consist of 4 years of survey data, many unexpected problems have been encountered that took more time to investigate. At the end of the pilot two questions still need to be answered before being able to continue:

- Is it possible to detect questionable benchmarks using the new method? Since no questionable benchmarks are present within the period of the pilot form 1995 to 1999 this was not possible yet;
- How to deal with the fact that contoured subsidence outside the bowl is much higher than expected and indicated by measured benchmark heights?

These are just two difficulties and it is likely that problems will turn up after solving these, which may be time consuming because of the research needed. It is therefore recommend to reconsider the goals of the overall project with the stakeholders and investigate other methods to derive the contour maps of subsidence before continuing this study over the whole time period ('1995 - 2018')

Appendix A: Total subsidence 1995 - 1999

About Antea Group

From city to countryside, from air to water: Antea Group's engineers and consultants have been contributing to our living environment in the Netherlands for years now. We design bridges and roadways, and create residential neighborhoods and water structures. But we are also involved in areas such as the environment, safety, asset management and energy. Under the name Oranjewoud, we expanded into an all-round, independent partner for companies and government bodies. As the Antea Group, we also apply this knowledge at a global level. By combining valuable knowledge, including on technical matters, with a pragmatic approach, we make solutions attainable and workable. Goal-oriented, with an eye for sustainability. In this way, we anticipate today's questions and tomorrow's answers. Just as we have been for over 60 years now.

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