Land Subsidence Due to Gas Extraction in the Northern Part of The Netherlands

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ABSTRACT Via precision levelling the motion processes are monitored over the gasfields in the North of The Netherlands. Monitoring in relation to subsidence prognosis is important to take timely action to prevent or reduce damage as a result of subsidence. A description of the precise levelling is given with also an outlook how geodetic monitoring can be improved. In addition a method to statistically test various subsidence models as a result of reservoir compaction against actual subsidence is presented to be able to improve the prognosis.

INTRODUCTION

Due to the location of The Netherlands by the North Sea (N.B. 60% of the country lies below high tide level!), the dense infrastructure of towns, roads and waterways and the very intensive land use (375 inhabitants per km²), the country is very vulnerable to land subsidence in general.

The most important kinds of damage that may occur due to land subsidence are:
- less production in farming and agriculture due to an increase of soil wetness;
- decrease of safety as a result of lower dikes and erosion of the dunes;
- ecological damage due to an other hydrological regime in the Waddenzee of currents and associated sand transport;
- decrease of quality of water management in the subsidence region.

After World War II, in The Netherlands large scale lowering of polder water levels has been applied to increase the carrying-capacity of the soil for agriculture. As a result of the fact that the upper soil of The Netherlands mainly consists of clay and peat, an unequal subsidence occured with structural damage to buildings at different places.

In 1964 the exploitation of natural gas started. The major part of the Dutch natural gas reserves are located in the two Northern Provinces, Groningen and Friesland, and under the Waddenzee (Fig. 1). The gas extraction causes in general a very slow and smooth subsidence. To prevent damage, measures are needed to adapt primarily the water management systems. To monitor the actual movements, over all gasfields in The Netherlands regularly precise levellings are made. The observed subsidence resulting from these levellings is composed of several factors:
- subsidence of the benchmark in a house or bridge due to the own mass of the construction, depending on the constitution of the soil;
FIG. 1 Map of gasfields in the Northern part of The Netherlands.
Land subsidence due to gas extraction

- natural compaction of unconsolidated sediments of Holocene, Pleistocene or Tertiary;
- compaction in the Holocene layers due to changes in the hydrological regime as a result of adaptations of polder water levels;
- subsidence due to depressurization in the gasfield.

The major problem - both scientifically and practically in view of financial compensation for damage due to gas extraction - is the difficulty to separate the influences of the four factors. See e.g. Fig. 2 where the annual subsidence of benchmarks in Groningen is shown before the start of the gas extraction.

![Graph showing subsidence (MM/yr) vs. number of benchmarks](image)

**FIG. 2** Subsidence of the benchmarks in Groningen which were placed before 1965.

THE GRONINGEN GASFIELD LEVELLINGS

**Background**

Soon after the start of the production of natural gas from the Groningen gasfield, a first prediction was made of the land subsidence caused by the production. The originally predicted number was 100 cm for the centre of the field, the latest prediction of 1990, however, is 33-43 cm.

As a natural means to verify this prediction and to monitor actual subsidence, the State Supervision of the Mines (SodM), the responsible Government Agency, imposed the concessionaire (the Nederlandse Aardolie Maatschappij B.V., NAM) the organization of a regular series of levellings. These levellings should be executed conform the regulations of the Survey Department of Rijkswaterstaat (MD), who are in charge of the national NAP network (Amsterdam Height Datum). The actual procedure is now such that NAM instructs one (or more) private companies to measure the network in accordance with the MD measurement scheme. NAM itself measures the connections of the network to the underground benchmarks (OM) of the NAP, because of the extreme importance of maintaining a good connection to one's reference. Next, NAM computes the free network adjustment and the constrained adjustment to the OM, and MD verifies the results. Finally the findings are reported to SodM and the Province of Groningen.

**Past Measurements**

One can divide the levelling networks in two types: the so-called 'large' and 'small' networks. The smaller ones are somewhat less
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FIG. 3 Boundary of networks for subsequent levelling campaigns.

The policy now is to measure a 'large' network every six years, which has not always been the case as one can see from the years mentioned above. Also the size of the network changed as the area of production and thus the area of land subsidence grew wider (Fig. 3). The measurements are made with invar rods and precise automatic levels.

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This whole set-up makes a final adjustment of the network possible using an a priori standard deviation of 1 mm/√Lkm. [Verhoef & Brouwer, 1991].

Analysis Method

For the analysis by MD, section tolerances are checked; runs are formed from sections, with special emphasis on the selection of junction points and on levelling runs which are not part of closed loops. Next the closures per loop are computed, which is still a very powerful means to detect and restore (measuring) errors. As a final result a free network adjustment (only one known height fixed) to detect any inconsistencies in the observed data and a constrained network adjustment are made. The latter serves to check on the stability of one's reference benchmarks and yields the final heights of all benchmarks of interest. These adjustment computations are made using the WSCAN-software suite, which performs a Least Squares adjustment, including quality control by statistical testing and reliability description on the basis of conventional alternative hypotheses, as developed by the Delft Geodetic Computing Centre [Teunissen, 1988]. NAM follows the same computational strategy, using
its own software. The whole procedure is fully automated, but still takes a lot of time when errors are suspected and have to be found and restored. And so far no network ever was without errors, as should be the case when collecting some 120,000 raw observations!

Results

All finally computed heights of relevant benchmarks are stored in the ORSNAP database of MD. At present the actual land subsidence is assessed by comparing the heights of benchmarks following from the 1964 (reference) network to the ones computed from the newest levelings, by simple subtraction, i.e. a so-called static approach. The subsidence is visualized - as a final product to SodM and the Province of Groningen - in three ways:

- a contour map with iso-subsidence lines (Fig. 4);
- selected profiles, following from levelling runs (Fig. 5);
- separate subsidence diagrams of some benchmarks.

The accuracy of the presented subsidence is of course a function of the standard deviation of the height determination. Using the 1 mm/\sqrt{km} assumption, for most benchmarks the standard deviation of the estimated heights is between 2-5 mm, relative to the chosen datum point (Gasselte). In view of this number, for the interpretation of the subsidence, it should be noted that the difference in height between two epochs should be at least 1 cm to be statistically significant.

OUTLOOK FOR GEODETIC TECHNIQUES

As concerned to levelling there are still a number of problems to be solved.

A. Stability of underground benchmarks (OM).

It is obvious that OM within the subsidence area are not usable
FIG. 5 Example of levelling profiles.
Land subsidence due to gas extraction

to serve as a reference. However, also the OM outside the area are not free of motions, due to e.g. geological processes or influence of groundwater extraction [Groenewoud et al., 1991]. What is therefore a safe way to assess stability of the OM?

B. Local instability of benchmarks.
Some benchmarks show a very deviating subsidence from its surroundings. Very probably this tells more about the foundations of the building where the benchmark is located than about subsidence due to gas extraction. However, it poses the very real problem to discern between different causes of motion: is it a trend or a local disturbance?

C. New benchmarks.
In The Netherlands some small percentage of the benchmarks disappear each year. Replacements are of course installed. However, the problem still remains to connect old and new benchmarks, and to avoid the introduction of 'fictive' heights at epoch 1964 for benchmarks installed only after 1964.

To tackle these kinds of problems, recently the MD, NAM and the Geodetic Computing Centre of the Delft University of Technology joined forces to perform a completely new analysis of all levelling data of the Groningen gasfield using another computing method, the so-called kinematic adjustment. In a kinematic adjustment next to heights of stations at a certain epoch, also velocities and where required accelerations are estimated, according to specified models: linear, polynomials, splines, etc. For this purpose also new software will be developed.

The objective is to improve our knowledge about the actual subsidence over the Groningen gasfield by solving the problems mentioned above on the one hand and to improve the quality description of the results in terms of precision and reliability on the other hand [Teunissen, 1988].

A quite other aspect concerning the outlook, is the application of GPS (Global Positioning System), the satellite navigation and positioning system of the U.S. Department of Defense. Measurements with geodetic - i.e. (sub)cm - precision to determine height differences are possible by working in a differential mode, even on long distances [Ashkenazi et al., 1990; Groenewoud & Brouwer, 1991].

The use of GPS for determining land subsidence in Groningen offers two attractive possibilities. Firstly, GPS is competitive to spirit levelling in an economical sense: measurements can be made faster - and thus cheaper - and one needs not to determine the heights of a lot of stations in between, which are not of relevance to the subsidence problem. This also means that stable reference benchmarks can be chosen further away from the subsidence area. In addition, the subsidence is essentially a pure deformation problem, so that uncertainty about the geoid - to which levelling refers - is irrelevant.

Secondly, the verification of models is of interest. The prognosis models for reservoir compaction predict a horizontal motion at the surface for the rim of the gas reservoir of 50% of the vertical motion. Three-dimensional GPS measurements can thus verify the prediction models integrally!

Investigations of how exactly to set up a GPS control network for the Groningen gasfield have just started.

PROGNOSIS OF SUBSIDENCE

The Mine Act demands at regular intervals (mostly 5 years) a prognosis of the subsidence for the Dutch gasfields, on the basis of the
most recent geological and mine engineering information. To compute the reservoir compaction and the resulting subsidence of the surface, the following input parameters are used:
- dimension of the reservoir (extension, depth and thickness);
- depressurization in the reservoir;
- uniaxial compaction coefficient $C_m$;
- permeability of the rock formation.

In the computing model, the gasfield is divided into blocks by an orthogonal coordinate grid. In addition, every block has a vertical division into layers. To compute the expected subsidence of the surface, all characteristic parameters of the reservoir per subblock are specified, and next both a "nucleus of strain" [Van Opstal, 1973] and a finite element [Thomas, 1984] approach are used. In 1990 NAM made its last prognosis in cooperation with KSEPL (Royal Dutch/Shell Exploration and Production Laboratory). This prognosis stated that the subsidence in the centre of the field would be between 33 and 43 cm in the year 2050, with 36 cm as the most probable value. The diameter of the subsidence bowl within the 2 cm subsidence contour would be approx. 60 km.

Here, the subsidence for the year 1989 according to the model is presented for the levelling line Groningen-Delfzijl as a solid line (Fig. 5). It is obvious that the measured subsidence deviates considerably at some benchmarks from the model. Further research is needed to assess whether deviations are the result of local effects in the undeep underground or that they follow from uneven compaction along fault surfaces in the gas reservoir.

FIG. 6 Comparison of levelling results and model prediction.

TEST PROCEDURE FOR SUBSIDENCE MODELS

Using statistical techniques, an attempt is made to ascertain what motion hypothesis most resembles the actually observed subsidence, taking into account the stochasticity of the heights of benchmarks determined from levelling. As an example the levelling line Warga - Ureterp (Fig. 6) is used [Pöttgens, 1989]. On the basis of the above mentioned linear elastic model a prognosis for subsidence in the period 1974-1987 is shown by the solid line. The actually observed subsidence is shown by the dashed line. Fig. 6 shows generally a clear relation between the subsidence of benchmarks at the surface and the gas extraction at greater depths. To have a statistical measure for the conformity of the two datasets, standard deviation
(s) and mean (x) of the difference at all benchmarks are computed. Then the test quantity $t = |x| \sqrt{(n-1)/s}$ is formed. This t has a Student distribution with expectation zero. As an alternative for the linear elastic model, the subsidence model of the unequal zig-zag line at the bottom of Fig. 6 is hypothesized, which was at some point suggested in the press ("lightnings"). The results of statistical testing for both motion hypotheses are shown in Table 1.

### TABLE 1 Student test of motion hypotheses.

<table>
<thead>
<tr>
<th></th>
<th>Linear elastic motion model</th>
<th>Unequal zig-zag motion model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of benchmarks</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Mean difference observed minus model</td>
<td>-2.30</td>
<td>-25.01</td>
</tr>
<tr>
<td>Standard deviation observed minus model</td>
<td>3.59</td>
<td>16.29</td>
</tr>
<tr>
<td>Student test statistic</td>
<td>2.48</td>
<td>5.94</td>
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</tbody>
</table>

Comparing the resulting test statistics with Student's critical values shows that the second hypothesis is more than 99.9% improbable, whereas an almost smooth subsidence in large areas is very likely.

All levelling line results are now confronted with the most recent models of the prognosis to have a better insight in the actual processes.

**CONCLUSIONS**

On the basis of the combined knowledge of rock mechanics, reservoir science and geodesy, as presented in the previous sections and many more studies of other aspects connected to surface subsidence in the North of The Netherlands, e.g. [Theeuw, 1973] and [De Waal, 1986], it can be stated that:

1. The geodetic measurements of the surface subsidence are reliable;
2. In general the levelling results and the prognosis on the basis of a linear elastic computing model are in correspondence;
3. Major deviations between model and observed height changes can mostly be explained by local factors, and are often related to changes in the water management system in combination with an inhomogeneous composition of the undeep subsoil.
4. Geodetic and geological knowledge as a result of the Groningen gasfield levellings and associated actions are also very valuable for the study of the natural, regional subsidence in The Netherlands [Groenewoud et al., 1991]. The latter is also closely related to the reliable prediction of relative sea level rise and its consequences for the low country by the North Sea, called The Netherlands.

**REFERENCES**


