

Surface subsidence in The Netherlands: the Groningen gas field*

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Abstract

In The Netherlands, surface subsidence as a result of hydrocarbon production has become more and more a subject of public interest because of the environmental and political aspects. The most pronounced case of this type of subsidence is demonstrated by the Groningen gas field situated in the north of The Netherlands. Since the start of gas production in 1963, the surface over the centre of the field has subsided by some 18 cm. To monitor reservoir compaction and surface subsidence in Groningen on a regular basis, an extensive monitoring programme was set up by the Nederlandse Aardolie Maatschappij BV, the operator in the Groningen concession. This programme includes yearly levelling surveys, measurements of shallow formation compaction (0 to 400 m below surface) in 14 observation wells and in situ reservoir compaction measurements in 11 deep observation wells drilled specifically for this purpose.

Prognoses of gas-production-induced surface subsidence, which are demanded by the State Supervision of Mines, are made using a three-dimensional grid block model to describe the gas-bearing reservoir and the associated aquifer. In the year 2050, when it is planned to abandon the gas field, the maximum subsidence (over the centre of the field) is calculated to be between 33 and 43 cm.

Introduction

Because of the expected impact of gas-production-induced surface subsidence on the water management in the Province of Groningen, the provincial authorities and Nederlandse Aardolie Maatschappij BV (NAM) agreed in 1983 that NAM should publish a prognosis every five years, outlining the future surface subsidence in the Province of Groningen resulting from the production of natural gas. This agreement prompted the setting up of the 'Commissie Bodemdaling Groningen' (Committee on Surface Subsidence Groningen) in which both the Province of Groningen and NAM are repre-

sented. On the basis of the NAM prognosis, this committee determines what measures must be taken to prevent, to minimize or to correct for effects of gas-production-induced surface subsidence. The committee also assesses what part of the costs should be compensated by NAM under the agreement.

Various theoretical models and experimental techniques are available to describe the reservoir compaction and resulting surface subsidence (Van Hasselt 1992). On the basis of experience with the Groningen gas field, this paper outlines the practical applications of these models and describes how the modelling results can be combined with field

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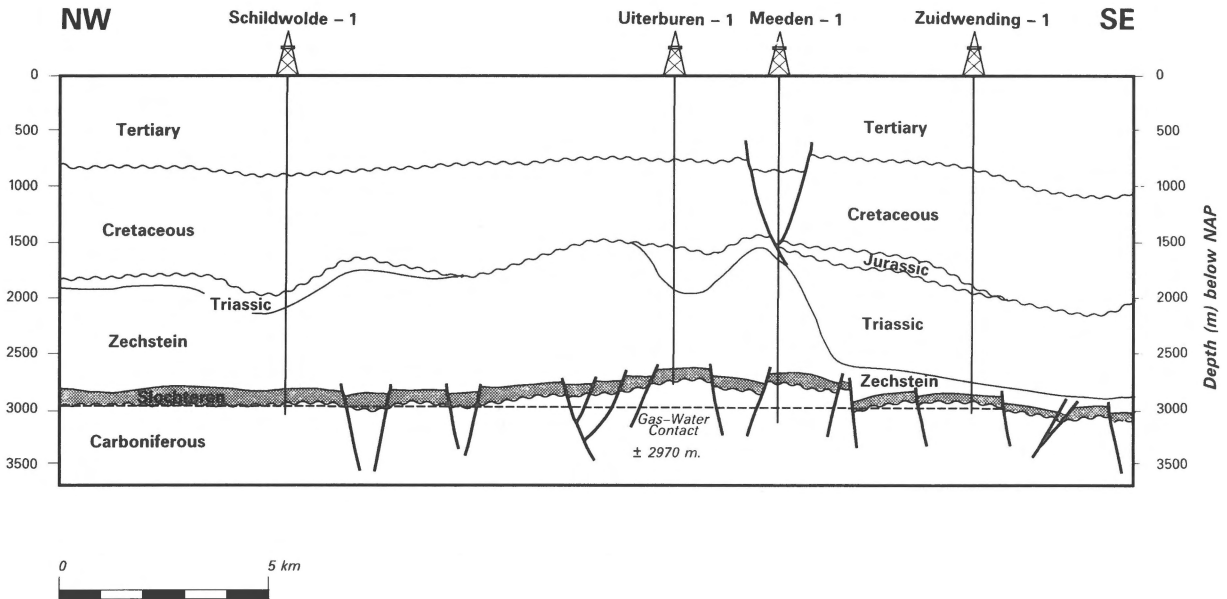


Fig. 1. Geological cross-section of the Groningen gas field.

data on compaction and surface subsidence to arrive at a reliable prognosis of surface subsidence.

First, an outline is presented of the geological setting of the Groningen field and its satellite fields; it includes a discussion of the boundary faults and in particular the aquifer. Subsequently, the various components of the monitoring programme, designed to measure compaction and surface subsidence in the field, are described. To conclude, following a brief discussion of the model used to describe the reservoir and its associated aquifer, a summary of the results and conclusions that can be drawn from the prognosis is presented.

Groningen field, satellite fields and aquifer

Figures 1 and 2 show respectively a NW-SE cross-section through the Groningen field and a map of the gas fields in the area. The Groningen field covers an area of approximately 900 km². The reservoir, the Slochteren Sandstone, is part of the Permian Rotliegend Group and is situated at a depth of about 2900 m. Its thickness varies from 70 m in the extreme SE of the field to 240 m in the NW (Stäuble and Milius 1970). About half of the

recoverable reserves of gas has been produced during the past 27 years (approximately 1200×10^9 m³). According to the 1990 levelling survey, the ensuing surface subsidence amounts to some 18 cm in the deepest point of the subsidence bowl.

In general, the depth and extent of a subsidence bowl depend strongly on the presence of an aquifer in communication with the reservoir. In particular, the ratio of the dimensions of the aquifer and the gas field determines whether the gas pressure in the reservoir will be supported by water encroachment ('aquifer support' in a small gas field with a large associated aquifer) or, as is the case in the Groningen gas field, the pressure in the aquifer will decrease gradually with the pressure in the gas-bearing reservoir ('aquifer depletion' in a large gas field with a small associated aquifer).

The aquifer activity in response to gas field depletion also depends on a number of other factors. When gas field and aquifer are located in a faulted geological setting, the degree of pressure communication will generally be lower than when the gas field is confined by a dipping structure (Fig. 3). In the first case the aquifer activity is determined by the transmissibility across the fault(s), while in the last case specific reservoir properties such as poros-

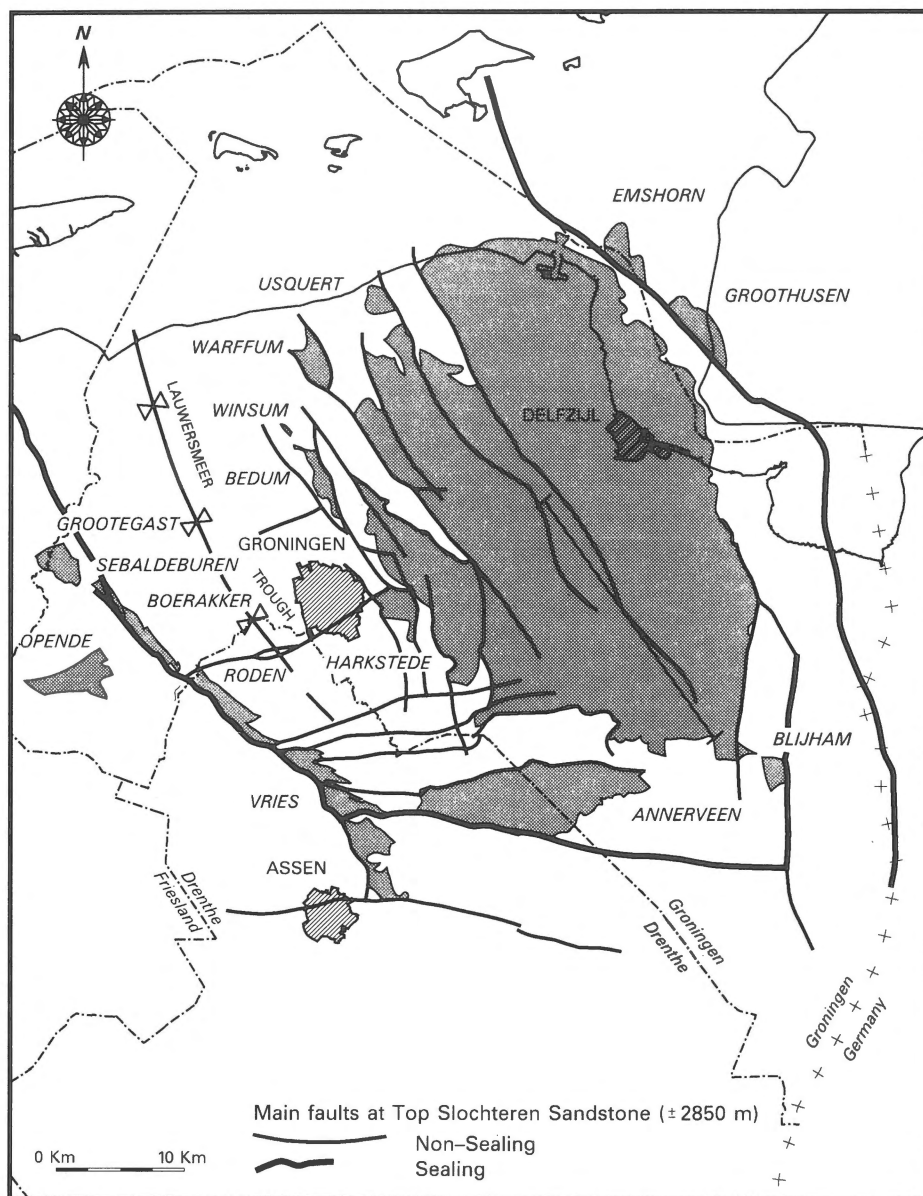


Fig. 2. Map showing outlines of gas fields (shaded) in Groningen area. Line of section of Fig. 1 indicated south of Delfzijl.

ity, permeability and thickness will be the determining factors.

From the regional geology (Figs 1, 2) it is apparent that the pressure reduction resulting from gas production from the Groningen field will most likely not be restricted to the reservoir; depletion of the aquifer has to be taken into account as well.

In theory the aquifer around the Groningen field could extend westwards as far as the border of the

Province of Friesland. There the farthest boundary is formed by a series of NW-SE striking sealing faults (Fig. 2). Closer to the gas field, a number of other structural elements may constitute an effective barrier to large-scale aquifer depletion, at least for the production life of the gas field. One of these elements is the 'Lauwersmeer trough', a NW-SE striking synclinal structure, in which the Slochteren Sandstone Formation is located much deeper than

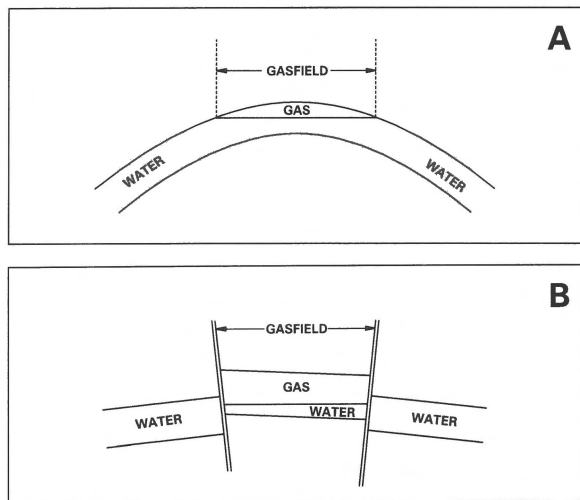


Fig. 3. Reservoir/aquifer boundaries. a) Dip-closed structure. b) Reservoir bounded by sealing faults.

in the gas field. On both the east and west sides of the trough this depth varies between 2900 and 3100 m. At the trough axis, the Slochteren Sandstone is situated at a depth of over 3400 m. From regional data it is known that burial to such a depth causes the sandstone to be less porous and permeable, resulting in a low aquifer transmissibility. Therefore, pressure communication between the gas field and the westernmost part of the aquifer is expected to be slow.

North of the field, the aquifer is situated at gradually increasing depths. The Rotliegend formation is shaped as a sedimentary wedge thickening from basin margin (alluvial fan deposits in SE) towards the basin centre (desert lake environment in NW). Also the increase in the amount of shale beds and thus the rapid decrease of the net sand thickness can be attributed to this facies change. The multitude of shale beds intercalated with the sandstone beds may, in combination with existing faults, form barriers to lateral pressure communication between the gas field and the aquifer. Moreover, analysis of levelling data and subsurface pressure data has shown that vertical communication between gas-and/or water-bearing sand beds separated by shale beds is also severely restricted.

In a southerly direction, the thickness of the Rotliegend formation decreases. The sandstone is

present in separate fault blocks that are also gas-bearing (e.g., the satellite fields Annerveen, Vries, Roden, Blijham). Aquifer effects may occur here too, albeit to a far lesser extent than on the west flank of the Groningen field, because of the proximity of the (partially) sealing faults indicated in Fig. 2.

At the eastern margin of the field, the potential aquifer is bounded by a major sealing fault system at reservoir level: the Eems fault. The Rotliegend beds on either side of the fault are not in communication, which is confirmed by pressure data from the Groothusen field, on the German side of the fault. These data indicate a pressure regime that is different from that in the Groningen field. There are also differences in the depths of the gas/water contact and in the gas composition.

Levelling surveys

Since the start of the gas production in Groningen in 1963, precision levelling surveys have been conducted regularly. As the cumulative gas production increased, the survey network and the measuring frequency were adjusted accordingly. The survey network is calibrated with subsurface base points (underground benchmarks) installed at a depth of approximately 40 m by the Survey Department of the Ministry of Public Works (Meetkundige Dienst van Rijkswaterstaat). These base points are located well outside the subsidence bowl.

The measuring frequency has been tuned to the expected surface subsidence. In 1980 it was decided to monitor a coarse grid annually (Limited Levelling Survey, 800 km, 1000 benchmarks) and to monitor a denser grid every six years (Extensive Levelling Survey: 1400 km, 2600 benchmarks). The distance between benchmarks along the various traverses is on average about 1 km. All benchmarks have been registered in the data base of the Survey Department of the Ministry of Public Works.

NAM subcontracts data gathering to surveying contractors, who perform the measurements following guidelines on measuring methods and tolerances for second-order levelling surveys. Adjustment of the levelling network by variation of coor-

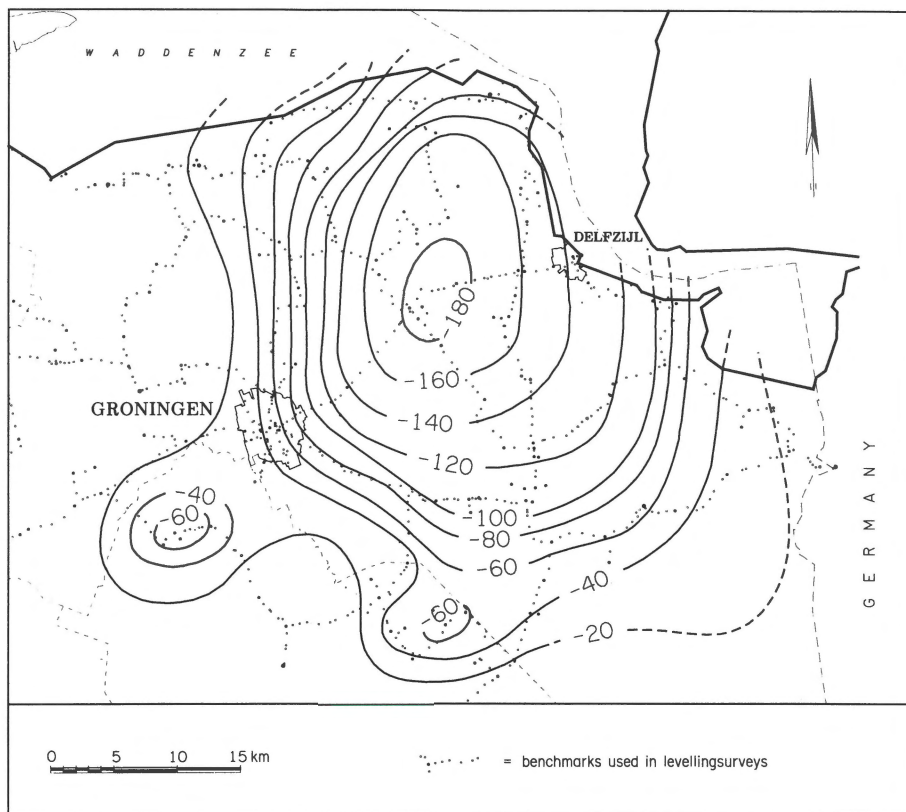


Fig. 4. Contour map showing surface subsidence in mm since 1964, deduced from the 1990 levelling survey.

dinates is carried out by NAM. After the internal accuracy has been checked with a 'free adjustment', the benchmark elevations are computed by means of a final adjustment. The Survey Department subsequently makes its own independent calculations. The accuracy of determining benchmark elevations in this manner is around $1 \text{ mm}/\sqrt{\text{km}}$.

The results of the levelling surveys are issued to the provincial authorities, the State Supervision of Mines and the Survey Department of the Ministry of Public Works.

Figure 4 shows the contour map for surface subsidence resulting from the 1990 Limited Levelling Survey. Surface subsidence since 1964 (first NAM levelling survey) amounts to approximately 18 cm in the centre of the bowl. The impact of satellite fields, which started producing later than the Groningen field, on the shape of the bowl can be clearly distinguished.

Levelling survey data reveal some aquifer activ-

ity, which up to now is restricted to the areas directly east and west of the gas field. This is expressed by a subsidence bowl that is slightly wider than might be expected on the basis of a pressure drop in the gas field alone. The aquifer activity is well demonstrated by the results of the levelling data in areas around the city of Groningen and east of Delfzijl.

Since the extent of the observed aquifer activity is still very limited and because the aquifer does not significantly support the reservoir pressure in the gas field, it is not surprising that the effects are not immediately apparent from the pressure data that are being recorded regularly in the gas field. Moreover, the amount of data available from wells outside the actual gas field is rather small.

Analysis of levelling survey data collected for several decades has demonstrated a linear relationship between the compaction of the reservoir rock and pressure drop (cf. example in Fig. 8).

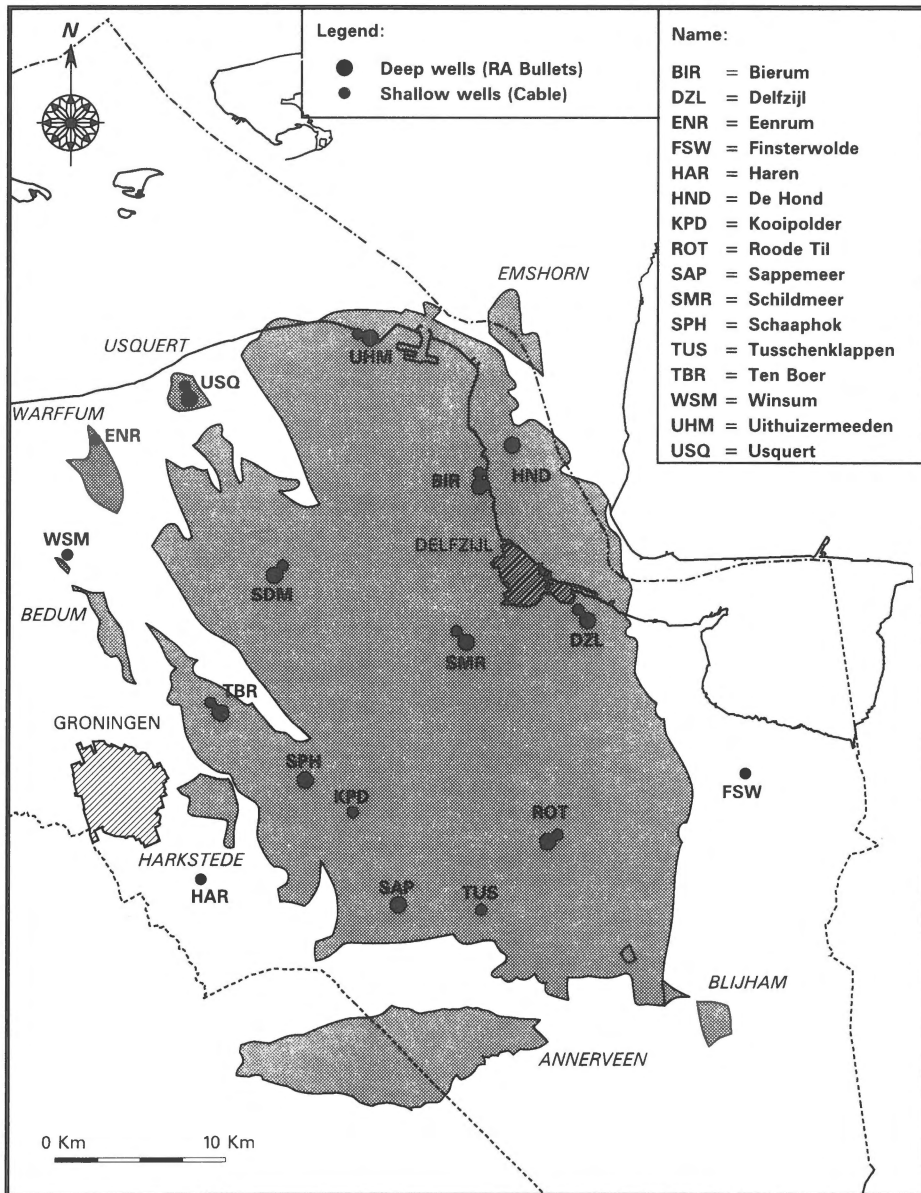


Fig. 5. Compaction observation wells in Groningen.

Compaction monitoring

The surface subsidence determined by levelling surveys may be the resultant of various components:

- Settlement of the object onto which the benchmark has been bolted (house, church, bridge, etc.) due to its own weight, depending on the type of foundation and the local soil conditions.
- Natural compaction of the unconsolidated sediments of Holocene, Pleistocene and Late Tertiary age. In comparison, natural compaction of the deeper consolidated sediments is considered to be negligible. Moreover, any compaction in the deeper sediments will equally affect the elevation of the base points used for calibration.
- Compaction of the Holocene as a result of

changing hydrological conditions (adjustments of the water level, etc.).

- Surface subsidence resulting from mining activities (e.g., gas production).

To enable any statement to be made on surface subsidence resulting from gas production, the results of the levelling surveys should be corrected for all other effects. Such corrections may differ from area to area and even from benchmark to benchmark, depending on soil conditions, water-level management and the foundation of the benchmark. Generally in the Province of Groningen, the amount of subsidence resulting from factors other than gas production ranges between 0 and 4 mm per year (NAM, 1991). In the preparation of subsidence contour maps the correction is largely achieved by focusing attention on the displacement behaviour of stable (well-founded) benchmarks.

Shallow compaction

In the early seventies, NAM started a project to monitor the compaction of the shallow sediments between 10 and 400 m depth in specific observation wells. This compaction occurs in sediments consisting of sand and clay beds of Pleistocene and Late Tertiary age and is at present recorded daily in fourteen shallow observation wells distributed over the Province of Groningen (Fig. 5). As stated earlier, natural compaction of the consolidated sediments in the interval between 400 m and the top of the reservoir is considered to be negligible in comparison.

The principle of the measurement is shown in Fig. 6. Surface equipment is fixed to a concrete substructure founded on Pleistocene sands to prevent uneven settlement. The measuring equipment consists of a balance bar, to which a cable is clamped that is connected on one side to an anchor weight at the bottom of a 400 m deep well and to counterweights on the other side to ensure a constant tension on the cable. When the distance between the anchor weight on the bottom of the well and the foundation of surface equipment changes, the balance bar will rotate around an almost frictionless turning point (knife-edge fulcrum). The

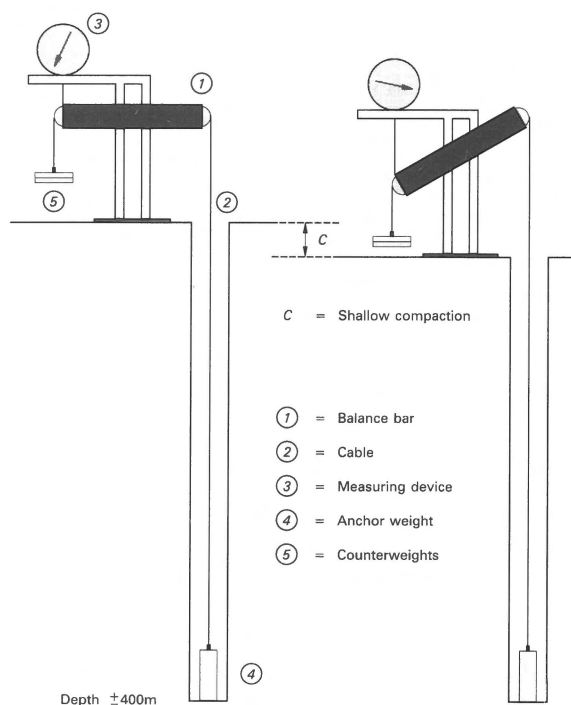


Fig. 6. Principle of cable-measurement method.

displacement of the bar, corresponding to the total compaction within the sediments between 10 and 400 m below the surface, is registered daily with a measuring sensitivity of approximately 0.05 mm. The recording devices are checked every three years and calibrated by the Netherlands Institute of Weights and Measures (NMI). Every month, an interim check is performed during which the recording cards are certified in the presence of a representative of the State Supervision of Mines.

Over the past years, the measurements were combined into an extensive data base, providing good insight into the compaction behaviour of the sedimentary complex directly underlying the Holocene surface beds. The results demonstrate a similar pattern for most locations. During the first six to seven years after installation, initial settling of the foundation occurred, expressed in the recordings by a fairly high rate of bar displacement (over 1 mm per year). After the settling phase, the actual natural compaction in the Pleistocene and Upper Tertiary beds was recorded. This compaction rate is fairly low, varying between 0.1 and 0.9 mm per

year in the Groningen area. The measurements can be plotted on graphs on a monthly, daily or even hourly basis, depending on the detail required. It was found that periodic vertical movements also occur, indicating seasonal effects (different ground-water level in summer and winter) and tidal effects near the coastline.

Holocene soil compaction, on average between 1 and 3 mm per year in The Netherlands, may have a dominating effect on the subsidence behaviour of objects that are not founded on Pleistocene sand. The reason for this is that Holocene soil layers are very unconsolidated, of an inhomogenous composition and are susceptible to compaction when loaded or subjected to changes in ground-water level. This compaction, however, is not included in the daily recordings since it occurs mainly in the soil beds above the foundation of the measuring equipment at approximately 4 to 12 m below surface.

Deep compaction

In eleven deep observation wells, compaction can be recorded in situ. The specific observation wells are distributed over the field as shown in Fig. 5.

The first measurements were carried out in 1968 using equipment that was sophisticated at the time, although still in a prototype phase. It took until 1973 before the measuring method and the equipment had been tested and improved to such a degree that the acquisition of useful data could start. Although the measuring method has remained virtually unchanged, data-processing techniques have improved dramatically since then.

In the deep observation wells, radioactive sources (3.7 MBq Cesium-137) were placed at regular 10 m intervals in the reservoir. By periodically measuring the relative displacement of these sources using a four-detector gamma-ray logging tool, the amount of compaction and the compaction coefficient (C_m) of the rock can be measured in situ (Fig. 7).

In a few wells, the sources were placed not only in the Slochteren Sandstone, but also in the directly underlying Carboniferous and the directly overlying Ten Boer Formation, thus enabling compari-

son of the compaction behaviour of the different formations. When the measurements were compared, it was found that, except in some sand/silt lenses, no noticeable compaction had occurred in the shales directly above and below the reservoir. This result was used to calibrate the recording equipment under in situ conditions, which was necessary because it had been found that surface calibration of the logging tools was prone to disturbance during the logging operation.

The deep observation wells are distributed over the entire field, incorporating all lithologies (shale, sandstone, well-cemented sandstone and conglomerates), thus enabling an attempt at characterising the compaction behaviour of every type of rock separately. The measurements show that compaction behaviour is indeed strongly lithology-dependent and that, contrary to the commonly held belief, it is much less affected by the porosity of the rock. The data also show that the C_m , determined in situ, is in agreement with the values deduced from history matches (in which the results of subsidence calculations are compared with the subsidence development observed since the start of gas production). The in situ values are considerably lower than was shown by laboratory experiments. It is also confirmed that the relationship between the pressure drop in the pores of the reservoir and the ensuing compaction is virtually linear (Fig. 8).

Reservoir model

The reservoir model on which the current subsidence prognosis is based, is the result of the most recent geological information obtained from 3-D seismic surveys, core studies and in situ measurements. For the calculation of reservoir compaction and the resulting surface subsidence, the following essential input parameters are used:

- reservoir geometry (areal extent, depth and thickness);
- pressure depletion distribution in the reservoir;
- rock properties, e.g., uniaxial compaction coefficient C_m and permeability.

In the model, the gas field and the aquifer are divided into grid blocks with variable reservoir

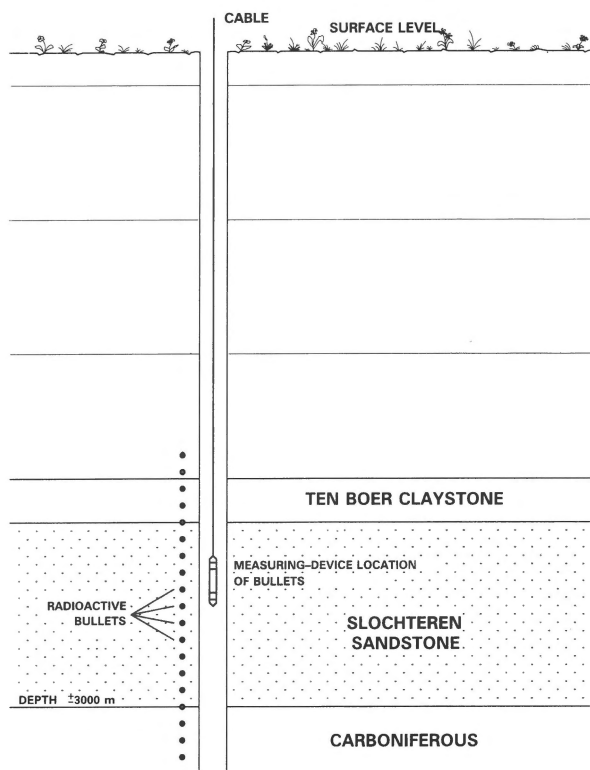


Fig. 7. In situ compaction measurement.

characteristics. For an optimum representation of the gas field and aquifer, the areal dimensions of these blocks should not exceed $1500 \times 1500 \text{ m}^2$, depending on the variation of rock properties in the area under consideration.

The depletion process in the water-bearing part of the Slochteren Sandstone may progress considerably more slowly than in the overlying gas-bearing zone as a result of the presence of partially sealing faults and/or shale layers in the reservoir, hence pressure lags can occur. Therefore a vertical division of the reservoir into layers has been incorporated in the model. The blocks in each layer have individual characteristics (thickness, depth, C_m , pressure drop, etc.).

The reservoir compaction within each block is calculated assuming isotropic, linear elastic reservoir deformation. The surface deformation induced by the compaction of each grid block is calculated using the 'nucleus-of-strain' technique with linear elastic deformation of the nonreservoir host

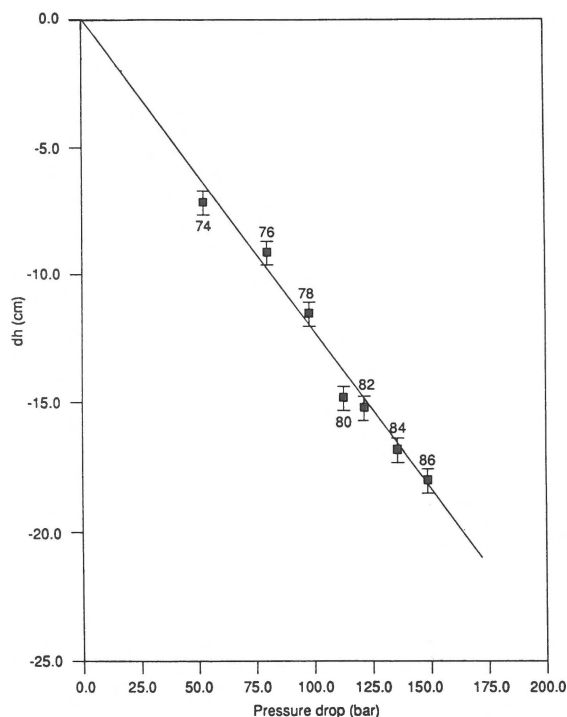


Fig. 8. In situ compaction (dh) vs. pressure drop in well Ten Boer 4. Data points shown represent measurements at two-year intervals. The slope of the inferred linear trend yields the compaction coefficient C_m .

rock (Geertsma & Van Opstal 1973) and a rigid-basement (Van Opstal 1973) depth, below which all deformations are assumed to be zero. The total subsidence for each surface grid block is determined by summing the contributions from all of the compacting reservoir blocks.

To assess future aquifer behaviour, a study was made using local and regional geological information (well data, 3-D seismic, geological reservoir model) together with data deduced from the subsidence history. The resulting reservoir simulation model, used for calculating the pressure drop in the gas field and the aquifer as a function of gas production, was calibrated by history matching with the evolution of the subsidence bowl. The model also incorporates the satellite fields Annerveen, Bedum, Blijham, Roden, Usquert, Vries, Warffum, Winsum and their related aquifers. The results of the study confirm that the extent of aquifer depletion decreases rapidly with increasing distance

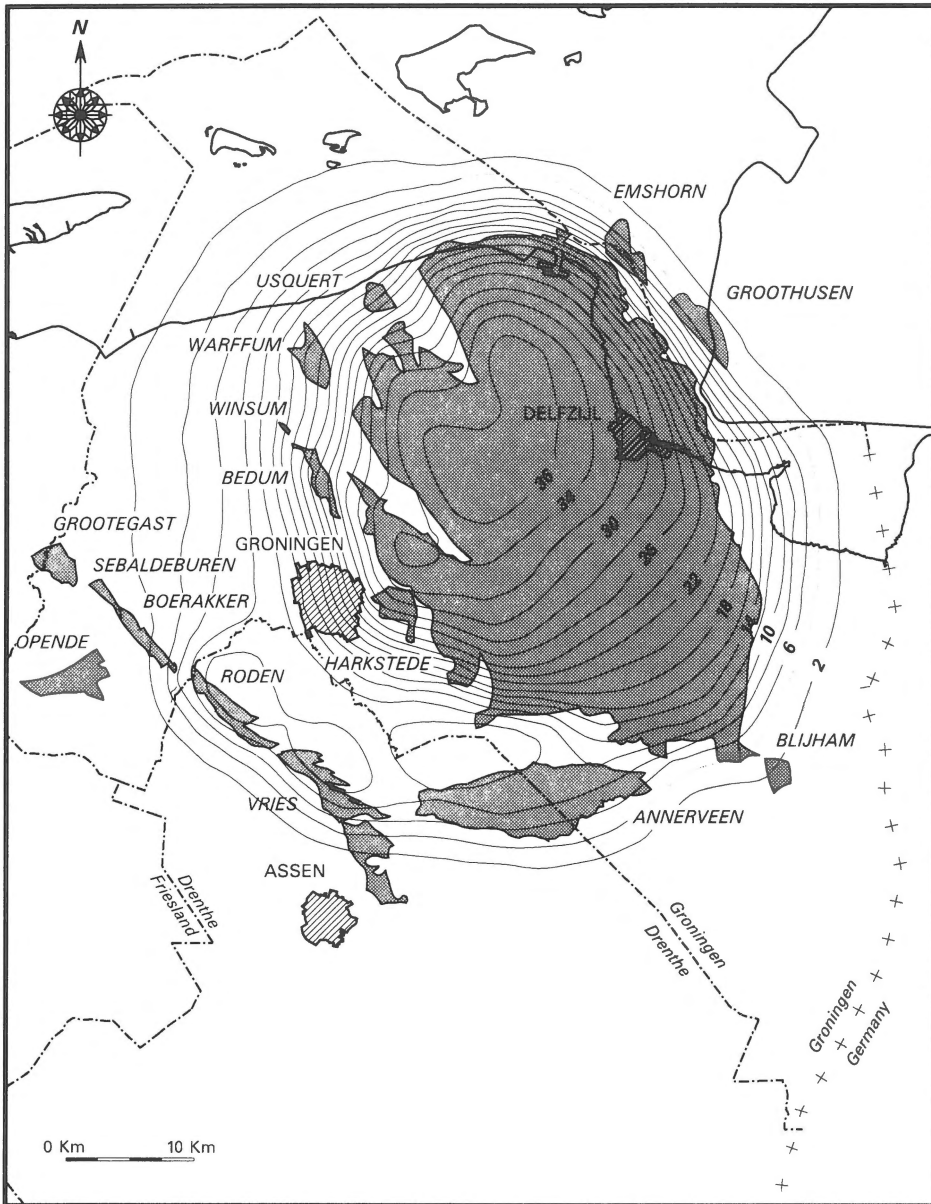


Fig. 9a. Prognosis for surface subsidence (cm) in the year 2050.

from the gas field. The history matches based on field data also indicate that the area subjected to aquifer depletion has expanded only slowly over the years. Since the availability of aquifer field data is still rather limited, only qualitative statements can be made on future aquifer behaviour. It is to be expected that the process of pressure equalization between the aquifer and the depleted gas field will

continue for a considerable time (a few hundred years) at a very slow rate, even after gas production has been stopped. In the aquifer the Rotliegend formation is situated deeper than in the gas field, and as rock mechanical properties vary among other things with depth, C_m will also be affected. Therefore the amount of subsidence above the

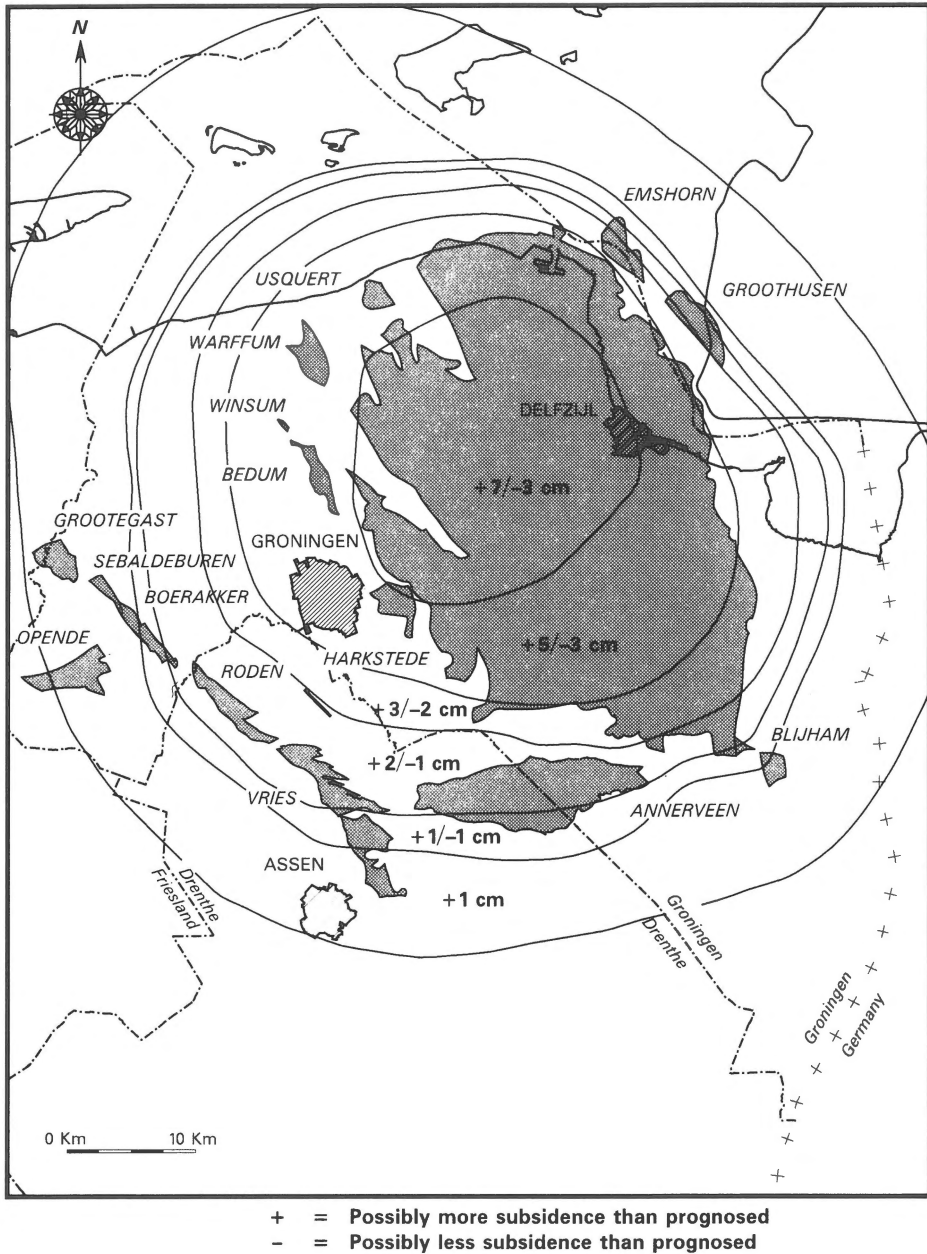


Fig. 9b. Confidence intervals for prognosis in Fig. 9a.

aquifer will be considerably less than the maximum value predicted for the gas field for the year 2050.

In comparison with the gas field the aquifer is too small to support the gas pressure. Any aquifer activity will therefore not noticeably affect the compaction process in the gas-bearing part of the reservoir.

Resulting prognosis

Figure 9a shows the prognosis of surface subsidence as a result of the production of natural gas, for the year 2050. In the preparation of this prognosis it was assumed that, in the forthcoming years, the gas pressure in the reservoir will develop according to

the Gas Sales Plan 1989, in which the expected gas sales until 2015 are outlined. In the calculations it is also assumed that around 2050 the reservoir pressure will have dropped to around 20 bar (1 bar = 10^5 Pa). The resulting surface subsidence in the deepest part of the subsidence bowl is currently predicted to be 36 cm.

The accuracy of any prognosis depends strongly on the uncertainties in the input parameters. To determine the effect of these uncertainties, a sensitivity analysis was performed, resulting in the 95% confidence intervals pictured in Fig. 9b.

The confidence intervals show local variations over the Groningen gas field, the satellite fields and the adjoining aquifer. These variations result from the distribution of sites from which the information is obtained; these are not distributed evenly over the entire area. For instance, far more well and seismic data are available for the gas field than for the aquifer. Hence the reservoir model for the gas field is defined more accurately. Proportionally, the uncertainty in the prognosis is smallest there.

Changes in the Gas Sales Plan will not seriously affect development of the subsidence bowl, shown on the contour maps presented in this paper; only the time at which a given situation will occur may change. After the year 2050, new production technologies may enable a further reduction in gas pressure in the reservoir. Additional surface subsidence as a result of this is expected to be limited to a maximum of 1 cm in the centre of the subsidence bowl. The implications of such plans will be taken into account in future prognoses.

Very slow pressure equalization between the gas field and the aquifer after the end of gas production, will not result in more subsidence over the gas field, but areas outside the gas field will indeed be affected. The aquifer-depletion model used in the present prognosis is based on the most probable scenario given the information currently available. More data (e.g., C_m and pressure distribution in the aquifer) will be required to improve the model.

Conclusions

1. It is currently foreseen that the surface subsidence as a result of gas production in the Province of Groningen will reach a value between 33 and 43 cm in the centre of the field around the year 2050 (95% confidence interval). The most probable value is considered to be 36 cm.
2. It is expected that future reservoir compaction (and the surface subsidence at the deepest point of the bowl) will continue to follow pressure reduction in the reservoir in a virtually linear way.
3. The associated aquifer is subject to pressure depletion because there is (limited) communication with the field. Surface subsidence will therefore also occur in areas above this aquifer, but the pressure equalization will progress very slowly and will probably take a few hundred years. Although the exact areal extent of the subsidence bowl is still uncertain because of the limited availability of aquifer field data, it was established that subsidence will be considerably less over the aquifer than over the gas field.
4. The expected aquifer activity will not have a noticeable effect on the eventual surface subsidence above the gas field.

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