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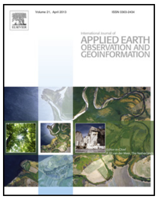

Inversion of double-difference measurements from optical leveling for the Groningen gas field

Peter A. Fokker*, Karin Van Thienen-Visser

TNO, Utrecht, The Netherlands

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ABSTRACT

Hydrocarbon extraction leads to compaction of the gas reservoir, which is visible on the surface as subsidence. Subsidence measurements therefore give information on the hydrocarbon extraction and can thus be used to better estimate uncertain reservoir parameters. Normally, optical height difference measurements are taken between benchmarks, adjusted and tested to arrive at estimated height differences (or subsequently, heights relative to a reference benchmark) and are differenced between epochs to arrive at subsidence estimates. These can subsequently be used in inversions for reservoir parameters.

We have designed, implemented and applied a new algorithm that uses measured optical height differences directly in the geophysical inversion. This eliminates the problems introduced by insufficient knowledge of the full covariance matrix of the subsidence estimates.

The procedure was applied to invert for compaction of the Groningen gas reservoir in the Netherlands. We used a linear inversion procedure to update an existing reservoir compaction field. This yielded areas of increased and reduced compaction relative to the existing compaction field, which correspond with observed discrepancies in porosity and aquifer activity.

1. Introduction

The Groningen gas field is a large onshore field in the Netherlands which has been produced since 1963. Pressures in the field have been closely monitored for reservoir management, and history matching of the reservoir model on the observed pressures has yielded a pressure distribution trend over the field consistent with the measured pressure and production data in the wells. The production of the Groningen field has caused subsidence, which has periodically been measured using optical leveling (Doornhof, 1992, 2006), in recent years augmented with satellite-based InSAR technology (Ketelaar, 2008).

Subsidence estimates are important for assessing the damage caused by, for instance, changes in groundwater levels and related intrusion of salt water in areas close to the sea. As the subsidence is a measure of the compaction in the field that results from the pressure reduction, such estimates can also be used to improve our understanding and parametrization of the subsurface. This is important not only for improving predictions of subsidence resulting from ongoing operations, but also for reservoir management. Recent studies have demonstrated the feasibility of using subsidence estimates for the quantification of aquifer activity and fault-sealing properties (Fokker et al., 2012, 2016). Other studies have highlighted the connection between reservoir compaction and induced seismicity (Bourne et al., 2014).

The present study focuses on improving the reservoir knowledge of the Groningen gas field by using the measured surface movement data obtained by optical leveling. A prior estimate of the compaction grid was available, based on the lithology, pressure depletion and porosity (Van Thienen-Visser et al., 2015). Subsidence calculated from this grid, however, did not match the values measured in a number of areas (Van Thienen-Visser and Breunese, 2015). To solve this issue we here employ an inversion to the compaction, using the measured subsidence. The inversion targets the better estimation and the reduction of uncertainty still present in the prior description. Uncertainty surrounds some of the parameters in the relationship between the reservoir depletion and the subsidence. The first one is the compaction coefficient, which depends on the rock type and porosity. There is also some uncertainty in the pressure estimates in some regions of the field, particularly in the connected aquifers, for which pressure measurements are hardly available. Furthermore, there is uncertainty in the propagation of compaction to subsidence, as the mechanical and geometrical properties of the subsurface are not fully known.

To go from optically measured height differences between benchmarks to subsurface parameters involves a number of steps.

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* Corresponding author.
E-mail address: peter.fokker@tno.nl (P.A. Fokker).

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The first is usually to estimate the benchmark heights for every measurement campaign by connecting the network to a datum, and then to calculate the extent to which these benchmarks have moved over time by subtracting the results of different campaigns. Reliable estimates require a proper propagation of uncertainty, but this propagation is often problematic, as estimated heights are commonly reported with a standard deviation only, whereas the height estimates of the benchmark locations are highly correlated and a covariance matrix is warranted. We therefore used the leveling measurement differently: we skipped the height estimation step in the geophysical inversion workflow and instead directly used the raw height difference measurements between benchmarks. Starting from a prior compaction field over time, a better estimate is then obtained with a geophysical inversion of the double-difference measurements inferred from the height difference measurements at the benchmark grid above the reservoir. This subsurface model must then be used both for estimation of historic subsidence and for predictions.

In the remainder of this paper we will introduce the Groningen reservoir and the available data (Section 2); the methodology of utilizing double-difference data (Section 3); the forward model predicting surface movement from compaction, the parametrization and the inversion step (Section 4); and the application to the Groningen gas field (Section 5). The paper closes with a discussion of the method and the results obtained (Section 6), and with conclusions (Section 7).

2. Available data for the Groningen gas field

The Groningen gas field has been in production since 1963. It is located onshore in the northeast of the Netherlands, covering the eastern part of the province of Groningen. Extensive geological, geophysical and reservoir engineering data have been used to establish reservoir characteristics such as geometry, stratigraphy, porosity and permeability. We had access to data on the pressure field for yearly dates from 1/1/1964 to 1/1/2017, obtained from a history match using a reservoir simulator. The prior estimate of the compaction grid at 9070 x-y locations for 54 time steps was determined from the lithology, pressure depletion and porosity (Van Thienen-Visser et al., 2015). The compaction was calculated using a Rate Type compaction model (de Waal, 1986; Pruiksma et al., 2015). A relation between porosity and the compaction coefficient was used, based on laboratory measurements of the reservoir rock (Van Thienen-Visser et al., 2015). We remapped the provided compaction values to locations on a regular $400 \times 400\,\mathrm{m}^2$ grid for easy manipulation. A map of the input compaction grid and the outline of the Groningen gas field in 2012 is provided in Fig. 1.

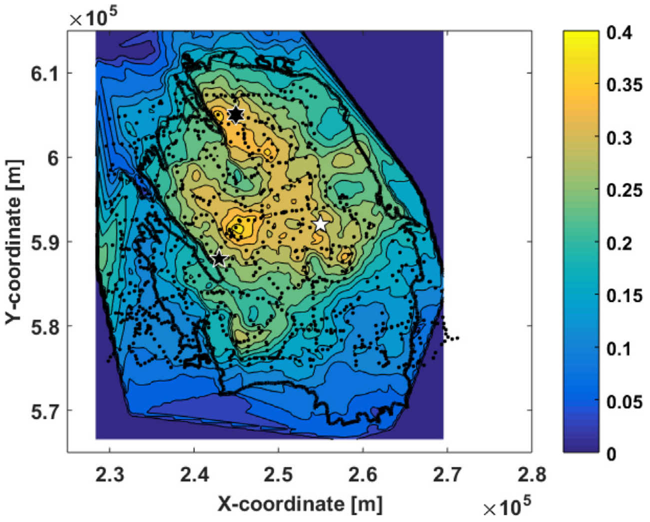

Fig. 1. Prior estimate of the compaction field of the Groningen gas field in 2013 (colour-coded, in m), outline of the gas-bearing layers (solid line) and surface locations of the benchmarks used in the study (solid dots). Cluster locations are given for Ten Boer (black pentagram), Delfzijl (white pentagram) and Uithuizen (black hexagram).

In the present study we used the raw surface movement data acquired through optical leveling campaigns. The only treatment applied to the data was an averaging of the difference measurements made for the multiple visits to the benchmarks. During a single measurement campaign, most differences were measured twice, in opposite direction; some were measured even more often. The data that we received had not been adjusted or tested.

Optical leveling campaigns have been performed many times in Groningen with different coverage. We had access to a total of 92 campaigns, dating from 1938 to 2013. More than 26,000 height differences had been measured at a total of 7995 benchmarks. In this set, 1572 benchmarks had been identified as stable (NAM, 2013) in the resulting optical leveling database.

3. Procedure to determine double-difference estimates

Usually, temporal differences of the estimated benchmark heights are used to estimate surface movement. The procedure to obtain these differences includes the integration along a path of measurements (Vanicek et al., 1980; Houtenbos, 2000). The best method is to employ an integrated procedure in which all available measurement campaigns are used and processed, taking due account of various sources of stochastic noise (Houtenbos, 2000). The estimated heights resulting from such a procedure are highly correlated and any application of them in a geophysical inversion exercise should use the full covariance matrix. This covariance matrix is, however, rarely provided, because often the outcome of the geodetic analysis is the end product. We therefore opted to use the measured height differences directly.

3.1. Principle of the method

The basic idea of our procedure is to relate a height difference measurement at a certain campaign to the height difference between the same benchmarks in the previous campaign. If this is not possible, first, a relationship is established with earlier campaigns. Then, the height difference measurement is combined with adjacent height difference measurements to see if this enables a comparison to be made with the previous campaign. The procedure is complicated by various factors: often not all benchmarks are visited in all measurement campaigns; benchmarks may have disappeared physically in later campaigns; new benchmarks may have been installed; and not all benchmarks may be stable. Furthermore, the benchmarks are not always visited in the same order, which leads to different height difference measurements for subsequent campaigns.

The procedure is best demonstrated with an example. Consider the situation of Fig. 2, where three measurement campaigns have been performed in which 12 benchmarks (BM 1 to BM 12) were visited in different configurations. The first campaign did not visit BM 2 and BM 3; in the second there was no connection between two parts of the network; in the third BM 2 was not visited.

Table 1 lists the height difference measurements that are associated to obtain double differences (DD 1 to DD 23). The first measurement in Campaign II to be compared with Campaign I (DD 1) is the height difference measurement {II: 10–7} (between benchmarks 10 and 7). This one is also present in Campaign 1 and the double difference and its standard deviation is immediately established. The second one is the height difference measurement