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NAM

Nederlandse Aardolie Maatschappij

Wadden Sea Long term Subsidence Studies – Overview report

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Summary

The 2011 extension approval of the Winningsplannen for the Dutch Wadden Sea area was granted under the condition that NAM would undertake a series of studies aimed at improving the long term predicive capability of subsidence models in this environmentally sensitive area. These studies should be delivered to the State regulator (SodM) by 1st July 2015.

Background for the requirement to perform these studies was that the Ameland field displayed a continuing surface subsidence even after pressure depletion had slowed down considerably. This behaviour was not well understood and required the introduction of a time dependent mapping function between pressure change in the Rotliegend gas reservoir and subsidence in order to mitigate the mismatch between model predictions and subsequent survey measurements. Whilst this time dependent function allowed for a better fit to the measured data, in the long term the use of a well characterised but unidentified diffusion process is unsatisfactory for both NAM, the regulatory authorities and other stakeholders.

This report summarises the key results and conclusions of the studies undertaken in the period 2012-15.

The key conclusions are:
[1] The time dependent subsidence effect is real and not an artefact of noise and uncertainty in the geodetic data.
[2] Time dependent creep behaviour is observed and predicted to be associated with compaction of the sandstone in the gas reservoir, pressure diffusion and partial depletion of the aquifers as well as flow of the overlying salt. Salt flow in isolation appears not to be a plausible explanation for time dependent subsidence, while the compaction and pressure depletion models remain viable hypotheses within the possible uncertainty ranges.
[3] Deformation experiments of Rotliegend reservoir corematerial under in-situ conditions show that reservoir compaction involves a porosity-dependent element of in-elastic deformation through graincracking and an elastic (reversible) element. The contribution of non-reversible inelastic strain increases with porosity.
[4] The subsidence modelling precision can significantly be improved by taking correlation structures in the surveillance data into account. By appropriately differencing the survey data, biases as well as complexities in covariance structures can be reduced. In addition methods have been developed for identifying and handling outlier measurements, data reduction techniques for large geodetic data sets, as well as improvements to processing and including GPS data.
[5] An improved and more formal statistical method is proposed to validate and test the quality of subsidence predictions against the survey data. It is based on a Bayesian framework that can provide a coherent structure for the creation of initial models built on prior information, the objective updating of these models using collected geodetic data and the quantitative testing of future predictions. A prototype inverse modelling workflow has also been developed [Park et al., 2015].

The improved quantification of noise and uncertainties as well as the better understanding of the physical processes developped in this study will lead to an improved subsidence modelling, prediction and monitoring workflow.

Introduction and Problem Statement

Fluid extraction from subsurface porous reservoir formations (e.g. gas, oil or water) causes a reduction in the pore fluid pressure. In response to this decline in pore pressure the reservoir rock compacts. This in turn deforms its surroundings and causes displacements of the ground surface above, both lateral and vertical. The downward vertical displacements are referred to as subsidence. Surface subsidence can have consequences for civil infrastructure and can have an impact on the environment, a particular concern for densely populated and/or sensitive environments such as low lying wetlands and marshlands. In the Netherlands, a densely populated country of predominantly low lying wetlands, gas production induced subsidence is therefore a matter of concern for the authorities and the public. This has led to a range of legal and regulatory requirements with regard to the rate, magnitude, measurement and modelling of subsidence above Dutch gas fields, with which the field operators must comply.

The issue of subsidence is an important part of 'License To Operate' [LTO] agreements in the Netherlands. These require that, within certain limits, the subsidence process is well characterised, predictable and, most importantly, controllable. This fundamentally relies on the validity and fidelity of the underlying physical models. This includes their functional form as well as the accuracy of the input parameters derived from measured data.

The basic method for modelling and prediction of subsidence relies on simulating the pore pressure changes due to production, using reservoir simulations that are constrained by well pressure measurements. This pressure field is then used to determine the resulting compaction in the reservoir via a simple relationship between pore pressure and volume strain, which in its simplest form assumes a linear relation between the volume strain and pressure change. A mechanical representation of the overburden is then used to calculate the resulting surface displacements. The simplest is to represent the subsurface as a homogeneous, isotropic, linear elastic half-space.

The actual surface displacements are monitored using geodetic survey methods. Historically this was done by performing levelling measurements at a number of fixed locations, but more recently this was supplemented with satellite based techniques (i.e. GPS, InSAR) particularly in an onshore environment. A comparison can then be made between predicted and measured displacements.

It is relatively simple to achieve acceptable matches between subsidence models and survey measurements where the constraining data have relatively large variances, limited spatial and temporal coverage and when first order accuracy is sufficient. However, as constraining data accumulated and accuracy improved over time, mismatches between predictions and measurements became more apparent, revealing the limitations of the basic subsidence models. Early mismatches could be rectified by the modification of parameters. An additional strategy has been the introduction of new parameters. This however needs to be pursued with caution, as the introduced extra degrees of freedom can potentially reduce long-term predictive power.

As the subsidence modelling and prediction process developed, the parameter complexity increased. The poromechanical compressibility relationship that maps the pore pressure change field into volume strain is no longer taken to be a simple constant, but now depends on the porosity, which itself is a three-dimensional field. A rigid basement at variable depth was introduced to mimic a steeper sided subsidence profile [van Opstal, 1974]. To account for an apparent increase in subsidence rate with pressure change, a bilinear poromechanical compressibility was introduced (initially stiff, transitioning through a threshold to a less stiff relationship). Eventually finite element models began to be adopted for subsidence modelling. This freed the models from having to assume that the constitutive properties in the entire subsurface have to be uniform or even elastic. It led to models with heterogeneous elasticity structures, complex visco-elasto-plastic flow laws being applied to salt formations, and multiple calibration scaling factors. This introduced a large number of weakly constrained parameters, all of which could be adjusted and calibrated in an effort to match models to historic subsidence data, but which could lead to erroneous subsidence predictions as predictive power is eroded. Additional parameter degrees of freedom provide increased flexibility but relax constraint. Great care and careful insight should guide the expansion in parameter degrees of freedom. Without an objective statistical measure of model fit this was very difficult to achieve.

A mismatch between subsidence model predictions and subsequent survey measurements for the Ameland gas field led to question the ability to accurately characterise, predict and control subsidence in this region. In an effort to match historic data in the past, key parameters had been adjusted to values that were outside their expected range. These provided reasonable matches to existing subsidence data but turned out to have lower predictive value than desired. A particular concern was that most models resulted in subsidence under-predictions. These repeated under-predictions required an explanation.

Concerns were focusing on three areas:

[1] Subsidence above the central reservoir was continuing even though the pressure depletion rate had slowed down significantly.
[2] The observed steepness of the edges of the subsidence bowl was bigger than predicted.
[3] The apparent reservoir poromechanical compressibilities required to match the geodetic data substantially differ from laboratory compaction measurements.

A review identified a number of inaccuracies in the reservoir simulations and geomechanical modelling workflow. However, even after these errors were rectified, the subsidence model for Ameland still had mismatches between predicted and measured subsidence and the continuing subsidence above the central Ameland field (“Naijleffect”) was unexplainable without the adoption of a time dependent mapping function between pressure change and subsidence. The simplest and most physically universal mapping of this type is an exponential time decay function.

Still, the observed behaviour cannot easily be explained by any of the processes in the standard subsidence modelling workflow, because these apparent long term time decay processes, in the order of years, are not well captured and predicted by the present reservoir simulations or (elastic) rock mechanics.

There are though, numerous other parts of the system that could potentially exhibit a time-decay asymptote towards equilibrium when the system is perturbed. The very universality of disequilibrium processes makes it difficult to precisely identify which part or parts of the system govern the decay time scale. The influence and magnitude, however, can be clearly determined from the available data and applied to prediction modelling. This was the methodology that has been followed to provide much improved fits to the temporal subsidence data while also allowing the use of material parameters consistent with laboratory observations, and is similarly applied to subsidence predictions.

However, in the long term the use of a well characterised but unidentified diffusion process is unsatisfactory for both NAM, the regulatory authorities and other stakeholders.

Hypotheses

Because of this discrepancy, a series of studies have been undertaken with the aim to improve the subsidence prediction procedures; identify if there are previously unidentified physical processes that can become dominant or major contributors to subsidence in the future and identify mechanisms that are responsible for discrepancies between subsidence predictions and observations.

It was realised up front that there is a wide range of possible mechanisms that could yield apparent time dependent subsidence behaviour which makes unambiguous identification extremely challenging. Hypotheses were proposed and where possible, tested to see if they could be accepted or rejected. The following were viewed as the key hypotheses:

1. The time dependent subsidence was an artefact and merely an apparent trend caused by noise structure and uncertainty in the surveilance data .
2. The time dependent subsidence was caused by salt flow.
3. The time dependence subsidence was caused by slow depletion in underlying aquifers not captured in the reservoir simulation.
4. The time dependent subsidence was due to anomalous pressure diffusion which could cause pressure equilibration to occur over longer time scales.
5. The time dependent subsidence is due to time dependent poromechanical compaction in the reservoir rock.

Discipline Studies

A series of studies were executed with the purpose of improving the characterisation of the various workflow components and of improving understanding and quantification of the uncertainties they introduce.

The key areas that have been addressed as part of these studies are:

- Pressure depletion in the aquifer below and adjacent to depleting gas fields
- Reservoir rock compaction in response to pressure depletion
- Improving the measurement of in-situ compaction
- Salt flow in response to compaction of an underlying gas reservoir
- Improvements for processing and preparing subsidence measurements for geomechanical model calibration
- Statistical testing/validation procedures of model results versus observations

Reservoir simulations typically have a large number of model parameters and a relatively small number of constraints. This yields a non-unique range in pressure change distribution and magnitude rather than a single solution. Of particular importance for determining the range of long term time dependent behaviours, is the behaviour of slow pressure diffusion into underlying and lateral aquifer zones over an acceptable time window [Seeberger 2015]. The impact of the more structured depletion associated with anomalous diffusion is also a potential mechanism for explaining the apparent anomalously long time scales required for poromechanical equilibration [Mossop, 2015a].

Rock poromechanical compressibilities for the Wadden Sea area were determined under in-situ conditions for the first time. The deformation experiments were carried out on core plugs obtained from the Rotliegend sandstone reservoir in the Nes field. Sample strains were measured over extended time intervals to provide data on time dependent compaction processes. Both uniaxial and stress free strain boundary conditions were applied, so that deviations from isotropic strain could be determined. The experiments show that the reservoir rock displays both inelastic (non reversible) as well as elastic (reversible) behaviour. The in-elastic behaviour is primarily caused by grain-cracking. In addition all samples show a time-dependent creep phase [Hol et al., 2015]

An improved workflow for interpreting in-situ compaction measurements from the Groningen gas field (thought to be potentially analogous) has been developed as a method of providing additional data/constraint [Kole, 2015]

With respect to geomechanical modelling, apparent discrepancies between subsidence displacement volumes and in-situ volume strain were raised as a potential concern by the project review panel. This was investigated and a corrected Geertsma type solution was derived [Mossop, 2015b]. Similarly concerns were raised as to the potential impact of inelastic poromechanical compaction of the reservoir rock on the modelling workflows. On analysis it is found that the constitutive law that governs the compaction process does not significantly alter the results for reservoirs that are not laterally extensive [Mossop, 2015c].

Research work on the possible significance of viscoplastic flow in salt in response to compaction in an underlying reservoir indicates that it could have a measurable and time-dependent effect on both the depth and extent of the subsidence bowl. [Marketos et al., 2015].

A number of potential explanations for the discrepancy between subsidence models and measurements can be proposed. Perhaps the most basic hypothesis would be that it is merely an artefact of noisy data and model uncertainty, and that the apparent mismatch is acceptable within the confidence bounds. This may at first seem trivial, but it highlights the more fundamental problem as to how well the noise models and uncertainties involved in the subsidence modelling and monitoring are understood and quantified, and equally important, how to objectively measure an acceptable or unacceptable match.
A research study was conducted with the aim to estimate the structure and scale of spatially and temporally correlated noise in levelling data as well as its impact on geomechanical models [Samiei-Esfahany & Bähr, 2015] The conclusion was that the modelling precision can significantly be improved by taking correlation structures into account.By appropriately differencing the survey data, biases as well as complexities in covariance structures can be reduced. A rational methodology for identifying and handling outlier measurements and data reduction techniques for large geodetic data sets were also proposed . Improved methods for processing and including GPS data have also been studied and reported on [Williams, 2015].

Statistical specialists have analysed how a more formal, statistical approach to the subsidence modelling, prediction and monitoring workflow could be implemented. They have proposed that a Bayesian framework can provide a coherent structure for the creation of initial models built on prior information (e.g. from laboratory experiments), the objective updating of these models using collected geodetic data and the quantitative testing of future predictions. A prototype inverse modelling workflow has also been developed [Park et al., 2015].

The results of the various discipline studies are summarised in some more detail below.

Summaries of the Discipline Studies

Reservoir Engineering

The report describes the prediction of reservoir pressures versus time in the gas bearing part and underlying water bearing part of the reservoir (aquifer) as a result of gas production in the Wadden Sea area. An assessment of gas and aquifer pressure depletion and its associated uncertainty range is an important input into the estimation of subsidence in the Wadden Sea area.

This report (Seeberger 2015) is an update of an initial 2005 report “Prediction of reservoir pressures in the Wadden Sea area” which was submitted prior to start of production in the Wadden Sea gas fields (Seeberger, 2005). The 2005 report was based on modelling of producing gas fields to the south of the Wadden Sea area, which served as analogues for future depletion of Wadden Sea gas fields.

Based on additional well pressure data as well as insights obtained from reservoir and compaction modelling simulation work, the following updates have occurred in the 10 years up to 2015:

- The Ameland gas field was included in the Wadden Sea pressure depletion prediction area.
- Aquifer pressure depletion in lateral and vertical direction with respect to depleting gas reservoirs is in general lower than previously assumed. In 2005 it was conservatively assumed that no residual gas would be present in the aquifers. However the measured aquifer pressures in recent wells as well as the results of modelling an aquifer production test are more consistent with the presence of residual gas. The presence of residual gas decreases associated pressure depletion of aquifers because a small aquifer pressure drop will be compensated by expansion of the residual gas. The expanding gas will in turn block pore throats, further reducing the effective water permeability in the aquifer[1].
- Aquifer pressure depletion in the vertical direction with respect to depleting gas reservoirs (bottom aquifer) is likely much lower than previously assumed. Formation pressure measurements in infill wells in depleted reservoirs in the area since 2005 showed near-virgin to virgin bottom aquifer pressures. This is caused by the (sometimes fine) layered nature of the reservoirs, where the presence of thin low-permeable streaks hamper vertical pressure transmission.

The following conclusions from the 2005 report remain valid:

- Permeability in aquifers is lower than in the gas bearing reservoir part leading to more

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[1] Depletion of aquifers occurs due to aquifer water flowing into the lower pressured gas reservoir. The volume of aquifer water moving into the gas reservoir hardly changes whether residual gas in the aquifer is present or not. However, if residual gas is present in the aquifer the outflow of aquifer water is almost fully compensated by expansion of residual gas and pressure depletion is severely slowed down . In contrast, in the absence of residual gas, the outflow is not compensated by the very limited expansion capacity of water alone, leading to faster and deeper depletion.

restricted mobility of aquifer water. The lower permeability is caused for example by diagenetic growth of clay particles in the pore space. This means that aquifers are expected to remain at a more elevated pressure level due to the lower permeability of the aquifer. The pressure difference between gas reservoir and aquifer is forecasted to exist for a significant period of time beyond the end of gas production.
N.B.: The presence of residual gas in aquifers and poorer vertical connectivity in aquifers significantly increases the time to pressure equalization between gas and aquifer reservoir, i.e. large pressure difference can exists far beyond the time of interest.
- Watering out of gas production wells is not expected on an early and large scale. This will result in high recovery factors and low gas pressures at abandonment. However perforations close to the GWC with an adjacent connected lateral aquifer and good reservoir properties can water out prematurely. If water production negatively impacts gas production the (partially) water producing perforations can be shut off and depletion of the gas reservoir can continue via perforation higher up in the gas reservoir formation.

In summary this leads to the following conclusions with respect to depletion:

Depletion levels		
	Good reservoir	Poor reservoir
Gas reservoir	High	Medium/High
Lateral aquifer	High (close to the gas reservoir) Medium (farther from gas reservoir)	Low
Bottom aquifer	Low/Medium (close to gas reservoir) Low/None (deeper part of aquifer)	Low/None

Rock Mechanics

This work investigates the constitutive behaviour of the Permian Rotliegend sandstones, the gas reservoir in the Wadden Sea area. The investigation focusses on the magnitude and temporal nature of the strain response to pore pressure changes, as well as the nature of the compaction mechanisms that operate in these reservoirs, with the aim to arrive at better constrained predictions of subsidence rate and magnitude. A large number of triaxial and uniaxial pore pressure depletion tests were executed, using core material obtained specifically for this study from the Nes gas field which straddles the Dutch Wadden Sea coastline, at a depth of about 3700 m.

The laboratory measurements show that pressure depletion results in total strain of 5×10^{-3} - 15×10^{-3} over the duration of the experiment of 5-12 weeks, with approximately 80% of the total strain response being close to instantaneous, and 20% time-dependent. The time-dependent behaviour shows a gradual decrease in strain rate with time. The response is dependent on porosity and stress state, but seems rather insensitive to temperature, and pore fluid composition. The trends seen in the elastic properties parameterized on the basis of the mechanical data show that stiffening occurs during depletion. This clearly suggests that a densification mechanism operates, and hence that a portion of the strain measured is inelastic. Analysis shows that samples with a high porosity exhibit up to ¾ inelastic strain (i.e. ¾ permanent strain, assuming no viscoelastic response), and low porosity samples show an opposite elastic-inelastic balance (¼ inelastic strain). Samples with a porosity of 20%, which is representative for the Permian sandstone reservoir considered here, exhibit a total strain response that is roughly ½ elastic and ½ inelastic. Depletion path constants vary between ~0.6

and ~0.8, and decrease as depletion progresses.

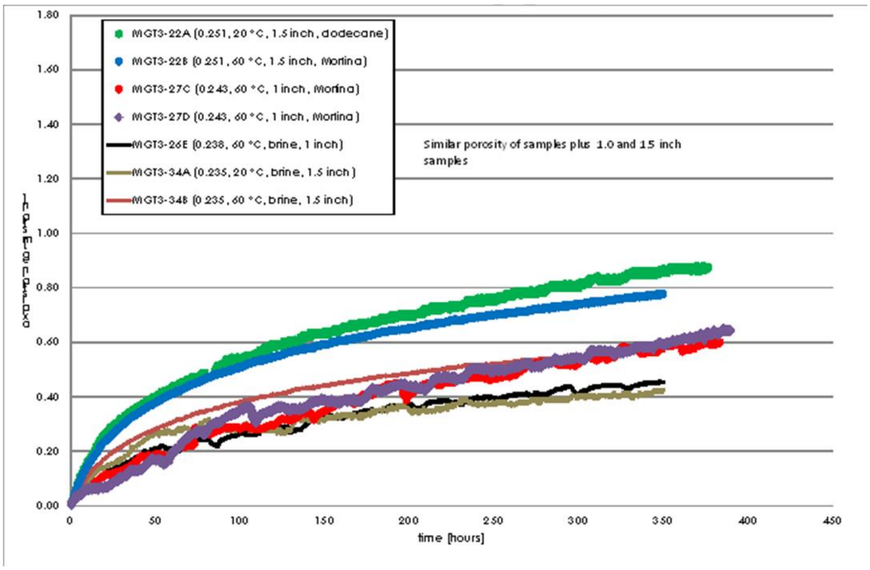

Fig. 1 Axial strain attained during the 300 hrs hold period under uniaxial strain conditions as a function of time for samples with aqueous and non-aqueous pore fluid.

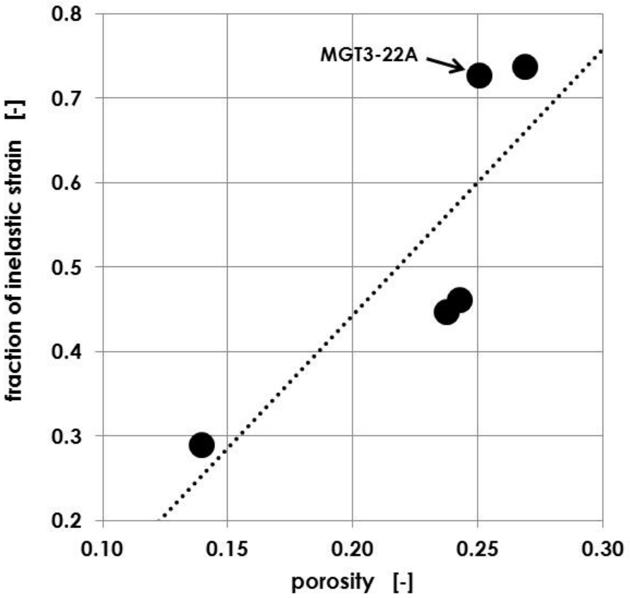

Fig 2. Contribution (fraction) of inelastic strain to total strain after full depletion for five representative samples versus their respective porosity. Note, that the trend projects to a fully inelastic strain (i.e. 1.0 on the y-axis) at values of porosity between 0.3 and 0.4, which would be in agreement with maximum porosities for close-packing structures.

The limited sensitivity of the data reported in this study, to temperature and pore fluid chemistry rules out a strong contribution of dissolution-precipitation mechanisms. By contrast, the strong role grain packing plays in the deformation of these samples, the fact that the uniaxial deformation clearly decelerates during the final hold period, and the increase in crack density observed using Scanning Electron Microscopy in the samples after testing, suggests that grain failure/re-arrangement is the dominant mechanism responsible for the inelastic deformation observed. Crack intensity in samples analysed increased by 10-30% post deformation. This confirms the observations recently made by NAM/Shell for Rotliegendes sandstone from the Groningen Field, and by Schutjens (1991) who reported compaction of quartz sand below ~300°C to occur primarily by granular cracking, and dissolution-precipitation mechanisms at higher temperatures. As grain cracking is fundamentally caused by exceeding a critical stress level required to fail an individual grain, the largest inelastic strains at a given applied effective stress can be observed in grain packs with a low coordination number, i.e. in samples with a narrow grain size distribution.

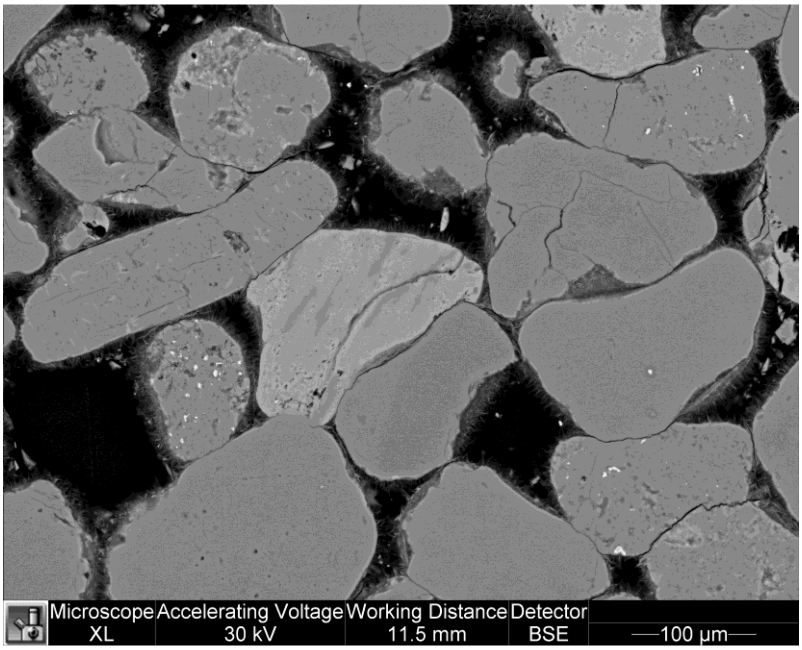

Fig. 3 SEM picture of a deformed sample. Clearly visible are the micro-cracks in the grains in the top right hand and central part of the image. This level of crack intensity is not observed in the virgin core samples.

An ultimate consequence of the microscale failure mechanisms considered, could be that the progression of local damage promotes shear failure of the samples. A comparison was made of the rock strength determined via triaxial compression, with the expected stress trajectory from the virgin in-situ effective stress in the reservoir to the final stress state in depleted conditions, using a worst-case experimentally obtained depletion path constant of 0.78±0.05. The rock strength determined and the onset of microscale failure affecting the ultrasonic wave propagation are clearly separated from the inferred stress path by several MPa. It is therefore unlikely that grain failure and re-arrangement during pore pressure depletion under uniaxial-strain boundary conditions results in shear failure, and hence that depletion under uniaxial strain conditions can be achieved within the mechanically stable regime. Additional tests in which radial stress was reduced after samples have gone through a full depletion cycle shows that their inherent compressive strength appears relatively unaffected, which confirms the mechanical stability.

The experimental work shows that while volumetric compaction of the sandstone reservoirs could be responsible for the magnitude of the subsidence observed in the Wadden area, it cannot directly explain the observed temporal relationship between subsidence and reservoir pressure decline, or at least not without some rescaling factor. Instead, other mechanisms such as salt flow or water-leg compaction should also be considered.

Various (semi-)analytical models have been proposed in the literature, and have been used actively by NAM and others, to history-match and/or forward-predict subsidence on the basis of laboratory rock compaction, or levelling data. For example, a recent review of such models by TNO (Ref) considers the soft soil isotach model, the stress-linearized isotach model, the standard Linear Solid (SLS) model, its special version, the time-decay model, and finally, the Rate Type Compaction Model. Without going into the mathematical details of the models, comparing the data presented in this report to the predictions made by the models is challenging for various reasons which are qualitatively considered. First, the models are one-dimensional, and as such, are not 3D constitutive equations, whereas the results presented in this study demonstrate an important role of lateral boundary conditions (zero lateral strain versus constant 3D applied stress during depletion). Second, the models are empirical and are, as such, not micromechanical constitutive equations. Consolidated, cemented sandstones are cohesive by nature and are hence capable of sustaining deviatoric stresses to some extent. This cohesion results in a resistance to stress, and hence dictates the magnitude and 3D nature of the stress-strain response. These sandstones cannot be compared with unconsolidated soils under axial loading for the sake of simplicity. Third, the models do not assume a priori knowledge on the elastic versus inelastic strain partitioning, as found in this experimental study, and can hence only be fitted successfully to the experimentally determined stress-strain data in one loading direction, unless mechanical properties are actively changed after loading.

In-situ Compaction

The compaction of the Rotliegend reservoir in the Groningen field is monitored in-situ by means of regularly spaced radioactive markers that are installed in the casing across reservoir sections in observation wells. The interval distance between these markers is measured using repeat gamma ray (GR) wireline logs. The progressive reduction of the interval distance is a direct measure for the reservoir compaction.. The reservoir compaction as mentioned in the report and in historic analysis of the data is represented by the change in the marker interval lengths with time (i.e. in between GR surveys, which are performed roughly every 3-5 years).

The accuracy of the analysis that is currently quoted ranges from 1-5mm per marker interval. The Groningen compaction rate is roughly 10mm/year over the full reservoir height, which equates to about 0.6mm/year per marker interval (intervals between radioactive markers being approximately 10m), meaning that every 3-5years, the compaction per marker interval is expected to be around 2-3mm, i.e. well within the current accuracy. In order to improve the accuracy, one could simply increase the survey cycle time and argue that over longer times the method is still accurate, however that way subtle variations in compaction rates cannot be detected because they are averaged out over the longer time scales. Instead of increasing the survey cycle time, this study investigates the possibility of improving the analysis accuracy, and introduces a new workflow for analysing the available in-situ compaction data (using a full signal cross correlation) with increased accuracy and control on data quality.

The historically reported compaction rates determined from the data are averages over the full reservoir height, where poorly interpretable marker intervals were ignored and the compaction over the more reliable intervals were added up. Instead of generalizing the compaction over the full reservoir height, an improved spatial resolution and improved reliability of each marker interval could allow to determine the compaction per marker interval individually. The refinement in turn makes it possible to compare the compaction rates for reservoir properties and characteristics such as porosity, gas/water fill, lower/upper Slochteren, etc. which has all been ‘averaged out’ in the existing analysis. Correlating the compaction rates with reservoir properties can help make the compaction and subsidence models more realistic. Moreover, the compressibility, C_m, can eventually be determined more accurately after the refinement, as the interval's pressure depletion from the reservoir models can be used instead of the reservoir's average pressure depletion.

The new analysis method works through cross correlation of signals. The advantages of cross correlations in these types of measurement are that random noise will be cancelled out in the process, resulting in a smooth output signal that only holds information of the correlation between two signals (the gamma ray spikes caused by the radioactive markers) on different length scales. Because there are four detectors on a CMI and FSMT tool, there are six detector pairs that can be cross correlated, resulting in six marker separation determinations per logging run. The cross correlation method uses less input than the currently used fitting method, in that it does not require knowledge of the detector separation.

It is noted that the accuracy of the existing analysis methods of the in-situ compaction data is already high given the nature of the signals, and serves its purpose in most reservoirs with high compaction rates. However, to detect small changes and subtle details of the compaction behaviour, it is necessary to improve the resolution as much as possible to be able to obtain as much detail and information as can be determined from the historic data. Using data simulations (assuming no unexpected tool movement) it is demonstrated that, using the cross correlation method, the accuracy in interval length for typical signals can be reduced to around 1mm.

In real data, however, there is the additional issue of unexpected tool movement, which occurs unfortunately frequently on similar length scales, which increases the uncertainty. The new analysis is able to detect unexpected tool movement better than the historic analysis methods, and therefore makes it possible to remove unreliable data from the analysis. The study demonstrates the detection on real data where the analysis procedure detects the transition from gas-filled to liquid-filled borehole from GR logs only, independent of other logs such as cable tension. Note that tool movement issues can only be detected, and not filtered out of the data, and will therefore, in most cases, be the main source of uncertainty.

In situ compaction data is only available in and around the Groningen field, as these GR markers have not been installed elsewhere. Direct in situ compaction monitoring of the Ameland field and other fields in the Wadden Sea area is therefore not possible; at best the Groningen data can be used as an analogue. In addition it is noted that Real Time Compaction Monitoring (RTCM) techniques deploying fibre-optic technology are now available. Compared to the system originally installed in the Groningen field, the RTCM systems are superior in resolution and spatial/temporal sampling. Installing them however requires a different type of well completion than currently used in the Wadden Sea area.

Salt Flow

The Ameland and Wadden Sea fields are overlain by a thick package of rock salt. Previous investigations (NAM, 2011) pointed out that the flow of rock salt has a significant temporal and spatial effect on surface subsidence as a result of gas production. The University of Utrecht was asked to study this effect in more detail using both simplified and complex realisations of the reservoir setting to test the following hypothesis:

- Reservoir compaction ceased when gas production ceased, and the observed on-going subsidence is simply caused by slow flow and readjustments in the Zechstein rock salt layers that overlie the Rotliegend gas reservoirs.

A simplified axi-symetrical 3D model shows that after the initial (instantaneous) reservoir compaction the subsidence bowl continues to deepen and narrow in response to the relaxation of shear stresses in the overlying rock salt layer (shear stress flow). However after some time a lateral flow is initiated (pressure flow) from the edges of the compacting bowl to the centre. This results initially in a reduction of the subsidence rate and ultimately may result in a slight reversal of the movement ultimately resulting in a shallower but wider subsidence bowl.

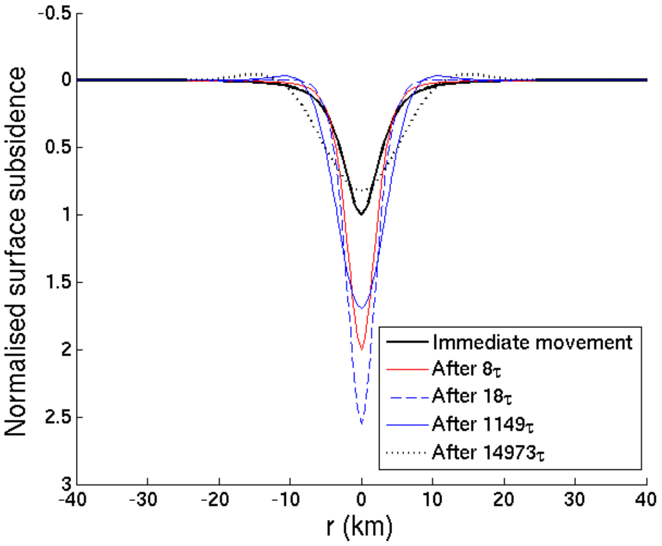

Figure 5. Evolution of the subsidence bowl. Vertical surface displacements are shown as multiples of the initial, maximum subsidence.

The simplified numerical models used in this study allowed for a thorough analysis of parameter sensitivity like salt thickness, viscosity and offset of the salt body with respect to the depth of the reservoir. The main conclusions from this model investigation are:
- Rock salt viscosity and thickness has a significant effect on the maximum subsidence and shape of the subsidence bowl.
- A simple extrapolation of subsidence observations in the earlier phase of production will lead to incorrect conclusions because the effect of salt flow on the subsidence will become more dominant and change in character with time.

The rheology of salt is complex and poorly constrained. Different mechanisms that govern the flow exist for the different levels of shear stress, temperature and salt composition. Most of the flow-laws that can be found in literature are empirically derived laws.

A more complex 3D model allows to investigate the impact of observed thickness variations of the rock salt above the Ameland reservoir on the modelled subsidence. A second objective is to capture the complex reservoir structure and pressure history of the field compartments in this model and observe their impact on the subsidence patterns. The model mimicks the salt geometry above and pressure history in the Ameland gas field. A basic comparison to the measure subsidence data has been performed. The results obtained are in line with previous NAM findings (NAM, 2011). It shows that the temporal behaviour of the subsidence signal at the production location could not be fully explained by salt flow only, even when testing it against a a range of viscosities and various flow laws. Whereas the width of the predicted subsidence bowl seems comparable, the model predicts the subsidence rate to rapidly decrease with time. This is inconsistend with the field data which show a much slower decrease in subsidence rate and consequently a deeper subsidence bowl .

Geomechanics Studies

It was noted during this study that there were apparent volumetric discrepancies in the standard geomechanical modeling approaches that have been developed and adopted by Shell/NAM. A request was made that this be investigated and explained. The results of that study are included in this report (Mossop, A., 2015b). The conclusion is that while an apparent volumetric discrepancy (i.e. the subsidence displacement volume is larger than the change in inclusion volume) is a natural outcome of the boundary conditions applied (a half space), that there was an error in the way the inclusion volume change is calculated. It had been assumed that the inclusion volume change was independent of distance from the free surface, (apart from the end member case where the inclusion was at the free surface). This is not the case and a depth dependent term needs to be included in the calculation of the reservoir volume strain. The depth dependent correction factor can be as large as $2(1 - \nu)$ for shallow inclusions, where ν is Poisson's ratio.

However, the error does not impact the calculation of subsidence, as the surface displacement function remains unchanged. With respect to subsidence modeling, prediction and monitoring, the exact formulation of the in-situ volume change of the reservoir inclusion is essentially an abstraction. It should also be noted, that for reservoirs that are approximately as deep or deeper than the are laterally extensive, which is the case for the Wadden Sea gas fields, the volume change correction factor will be small (< 10 %).

An additional concern that was raised was the impact that irreversible inelastic contraction of the reservoir inclusion would have on the validity of the geomechanical model concepts that are applied, which assume linear elasticity.
A research note analyzing and discussing this issue is also included as attechment (Mossop, A., 2015c)
On investigation it is found that the constitutive law governing the transformation strain of the reservoir inclusion is immaterial, and doesn't actually enter into the subsidence calculation (or calculation of any of the displacement terms). Only the constitutive law that governs the elastostatic equilibrium is required, as this will essentially involve small strains, the assumption of linear elasticity is reasonable.

Geodesy

Improvements for preparing subsidence measurements for geomechanical model calibration have been investigated in the geodetic part of the research programme. As an essential prerequisite for testing candidate hypotheses on geomechanical models, appropriate stochastic models for geodetic datasets have been proposed. It was shown that taking into account correlation structures significantly improves the precision of geomechanical model predictions. Furthermore, several effective measures to optimise the model calibration workflow have been identified, aiming at minimising uncertainties and biases due to simplifications and not validated assumptions.

With levelling, Interferometric Synthetic Aperture Radar (InSAR) and Global Positioning System (GPS), the research has covered the three essential measurement techniques that are in use for subsidence monitoring at NAM. It was subdivided into two work packages: The "Research and Development Project for Geodetic Deformation Monitoring" has examined the geodetic processing workflow in the context of geomechanical modelling with focus on observations from levelling and InSAR [Samiei-Esfahany & Bähr, 2015] This project has been conducted by NAM with substantial support from Delft University of Technology (The Netherlands). It has been complemented by an expertise on "Description of GPS Uncertainties within the Long Term Study on Anomalous Time-Dependent Subsidence" that NAM requested from Dr. S. Williams (National Oceanographic Centre, United Kingdom) [Williams, 2015]

Both studies indicate that considerable improvements can be made to geodetic processing with demonstrated benefit for geomechanical modelling. This consideration will add value to the development of a testing framework for candidate hypotheses. The proposed stochastic models also provide opportunities for a substantiated optimisation of the current survey design.

Stochastic modelling:

The stochastic model for geodetic data that is currently deployed for geomechanical calibration at NAM is simplified, because it only accounts for the uncertainty of the measurement itself but does not take correlations into consideration. However, when identifying subsidence due to gas extraction as the signal of interest, any deformation caused by other (shallower) sources should be considered noise and thus included into the uncertainty model. Complementing the technique-related measurement noise with this so-called idealisation noise is a major improvement proposed by this study. Idealisation noise is by far the most dominant noise component. However, its quantification in parametric models is much less reliable compared to measurement noise.

In the case of levelling and InSAR, NAM proposes to use specific state-of-the-art models to describe the measurement noise. An idealisation noise model has been derived from levelling surveys outside the influence area of gas production where other (shallow) deformation effects can be characterised and isolated without disturbance by deep source subsidence. The obtained model parameters are deemed representative for the Wadden Sea area but not for upcountry regions with different soil properties. NAM proposes to also use this model to approximate idealisation noise in InSAR data.

For an uncertainty description of GPS data, some state-of-the-art candidate models for both permanent GPS stations and campaign surveys are proposed. They are based on a comprehensive literature study as well as analysis of existing data from NAM and independent sources. The models needed some subjective tuning based on expert knowledge due to noise reduction in the currently deployed non-standard processing approach and to account for noise components that cannot be quantified empirically from the data.

Workflow optimisation:

To integrate datasets from different measurement techniques into the workflow of geomechanical model calibration, NAM proposes not to combine them prior to modelling. To avoid interpolation artefacts, techniques should be introduced separately into the modelling. For InSAR, NAM proposes a consistent approach for data reduction in order to cope with the large data volume. Replacing the currently deployed approach of resampling InSAR observations to levelling benchmark locations, the new approach better exploits the full potential of the technique.

Many valuable learnings are derived from the geodetic research originate from the *output level study*. Based on simulations with a simple geomechanical model, the optimal interface between geodetic data processing and geomechanical modelling workflow has been investigated. Recommendations aim at maximising modelling efficiency while minimising not fully validated assumptions and computational complexity.

The following conclusions were drawn from the output level study: Biases in geomechanical calibration can be mitigated by selecting the output level of spatially and temporally differenced instead of pseudo-absolute subsidence measurements. A demonstrated bias can be easily avoided by calibrating model predictions against InSAR observations in the original line-of-sight (LOS) geometry instead of relying on the incorrect assumption of purely vertical ground deformation.

It was shown that the currently implemented simplified processing compromises the precision of the geomechanical model parameters. Thus, the uncertainty of model predictions can be significantly reduced by taking covariances into account for geodetic data. A similar effect has the use of multiple reference points and multiple reference epochs for the individual double difference observations. Finally, not removing the atmospheric signal component from InSAR deformation time series may have some considerable advantages for bias mitigation.

Considering outlier handling in the geodetic processing workflow is most relevant for levelling data, in which unavoidable human errors regularly cause huge discrepancies. Rigorous outlier handling, however, requires reliable knowledge on geomechanical model uncertainties. Since this is not available, NAM proposes to focus on the very obvious outliers that can be identified without that knowledge, using a pragmatic approach. For InSAR, outliers are generally a minor issue due to the high spatio-temporal sampling. NAM proposes to address a subclass of InSAR outliers that may become critical for geomechanical modelling. For both levelling and InSAR, a sensitivity analysis in operational modelling can help quantifying the actually impact of outliers.

Statistics

Model predictions of displacements at the surface of the earth due to reservoir compaction are subject to uncertainties due to the fact that:

1. Some of the physical processes are not well understood, and multiple candidate models may be proposed which may be similar in their ability to explain historic data but different in their predictions of future displacements.
2. For any given model, estimates of model parameters are uncertain.
3. Model input, in particular spatio-temporally resolved estimates of pressure declines and rock porosity, are subject to uncertainties.

Additionally, measurements of displacements are subject to errors and part of the displacements may be caused by non-reservoir related processes which are not accommodated in the models. A rational framework is required to enable quantification of uncertainties in model parameters and predictions, and to compare the relative ability of models to explain the variability in future measurements. For this purpose, an outline is given of a Bayesian statistical framework which is flexible enough to accommodate the use of prior information surrounding model parameters (e.g. prior knowledge from an understanding of physical processes or laboratory measurements), uncertainties in model input, and errors in measurements. A key advantage of the Bayesian statistical framework is that it offers a natural framework for estimating probability distributions for key quantities of interest such as future observations.

Conclusions and Recommendations

The candidate hypotheses that were put forward as potential explanations of the apparent time dependent subsidence are discussed belwow.

[1] The apparent time dependence was an artefact and merely due to noise structure and uncertainty.

The geodetic study work indicates that spatially and temporally correlated noise in the survey data are not negligible. However, the estimated magnitudes are too small to explain the observed time dependence. This conclusion is also corroborated by the statistical analysis work. Therefore the observed trends represent a real signal and this hypothesis can be rejected as a possible explanation.

[2] The time dependent subsidence was caused by salt flow.

The hypothesis that salt flow on its own can explain the observed time dependence does appear to be rejectable based on the mismatch in functional temporal response, i.e. adjustment of the salt flow parameters cannot reproduce the functional form. That is not to say that influence of salt flow on subsidence can be neglected, merely that it cannot solely explain the observed time dependence.

[3] The time dependence subsidence was caused by slow depletion in underlying aquifers not captured in the reservoir simulation.

Aquifer depletion seems improbable as the sole cause based on the evidence from the gas fields near to Ameland. However, sufficient uncertainty remains which precludes complete rejection at this stage and some level of aquifer depletion will need to be considered.

[4] The time dependent subsidence was due to anomalous pressure diffusion which could cause pressure equilibration to occur over longer time scales.

Similarly anomalous pore pressure diffusion due to long tail distributed permeability, leading to significantly increased pressure equilibration time scales, is an unfamiliar process, but the large parameter range and associated uncertainty mean that it cannot be rejected as yet.

[5] The time dependent subsidence is due to time dependent poromechanical compaction in the reservoir rock.

The hypothesis that the apparent time dependent subsidence is due to time dependent compaction is also not rejectable. The temporal compaction response observed in the laboratory is not an ideal fit, but the functional form of the field determined time dependence is noisy and uncertain. Otherwise the magnitudes and basic time scales correspond to those derived from subsidence survey data.

In conclusion the hypothesis testing suggests that for the modelling workflows going forward time-dependent poromechanical reservoir compaction augmented with some level of lateral aquifer depletion/pore pressure diffusion and salt flow will need to be taken into consideration to arrive at an acceptable explanation of prior and forecasted subsidence. These improved workflows will be tested on the Ameland field. In this context NAM will also explore deterministic (scenario based) versus probabilistic approaches whereby, given the vast range of independent parameters the likelihood of arriving at a fully probabilistic workflow is considered low.

In addition to the above general conclusion, the study program gives rise to a number of more specific recommendations with respect to improving the subsidence modelling and monitoring workflow:

1. Subsidence predictions should ideally be updated in a Bayesian manner as geodetic survey data becomes available. When this data is not (yet) available, first order subsidence predictions can be made based on proxies, e.g. a general relationship between porosity and rock poromechanical compressibility and/or a non-unique reservoir and aquifer depletion model, but it should be realised that this makes the forward model prone to temporal and spatial biases.

2. In view of the uncertainties inherent in the previous point and the need to objectively include past geodetic survey data to update subsidence prediction models, a subsidence prediction methodology that utilises inverse modelling techniques or equivalent optimisation methods is recommended. Forward modelling is an excellent method of producing a 'prior' subsidence model, but forward modelling with subsequent calibration using survey data can be prone to error and biases.

3. Because of time correlated uncertainties (and the lack of knowledge about such uncertainties), subsidence predictions should only be made over limited and clearly defined time periods and associated errors need to be time dependent (i.e. grow with time).

4. Covariance in geodetic data (spatial and temporal) should be taken into account in the subsidence prediction and monitoring cycle. This can be achieved by adopting a double differencing approach.

5. It is recommended to investigate the options within the existing monitoring capability to measure both lateral and vertical displacements during geodetic surveys. This will better constrain models of subsurface compaction, salt flow, and the understanding of the subsidence process.

6. The assumption of isotropic stress-free compaction behaviour is questionable and has an impact on the fundamental solutions that underlie the geomechanical modelling. It is recommended to further investigate the applicability of other nuclei of strain (i.e. force sources)

7. Uncertainties in the reservoir simulation of the pressure depletion field should be quantified for both the reservoir and the aquifer. This will better bound the subsidence model predictions. This can be achieved through a scenario based modelling strategy or (ideally)

through a fully probabilistic workflow (using Experimental Design techniques). The likelihood of getting a fully functioning probabilistic workflow is however considered low.

8. It is not recommended to install further gamma ray source compaction monitoring systems in future and consider present day fibre optic based Real Time Compaction Monitoring systems instead as these are superior in resolution and spatial/temporal sampling. However installation wuld require a well completion different from that deployed in the current Wadden Sea area wells

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