Progress Report: Development seismicity during pressure equilibration in the Groningen gas field

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Datum July 2024

Contents

1. Introduction

Relevant document:

1. Study Plan seismicity Groningen during pressure equilibration period, Jan van Elk, Anke Jannie Landman, Clemens Visser and Jeroen Uilenreef, 1 November 2022.

In October and November 2021, NAM published reports on the earthquake swarm near Zeerijp which lasted from 4th to 6th October 2021 (Ref. 2) and on the Garrelsweer earthquake on 16th November 2021 (Ref. 3 to 7). The seismic monitoring reports for the three years 2020 to 2022 (Ref. 8 to 14) showed the observed seismic event rate had been close to the upper range of the uncertainty band for the forecasted seismic event rate. Following these reports further studies into the development of the seismicity in the Groningen gas field during the pressure equilibration phase were initiated.

In a letter of 14th April 2022 (Ref. 15) SodM requests NAM to carry out additional studies into the seismicity in the Groningen gas field. The objective of these studies is to improve the forecasting of the seismicity during the pressure equilibration phase, with a focus on time-dependent effects like creep. In a meeting between NAM and SodM on 30th May 2022, expectations were shared and the activities that could potentially be included in the study plan discussed.

Studies carried out between 2012 and 2018 as part of the Study and Data Acquisition Plan led by NAM were based on data obtained during a period of relatively high production levels from the Groningen gas field. During this period of high production levels subtle time- or rate-dependent effects were potentially obscured. Studies into time- or rate-dependent effects in seismicity were therefore carried through laboratory experiments. These experiments were started at University Utrecht in 2015 (using samples from the core taken in the newly drilled Zeerijp-3 research well) (Ref. 16 and 17). Low production levels declining to nil offer the opportunity to study these potential effects based on data obtained in the field. NAM was therefore keen to restart their research effort.

In June 2022, NAM contacts Prof. dr. Jean-Philippe Avouac of Caltech to agree and set up a joint research program to address this research scope. The first studies commence in August 2022. The study plan is finalised in October 2022 and approved by SodM (Ref. 1). The study plan provides a short discussion of the mechanisms that could potentially lead to a longer time-delay between gas production and seismicity, followed by a description of the studies proposed to better understand the time-delay.

The study results have been documented in a number of reports available on the NAM website and scientific papers published in peer-reviewed journals. These papers are published as open access papers and can be obtained from the website of the scientific journal. This progress report provides a summary of the main research results presented in these reports and papers, with a focus on possible causes for a potential delay in the observed decline of the seismic event rate, compared to the forecasted event rate.

2. Forecasting Seismicity Event Rate

Studies carried out:

1. Seismicity Recalibration 2023, NAM, Valesca Peereboom and Marc Broersma (Feb 2022).
2. Recalibration of the Seismicity Model, NAM, Valesca Peereboom and Marc Broersma (Feb 2022).

Model calibration

Early 2024 a comparison was prepared of the observed number of earthquakes and the number of earthquakes forecasted by the HRA. The seismological forecasting model was calibrated against the earthquake catalogue of all earthquakes in Groningen with a magnitude of $M_L \geq 1.5$ until 1st January, 2024.

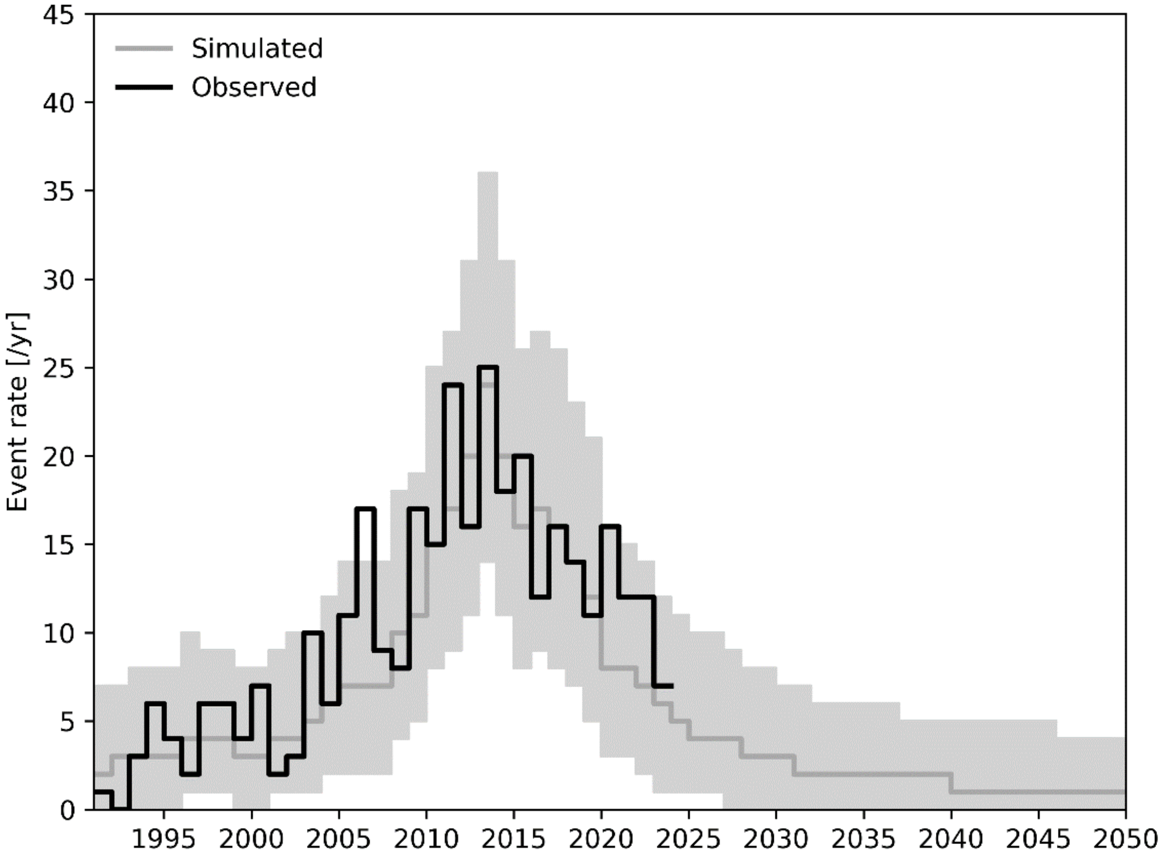

Figure 1 Calibration of the seismological model based on the earthquakes with a magnitude $M_L \geq 1.5$ until 1 January 2024.

The calibration of the seismological model was done based on data from the seismic monitoring network operated by KNMI. KNMI reports two versions of the observed Groningen earthquake magnitudes, the first is to 5 decimal places without rounding, and the second is to 1 decimal place after rounding. The earthquake catalogue that KNMI makes available as a pdf-file contains magnitudes rounded to one decimal place. KNMI also provide the unrounded magnitude of the earthquakes[1]. NAM uses the unrounded earthquake magnitude for the calibration of the seismological model. In the comparison of the historical earthquake record with the earthquake forecast prepared with the seismological model also unrounded earthquake magnitudes are used (Ref. 18 and 19).

NAM uses the unrounded version for their analysis to avoid three known significant sources of bias associated with using magnitudes rounded to 1 decimal place. Firstly, this avoids bias in counting the

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[1] These are available using FDSNWS - Event URL Builder (knmi.nl) of rdsa.knmi.nl/fdsnws/event/1/query?format=csv&nodata=404.

number of observed events that exceed a given magnitude threshold. For example, the number of observed M ≥ 1.5 events will be over-stated, if magnitudes rounded to 1 decimal are counted since magnitudes in the range 1.45 ≤ M < 1.5 will have been round to M = 1.5 and then counted even though they are all actually below the threshold. Counting the unrounded M ≥ 1.5 events yields the correct result.

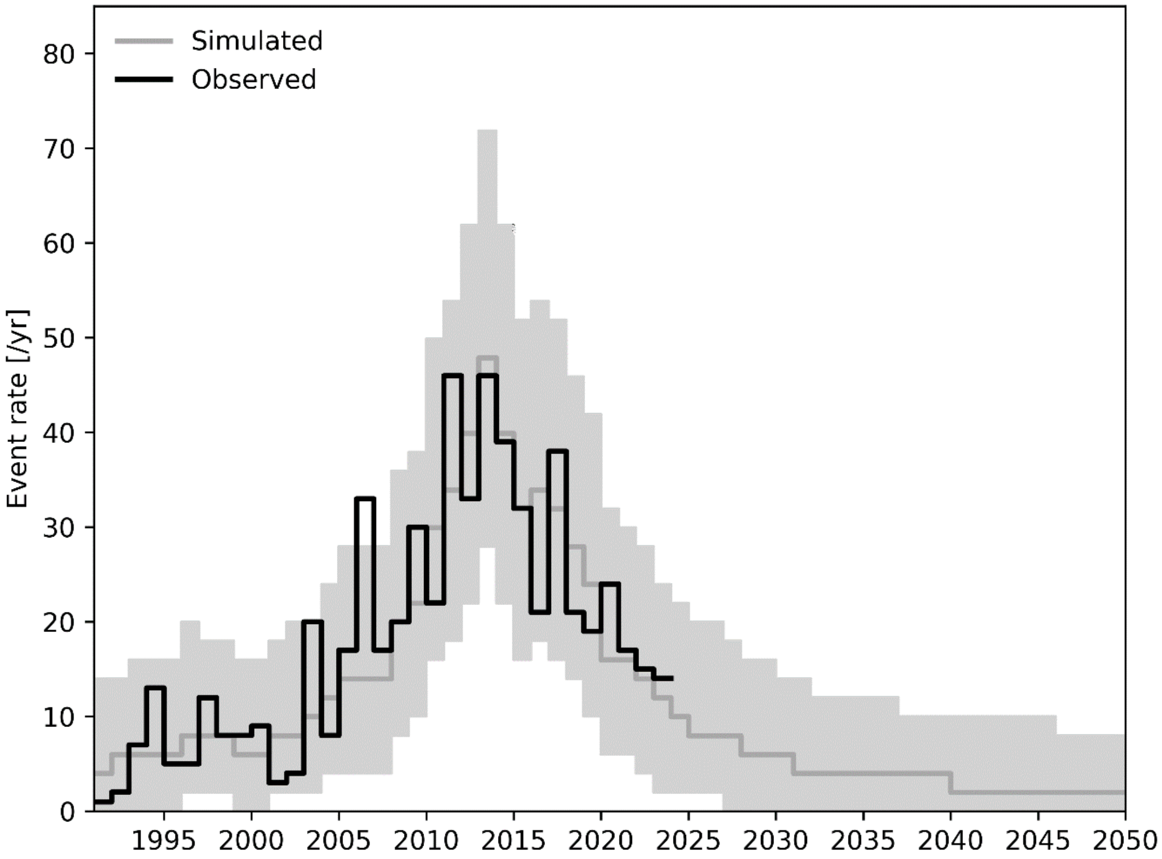

Figure 2 Calibration of the seismological model based on the earthquakes with a magnitude $M_L \geq 1.2$ until 1 January 2024.

Secondly, this avoids bias in the training of the Activity Rate part of the Seismological Model, by training the model on events that exceed the chosen magnitude threshold, rather than a lower threshold that depends on the rounding as already described.

Thirdly, this avoids bias in the training of the magnitude part of the seismological model, by training the model on events that exceed the chosen magnitude threshold without needing to make an additional correction to account for the biasing effect of rounded magnitudes.

Comparison of the Observed and Forecasted number of Earthquakes

Figure 3 shows a comparison of the observed earthquakes with a magnitude $M_L \geq 1.5$ in the Groningen gas field with the forecasted number of earthquakes. During three consecutive years (2020 to 2022) the number of observed earthquakes was above the expected number of earthquake, close to the upper end of the uncertainty range (Ref. 20 to 22). In 2023, seven earthquakes with a magnitude $M_L \geq 1.5$ were observed. This was close to the expected number of earthquakes for that year. In the first six months of 2024 (until 1st July) three earthquakes with a magnitude $M_L \geq 1.5$ were observed. All three of these were in April. This corresponds to some 6 earthquakes with a magnitude $M_L \geq 1.5$ on an annual basis and falls within the uncertainty band.

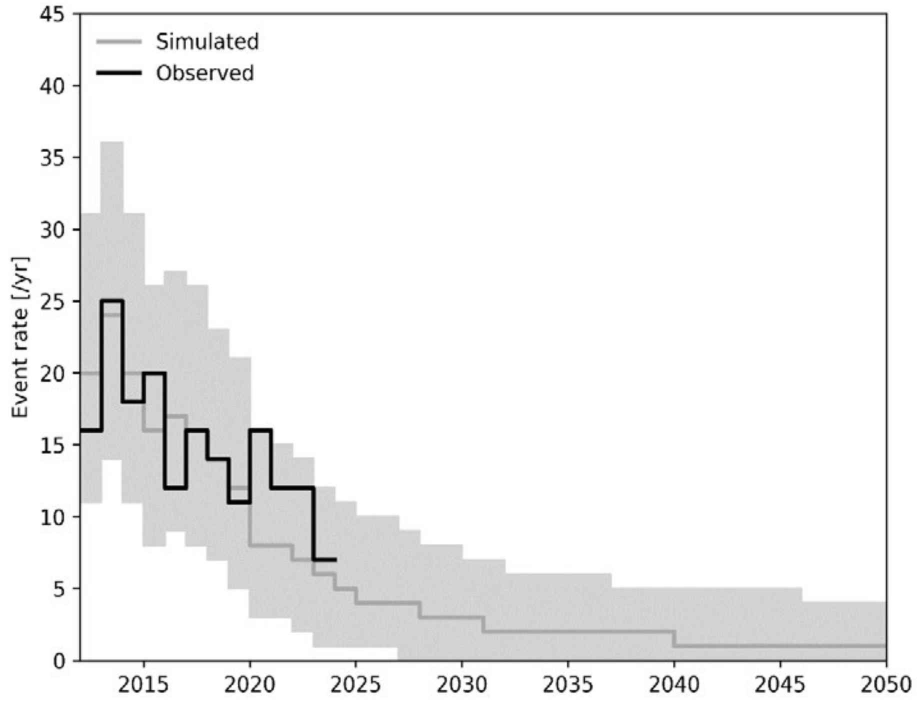

Figure 3 Forecasted number of earthquakes in the Groningen gas field with a magnitude $M_L \geq 1.5$.

In addition to a comparison of the observed and forecasted number of earthquakes with a magnitude $M_L \geq 1.5$, also a comparison for $M_L \geq 1.2$ was prepared. An exceedance magnitude for seismic reporting of $M_L = 1.2$ is used in the Mijnbouwregeling article 1.3a.5. Due to the higher number of earthquakes this provides a more reliable comparison.

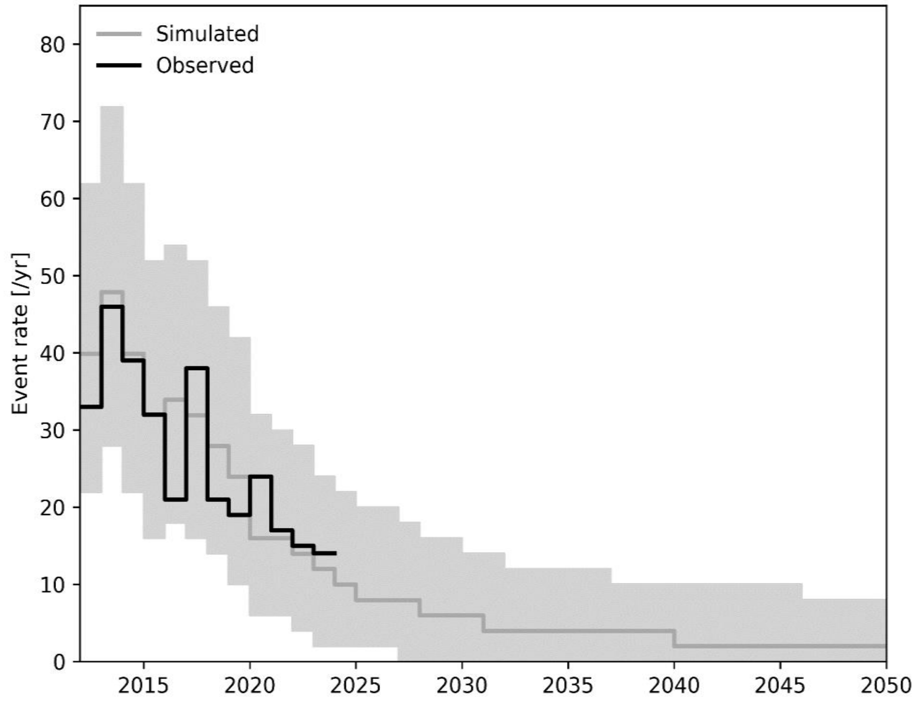

Figure 4 Forecasted number of earthquakes in the Groningen gas field with a magnitude $M_L \geq 1.2$.

Figure 4 shows a good correspondence between observed and forecasted number of earthquakes. In the first six months of 2024 (until 1st July), four earthquakes with a magnitude $M_L \geq 1.2$ were observed.

This corresponds to 8 earthquakes with a magnitude $M_L \geq 1.2$ on an annual basis, which falls below the expected number of earthquakes for 2024.

3. Modelling the Decline in Event Rate

Seismicity could potentially be affected by a delay in the seismic response to gas production. To understand the decline in seismicity after the steep reduction in gas production, which was followed by a close-in of the field, four mechanisms that could potentially cause a delay between gas production rate changes and seismicity rate changes need to be understood. These four mechanisms are:

1. Pore pressure diffusion causes a delay between gas production rate changes and reservoir pore pressure changes that increases with distance from the production well.
2. Inelastic creep potentially causes a delay between reservoir pore pressure changes and reservoir strain changes.
3. Slow fault creep during the earthquake nucleation phase potentially causes a delay between the fault stress changes induced by reservoir strains and seismicity rate changes on the fault.
4. Aftershock sequences cause a delay between the parent earthquakes and their associated aftershock earthquakes[2].

The progress and results of the studies into each of these possible causes of a delay affecting the decline of the seismicity following cessation of production are discussed below.

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[2] Note that 3 and 4 can be related. The time evolution of aftershocks can be explained by the nucleation process, but it is not the only possible explanation.

Delay in Reservoir Pressure

The studies into reservoir pressure are documented in the following reports and papers:

1. Groningen Dynamic Model Update 2023, NAM, Anke Jannie Landman, July 2023.
2. Evaluatie Monitoring Strategie Groningenveld, Anke Jannie Landman and Jan van Elk, June 2022.
3. Recent Reservoir Pressure Measurements in the Groningen gas field Anke Jannie Landman, March 2024.
4. An integrated framework for surface deformation modelling and induced seismicity forecasting due to reservoir operations, H. Meyer, J.D. Smith, S.J. Bourne and J.P. Avouac (2023), Geological Society, London, Special Publications 528 (1), SP528-2022-169.

The dynamic reservoir model for the Groningen gas field was built between 2010 and 2012 and has since then been updated regularly. The latest update was completed in June 2023 (Ref. 23). Reservoir pressure measurements are obtained in observation wells and wells previously used for production (Ref. 24). These measurements have last been reported in March 2024 (Ref. 25). Since this report on measurements of reservoir pressure was issued, two more SPG (Static Pressure Gradient) measurements have been taken.

Date	Well	Measured Pressure [Bar]	Model Pressure [Bar]	Difference: Model pressure – Measured pressure [bar]
13 May 2024	SDB-2	68.7	69.4	0.7
11 June 2024	AMR-3	71.3	71.9	0.6

Table 1 Recent reservoir pressure measurements taken in the Groningen gas field compared with the model forecast.

The difference between measured and predicted reservoir pressure is much smaller than the estimated uncertainty in the predicted reservoir pressure of 3 bar. All 10 recently obtained reservoir pressure measurements were within 3.0 bar of the model prediction and 8 of these pressures measurements were within a single bar from the model prediction. Measured reservoir pressures are just as often (slightly) higher than lower and there does not seem to be any consistent pattern in de differences in time or space.

The reservoir pressure measurements in the field closely follow the modelling predictions. The causal relationship between gas production and reservoir pressure is therefore not a source of delay in the seismicity, beyond the model prediction.

To be able to incorporate reservoir modelling in the integrated seismic modelling framework a Vertical Flow Equilibrium reservoir model (Meyer et al., 2022) was developed and tested. The assumption of Vertical Flow Equilibrium is justified in the case of Groningen given the large horizontal extent of the reservoir (>10km) compared to its thickness (<300m). The reservoir model is therefore 2-D and cost effective. The initial model was considering only one phase and was therefore neglecting interactions with bounding aquifers. The model was extended to multiphase flow (Ledevin et al., in preparation). This reservoir model yields history matching performance comparable to the 3-D reservoir model of NAM (MoReS), with a RMSE to the measured well head pressure measurements of the order of 0.5 MPa.

Delay in Compaction

The studies into compaction are documented in the following reports and papers:

1. The effect of loading rate on mechanical behavior and deformation mechanisms in Slochteren sandstone, Mark Jefferd, Taka Shinohara, Ronald P. J. Pijnenburg, Suzanne J. T. Hangx, Christopher J. Spiers, 25 November 2021.
2. Compaction in Slochteren sandstone of the Groningen Gas Field, Utrecht University, Suzanne Hangx, August 2023.
3. Rate-dependent compaction models for reservoir rock, Florian Lehner, Teng-Fong Wong, Anthony Mossop, Peter Schutjens and Mateo Acosta, June 2024.
4. Reconciling the long-term relationship between reservoir pore pressure depletion and compaction in the Groningen region. Smith, J. D., Avouac, J.-P., White, R. S., Copley, A., Gualandi, A., & Bourne, S. (2019), Journal of Geophysical Research: Solid Earth, 124, 6165–6178. https://doi.org/10.1029/2018JB016801.
5. Insar monitoring of elastic and inelastic deformation in compacting reservoir due to surface operations, Y. Li, M. Acosta, K. Sirorattanakul, S.J. Bourne, and J.-P. Avouac, submitted to Remote Sensing of Environment.

The experimental studies on core material from the Groningen reservoir formations (Ref. 16, 17 and 26) confirm the significance of a time dependent inelastic component in the compaction of the Groningen field. These experiments indicate that time-dependent inelastic deformation plays a role in controlling reservoir deformation, such as of the Groningen gas reservoir. The present laboratory experiments provide important data for developing physics-based constitutive models for predicting rate/time-dependent reservoir compaction.

For the Groningen field an extensive geodetic data set is available consisting of optical levelling data, GPS measurements and data obtained from several satellite observations. An assessment of the long-term relationship between reservoir pore pressure depletion and compaction (Ref. 28) was made based on available geodetic data for the period from 1964 (when gas production commenced) to 2016. A principle component analysis inversion shows that a single spatially varying component explained 97% of the data variance. The temporal component of the principle component showed no discernible trend from the mean uni-axial compressibility value, with values close to the mean value. This lack of variation of uniaxial compressibility with pressure depletion showed the reservoir has (within the stress levels the reservoir had until 2016 been subjected to) a predominant linear poro-elastic response.

The most recent study (Ref. 29) analysing geodetic data from both the Groningen gas field and the Norg underground gas storage for the period until 2023 (for the GNSS stations) builds on the results of the study by Smith et al. (2019) (Ref. 28). For the period analysed by the earlier study (Ref. 28) this study finds similar results. However, from 2015 onwards, a discrepancy appears between the modelled compaction based on a spatially varying uniaxial compressibility and the observed subsidence derived from satellite observations (Radarsat2 and TerraSAR-X InSar). This discrepancy seems to appear from 2015 onwards when gas production rates from the field were reduced significantly. This shows as an increasing apparent uniaxial compressibility over time from 2015 onwards, indicating a time varying inelastic component to the compaction. The performance of one of the time-dependent compactions models, the rate-type compaction model (RTCM), to model the observed compaction is tested. Prior to 2000 the difference between the elastic and RTCM model are insignificant. But especially from 2015 onwards the two models deviate, with the RTCM model providing a superior match to the observed subsidence. This demonstrates that an inelastic component contributes to reservoir compaction in the Groningen gas field. This should also result in a longer tail in seismicity after depletion, compared to the prediction based on simple linear poro-elasticity. The latest work currently in progress will show how significant his delay is. Due to the co-variance amongst the model parameters, this is expected to be small (possibly in the order of 3 months).

These results are in agreement with those of the data assimilation study conducted in 2020 by NAM in collaboration with the Shell Statistic Group (Ref. 30 and 31) on the compaction of the Groningen field. Geodetic levelling data up to 2018 were used in a Bayesian Markov Chain Monte Carlo framework to determine the compaction parameter values in a compaction model that also allows for rate-type compaction behaviour (RTCM). The model describes a transition to a higher value of the compressibility when the deformation rate is increased. This used geodetic dataset showed that time-dependent compaction is significant in the Groningen field. This is also validated by the available InSAR measurements, GNSS measurements and a distributed strain sensor that measures the in-situ compaction at the Zeerijp location in the Groningen field.

Delay in Earthquake Nucleation

The studies into earthquake nucleation are documented in the following reports and papers:

1. Earthquake nucleation characteristics revealed by seismicity response to seasonal stress variations induced by gas production at Groningen, M. Acosta, J.P. Avouac, J.D. Smith, K. Sirorattanakul, H. Kaveh and S.J. Bourne (2023), Geophysical Research Letters 50 (19), e2023GL105455.
2. An integrated framework for surface deformation modelling and induced seismicity forecasting due to reservoir operations, H. Meyer, J.D. Smith, S.J. Bourne and J.P. Avouac (2023), Geological Society, London, Special Publications 528 (1), SP528-2022-169.
3. Stress-based forecasting of induced seismicity with instantaneous earthquake failure functions: Applications to the Groningen gas reservoir, J.D. Smith, E.R. Heimisson, S.J. Bourne and J.P. Avouac (2022), Earth and Planetary Science Letters 594, 117697.
4. Coulomb threshold rate-and-state model for fault reactivation: application to induced seismicity at Groningen, E.R. Heimisson, J.D. Smith, J.P. Avouac and S.J. Bourne (2022), Geophysical Journal International 228 (3), 2061-2072.

The seismological model incorporated in the HRA is based on the Coulomb friction model with an initial strength excess to be able to take into account the delay in the first occurrence of seismicity after the start of gas production resulting in stress changes (Ref. 32 and 33). This assumes an instantaneous nucleation process. However, the nucleation process might not be instantaneous (Ref. 34). Using the rate-and-state friction model, the duration of the nucleation process can be accounted for in the seismological model.

The strong seasonal variation in the gas production from the Groningen gas field resulted in significant seasonal variation in the seismic event rate. This allowed estimation of the nucleation time scale and the potential delay in the manifestation of the seismicity (Ref. 35). This could potentially be a cause for a delay in the decline of seismicity during the period of reduction and ultimately cessation of gas production. Additionally, a bias could be introduced when ignoring in the calibration process of the model, the large production, reservoir pressure and stress variations occurring within a year.

Using monthly timesteps for the analysis of the relationship between stress and manifestation of seismicity, the Shuster analysis shows a delay in the seismicity of about 2 to 3 months. The peak in seismicity in a year is observed around late-March some 2 to 3 months after the peak in gas production in mid-January. This indicates that the previous choice to use an instantaneous Coulomb failure model of earthquake nucleation in the HRA remains appropriate for evaluating annual average seismicity rates and their associated hazard metrics.

Further research into the time delay in seismicity due to the combination of both the inelastic component of compaction (as captured by for instance the RTCM model) and a finite duration of the nucleation process (as captured by the rate-and-state model) is in progress.

Delay due to Aftershocks

The studies into after-shocks are documented in the following reports and papers:

1. Aftershock analysis of Groningen earthquake catalogues using the method of Zaliapin and Ben-Zion, Steve Oates, June 2023.
2. Burst of fast propagating swarms of induced earthquakes at the Groningen gas field, K. Sirorattanakul, J.D. Wildig, M. Acosta, Y. Li, Z.E. Ross, S.J. Bourne and J.-P. Avouac, 2024, manuscript submitted to Seismological Research Letters.
3. Research Note: Groningen seismicity catalog generation, John Wilding, March 2023.
4. Enhanced catalogue Groningen seismicity, John Wilding, March 2023.

Using an automated method developed for earthquakes in California, and since then used in several other areas, the continuous data from the Groningen seismic monitoring network was reprocessed to identify additional (often smaller) earthquakes (Ref. 39). Over the study period from 2015 to 2022 the method identified 709 of the 739 earthquakes in the KNMI catalogue, but also identified 660 previous unidentified events bringing the total to 1369 earthquakes. Analysis shows that clusters account for 28% of the earthquakes. A quarter of these are aftershocks and the remaining three-quarter consists of earthquake swarms. Five swarms consisting of 10 to 20 events, with magnitudes below $M_L = 1.5$, were identified in the Zechstein.

The clusters identified in the catalogue have a duration of a few days. The five swarms lasted 1 to 5 days. Aftershocks and swarms of earthquakes are therefore not a potential cause for significant delay in the decline of earthquakes, which is reported on an annual basis.

4. Magnitude of Earthquakes

The studies into earthquake magnitude are documented in the following reports and papers:

1. Induced Seismicity forecasting with Uncertainty: Quantification: Application to Groningen Gas Field, H. Kaveh, P. Batlle, M. Acosta, P. Kulkarni, S.J. Bourne and J.P. Avouac (2022), Seismological Research Letters (2024) 95 (2A): 773–790. https://doi.org/10.1785/0220230179.
2. Presentation: Workshop on the Seismological Model (magnitude) with NAM, KEM-Panel, TNO, SodM and ministry of Economic Affairs and Climate Policy, S.J. Bourne, J.-P. Avouac, J. Tawn and J. van Elk, 3 October 2023.
3. Magnitude-Frequency Distribution of Induced Seismicity, L. Li, K. Im and J.-P. Avouac, 2024, Conference Poster.

In 2019 NAM proposed to include a seismological model with a taper in the logic tree for seismic risk assessment in the Groningen gas field. Since then, several authors have confirmed that the tapering of the magnitude-frequency distribution is statistically significant; A.G. Muntendam-Bos and N. Grobbe (2022) (Ref. 47), D. Dempsey and J. Suckale (2023) (Ref. 45), Z. Varty and J. Tawn (2021) (Ref. 48 and 49) and H. Kaveh et al (2022) (Ref. 42). These studies have further strengthened the case for including a seismological model with a taper in this logic tree for the hazard and risk assessment.

On 27th June 2023 and 3rd October 2023 discussions were held with TNO, SodM, KEM-Subpanel and the ministry of EZK to discuss the seismological model. At the meeting of 3rd October 2023, presentations were held by Stephen Bourne, Steve Oates, Jonathan Tawn, Jean-Philippe Avouac and Jan van Elk (Ref. 43).

A study currently in progress at Caltech (Li, 2024) (Ref. 49) investigates different methods for establishing whether a taper is present in the magnitude-frequency distribution. Observations in different fields are evaluated and a potential mechanism is proposed.

5. Conclusions

The studies into the development of seismicity during the pressure equilibration phase supports the following conclusions:

- After a period of three consecutive years, from 2020 to 2022, with a seismic event rate for earthquakes with magnitude $M_L \geq 1.5$ above the expected forecast rate event rate and near the upper end of the forecast 95% uncertainty interval, the event rate has for the following 1 ½ years returned closer to the expected forecast rate and within the forecast 95% uncertainty interval.
- The event rate for earthquakes with magnitude $M_L \geq 1.2$ has to date been close to the expected forecast rate during the entire pressure equilibration phase.
- The 10 reservoir pressure measurements obtained since the dynamic model of the Groningen gas field was last history-matched in 2022, all show a close correspondence with the reservoir pressure predicted by this model. The causal relationship between gas production and reservoir pressure is therefore not a source of additional delay in the decline of seismicity.
- Compaction shows a clear non-linear response to larger pore pressure depletions, which is especially visible in the surface subsidence measurements obtained since 2015. Including a non-linear component to the compaction model may, under some physical mechanisms yield a time delay in compaction relative to depletion and so add an additional time delay of the modelled seismicity rates relative to the reservoir pressure depletion rates.
- Analysis using the large within year variations in gas production and to a lesser extent seismicity, estimated the duration of the nucleation process at some 2 to 3 months in a process consistent with the physics of Rate & State friction.
- Clustered events, after-shocks and swarms, last less than 5 days and are therefore not a cause for delay of seismicity, as earthquakes are reported annually.
- The two main potential causes of a possible delay in the decline of seismicity are a transient component in the compaction response to depletion changes and the finite duration of the nucleation process in response to fault stress changes. A study into a combination of these two effects on seismicity is in progress.

6. Proposal for the continuation of the study plan into the development of seismicity in the Groningen gas field during the pressure equilibration phase

The studies into the development of seismicity in the Groningen gas field have delivered important results and new insights over the last two years. NAM will therefore continue this research program with the GMG research team at Caltech led by prof. Jean-Phillipe Avouac.

Five areas of further research have been identified:

Task 1- Finalise current activities and publish results in peer-reviewed journals. This will be finalised in 2024. Complete the revision and publish the studies that were submitted recently regarding the multiphase VFE model (Ledevin et al., in preparation), and the enhanced seismicity catalogue (Sirorattanakul et al., in revision), the quantification of inelastic compaction of the reservoir based on the geodetic and SAR data (Li et al., submitted), and the effect of stress and stress rate on magnitude probability (Tamama et al., submitted).

New studies extending the current research program. These will commence September 2024 and run through 2025.

Task 2: Complete and submit the work of Mateo Acosta on the geomechanical modelling of inelastic reservoir compaction. The objective is to test quantitatively various rheological models against the available laboratory and geodetic observations and assess the impact on earthquake forecasting. The activities that remains to be completed regards the inversion of the model parameters for the laboratory measurements, and drafting the draft article.

Task 3: Use the existing database of seismic moment tensors to test the various stress models, assess the influence of pre-stress and pre-existing fault orientations, throws, and density on the induced seismicity response to pore pressure depletion. Extend the seismological model to forecast seismic moment tensors given the stress and failure models.

Task 4- Explore more in depth the factors that control earthquake magnitudes. We will using quasi-dynamic simulations calculated with the GMG earthquake simulator Quake-DFN (Im and Avouac, 2024) ,which allows to take actual fault geometries into account. The implementation of a H-matric approach in Quake-DFN has just been completed. The application of Quake-DFN to the Groningen example is now possible. We will use stress models computed. We will test the sensitivity of the magnitudes of the simulated earthquakes to the reservoir thickness, fault displacement, stress and stress rates due to the reservoir compaction and compare with observations.

Task 5: Update the modelling framework to allow for the Magnitude Frequency Distribution model (which quantifies the probability of earthquake magnitude) to vary as a function of variables that can / might be space- and time-dependent (reservoir properties, fault geometries).

7. References

1. Study Plan seismicity Groningen during pressure equilibration period, Jan van Elk, Anke Jannie Landman, Clemens Visser and Jeroen Uilenreef, 1 November 2022.
2. Special Report on the Zeerijp Earthquake Swarm starting 4th October 2021, Jan van Elk and Jeroen Uilenreef, NAM, Oct 2021.
3. 48-uur brief voor de Garrelsweer aardbeving aan SodM, NAM, NAM, Nov 2021.
4. 48-uur brief voor de Garrelsweer aardbeving aan ministerie EZK, NAM, NAM, Nov 2021.
5. Special Report on the Garrelsweer Earthquake 16th November 2021 with Magnitude $M_L = 3.2$, Jan van Elk and Jeroen Uilenreef, NAM, Nov 2021.
6. Supplement to Special Report on the Zeerijp Earthquake Swarm starting 4th October 2021, Jan van Elk and Jeroen Uilenreef, NAM, Nov 2021.
7. Letter SodM to minister EZK: Beoordeling SodM halfjaarrapportage seismiciteit Groningen, overschrijding grenswaarde aardbevingsdichtheid en beving Garrelsweer, SodM, 9 December 2021.
8. Rapportage seismiciteit Groningen – mei 2020, Jan van Elk, NAM, June 2020.
9. Rapportage seismiciteit Groningen – november 2020, Jan van Elk, NAM, December 2020.
10. Rapportage seismiciteit Groningen – mei 2021, Jan van Elk, NAM, June 2021.
11. Rapportage seismiciteit Groningen – november 2021, Jan van Elk, NAM, December 2021.
12. Rapportage seismiciteit Groningen – mei 2022, Jan van Elk, NAM, June 2022.
13. Rapportage seismiciteit Groningen – november 2022, Jan van Elk, NAM, December 2022.
14. Letter minister EZK to House of Representatives (Tweede Kamer): Recente ontwikkelingen aardbevingen Groningen, minister of EZK, 16 December 2021.
15. Letter SodM to NAM: Verzoek tot doen van nader onderzoek naar de afwijking tussen de voorspelde en waargenomen seismische activiteit in het Groningen-gasveld, SodM, 14 April 2022.
16. The effect of loading rate on mechanical behavior and deformation mechanisms in Slochteren sandstone, Mark Jefferd, Taka Shinohara, Ronald P. J. Pijnenburg, Suzanne J. T. Hangx, Christopher J. Spiers, 25 November 2021.
17. Compaction in Slochteren sandstone of the Groningen Gas Field, Utrecht University, Suzanne Hangx (Aug. 2023).
18. Seismicity Recalibration 2023, NAM, Valesca Peereboom and Marc Broersma (Feb 2022).
19. Recalibration of the Seismicity Model, NAM, Valesca Peereboom and Marc Broersma (Feb 2022).
20. Rapportage seismiciteit Groningen – mei 2023, Jan van Elk, NAM, June 2023.
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22. Rapportage seismiciteit Groningen – mei 2023, Jan van Elk, NAM, June 2023.
23. Groningen Dynamic Model Update 2023, NAM, Anke Jannie Landman, July 2023.
24. Evaluatie Monitoring Strategie Groningenveld, Anke Jannie Landman and Jan van Elk, June 2022.
25. Recent Reservoir Pressure Measurements in the Groningen gas field Anke Jannie Landman, March 2024.
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The scientific reports are available at the onderzoeksrapporten-webpage of www.nam.nl. The scientific papers are available as open source documents at the website of the journals or the researchgate website.

Appendix A – Cover pages of the scientific Papers

AGU100 ADVANCING EARTH AND SPACE SCIENCE

JGR Solid Earth

RESEARCH ARTICLE
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Reconciling the Long-Term Relationship Between Reservoir Pore Pressure Depletion and Compaction in the Groningen Region

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Abstract The Groningen gas reservoir, situated in the northeast of the Netherlands is western Europe's largest gas reservoir. Due to gas production measurable subsidence and seismicity has been detected across this region, attributed to the deformations induced by reservoir pore pressure depletion. We investigate the surface displacement history using a principal component analysis-based inversion method to combine a diverse set of optical leveling, interferometric synthetic aperture radar, and Global Positioning System data to better constrain reservoir compaction and subsidence history. The generated compaction model is then used in combination with prior pressure depletion models to determine a reservoir uniaxial compressibility. The best fitting model of uniaxial compressibility is time independent but spatially variable. The absence of evidence for any significant time delay between changes in depletion and compaction rates supports an instantaneous poroelastic reservoir response. The absence of nonlinear yielding at the largest compaction strains suggests that anelastic deformations are a minor part of reservoir compaction.

Key Points:

- Seismicity is located within the reservoir levels
- Variations and changes in gas extraction are not manifested in subsidence data
- Pressure depletion within reservoir levels is modeled using geodetic inversion

Supporting Information:

- Supporting Information S1
- Table S1

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1. Introduction

The Groningen gas field, situated in the northeast of the Netherlands (Figure 1), has been in production since 1963, with 70% of the estimated 2,800 billion cubic meters (bcm) of gas now extracted (e.g., Bourne et al., 2014). Prior to gas extraction the region was considered naturally aseismic with no recorded historical events. However, since the 1990s small-magnitude earthquakes have been detected, with these shallow events causing nonstructural building damage and public concern (Dost et al., 2012). The last decade has shown an increase in both the mean frequency and the magnitude of earthquakes. On 17 January 2014 gas production of the Groningen field was limited to 42 bcm per year, in response to the increasing frequency and magnitude of seismicity across the region. This reduction was achieved through reduced extraction from the northern gas extraction sites, in the Loppersum area (Figure 1). In 2015, the reservoir extraction rate dropped further to 27.5 bcm per year (van Thienen-Visser & Fokker, 2017).

The seismicity is thought to be due to strain induced by the decrease of the bulk reservoir volume (Bourne et al., 2015; Dempsey & Suckale, 2017; Nederlandse Aardolie Maatschappij, NAM, 2016), but the details of the underlying mechanisms remain poorly understood (Spiers et al., 2017). Progressive fluid extraction from this reservoir has lead to a documented decrease in reservoir pore fluid pressure by 25 MPa as of 2017 (Bourne & Oates, 2017). The resulting increase in the effective vertical stress must have driven compaction of the reservoir, due to the combination of linear poroelasticity (Wang, 2000) or to anelastic compaction (Schneider et al., 1996), leading to surface deformation (Figure 1).

An improved understanding of the geomechanical properties of the reservoir would help reconcile the compaction response to changing pressure depletion. For a purely poroelastic medium, the elastic deformation of the porous material is coupled to fluid flow, as described by Biot's theory of a porous elastic medium saturated with a compressible fluid. In that case, strain at any point within the reservoir is linearly proportional to the local pressure change. In contrast, in the case of an anelastic response of the reservoir, strain at any point within the reservoir would depend on the entire time evolution of the reservoir pressure depletion and would result in a nonlinear relationship between compaction and pressure change. This formulation

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Probabilistic earthquake locations of induced seismicity in the Groningen region, the Netherlands

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SUMMARY

The Groningen gas reservoir, situated in the northeast of the Netherlands, is western Europe's largest producing gas field and has been in production since 1963. The gas production has induced both subsidence and seismicity. Seismicity is detected and located using the Koninklijk Nederlands Meteorologisch Instituut shallow-borehole array for the period 2015–2017, incorporating the back projection techniques of QuakeMigrate and the nonlinear location procedure to constrain earthquake locations and depths. The uncertainties on the estimated depths are estimated taking into account velocity model, changes in station array geometry and uncertainties in the measurement of arrival times of the P and S waves. We show that the depth distribution of seismicity is consistent with nucleation within the reservoir (28 per cent) or in the overburden (60 per cent) within ~500 m from the top of the reservoir. Earthquakes with hypocentres in the overburden likely originate from overlying Zechstein anhydrite caprock. Based on their depth distribution, it seems like the earthquakes are primarily driven by the elastic strain in the reservoir and overburden, induced by the reservoir compaction. We estimate the probability of earthquakes nucleating beneath the reservoir in the underlying Carboniferous limestone and basement, to be no more than 12 per cent.

Key words: Earthquake hazards; Earthquake source observations; Induced seismicity.

1 INTRODUCTION

The Groningen gas field, situated in the northeast of the Netherlands (Fig. 1), has been in production since 1963, with 70 per cent of the estimated 2800 billion cubic metres (bcm) of gas now extracted (Bourne *et al.* 2014). Prior to gas extraction the region was considered aseismic with no recorded historical events. However, since the 1990s small magnitude earthquakes have been detected, with these shallow events causing non-structural building damage and some public concern (Dost *et al.* 2012). The last decade has shown an increase in both the mean frequency and the magnitudes of earthquakes, leading to the Netherlands Minster of Economic Affairs instructing a reduction in gas extraction since 2014, with the aim of reducing the frequency of future earthquakes (van Thienen-Visser *et al.* 2015). On 2014 January 17, gas production of the Groningen field was limited to 42 bcm yr^{-1}, in response to the increasing frequency and magnitude of seismicity across the region. The regulator of the reservoir, Nederlandse Aardolie Maatschappij, has released a series of publications investigating the induced seismicity, surface subsidence and geomechanical response from gas production. The publication from Nederlandse Aardolie Maatschappij (2016) summarize the advances made since the initial Nederlandse Aardolie Maatschappij (2013) publication.

Seismicity is attributed to changes in induced strain caused by the bulk reservoir volume decrease (Bourne *et al.* 2015; Nederlandse Aardolie Maatschappij 2016; Dempsey & Suckale 2017), with this induced strain expected to be dependent on the possible spatial and temporally varying reservoir properties. Accurate determinations of the hypocentral locations of the generated earthquakes are required to understand the geomechanical behaviour of the reservoir in response to gas extraction. The latest seismicity catalogues of Spetzler & Dost (2017) and Willacy *et al.* (2019) are relatively consistent, with epicentral locations typically within 1 km and hypocentral locations within agreement of 300m. The epicentral location difference is larger than the depth uncertainty due to differences in the imposed regional 1-D or 3-D velocity models and is discussed further in Section 3. Given the typical 300 m thickness of the reservoir, these hypocentral locations are not sufficiently precise to determine whether the earthquakes occur within the reservoir, or just external to the reservoir in the overburden or underburden basement. As a result the mechanism by which earthquakes are induced or triggered remains uncertain. The purpose of this study is to improve the accuracy of the hypocentral

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Stress-based forecasting of induced seismicity with instantaneous earthquake failure functions: Applications to the Groningen gas reservoir

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ABSTRACT

In this study we use the Groningen gas field to test a new method to assess stress changes due to gas extraction and forecast induced seismicity. We take advantage of the detailed knowledge of the reservoir geometry and production history, and of the availability of surface subsidence measurements and high quality seismicity data. The subsurface is represented as a homogeneous isotropic linear poroelastic half-space subject to stress changes in three-dimensional space due to reservoir compaction and pore pressure variations. The reservoir is represented with cuboidal strain volumes. Stress changes within and outside the reservoir are calculated using a convolution with semi-analytical Green functions. The uniaxial compressibility of the reservoir is spatially variable and constrained with surface subsidence data. We calculate stress changes since the onset of gas production. Coulomb stress changes are maximum near the top and bottom of the reservoir where the reservoir is offset by faults. To assess earthquake probability, we use the standard Mohr-Coulomb failure criterion assuming instantaneous nucleation and a non-critical initial stress. The distribution of initial strength excess, the difference between the initial Coulomb stress and the critical Coulomb stress at failure, is treated as a stochastic variable and estimated from the observations and the modelled stress changes. The exponential rise of seismicity nearly 30 years after the onset of production, provides constraints on the distribution of initial strength. The lag and exponential onset of seismicity are well reproduced assuming either a generalized Pareto distribution, which can represent the tail of any distribution, or a Gaussian distribution, to describe both the tail and body of the distribution. The Gaussian distribution allows to test if the induced seismicity at Groningen has transitioned to the steady-state where seismicity rate is proportional to the stressing rate. We find no evidence that the system has reached such a steady-state regime. The modeling framework is computationally efficient making it possible to test the sensitivity to modeling assumptions regarding the estimation of stress changes. The forecast is found robust to uncertainties about the ability of the model to represent accurately the physical processes. It does not require in particular a priori knowledge of the location and orientation of the faults that can be activated. The method presented here is in principle applicable to induced seismicity in any setting provided deformation and seismicity data are available to calibrate the model.

1. Introduction

The Groningen gas field, situated in the north-east of the Netherlands (Fig. 1), has been in production since 1963. Prior to gas extraction, no historical earthquakes had been reported in the area (Dost et al., 2017). Starting in the 1990s small magnitude earthquakes have been detected, with some of these shallow events causing non-structural damage and public concern (Fig. 1; Dost et al., 2017). As a result, it was decided to reduce production from 2014 on (van der Molen et al., 2019). The concern caused by induced seismicity at Groningen has prompted large efforts to monitor the seismicity and surface deformation induced by the reservoir compaction and to develop quantitative models of the seismicity response to the reservoir operations (e.g. Bourne and Oates, 2017; Bourne et al., 2018; Dempsey and Suckale, 2017; Dost et al., 2017, 2020; Richter et al., 2020).

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Coulomb threshold rate-and-state model for fault reactivation: application to induced seismicity at Groningen

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SUMMARY

A number of recent modelling studies of induced seismicity have used the 1994 rate-and-state friction model of Dieterich 1994 to account for the fact that earthquake nucleation is not instantaneous. Notably, the model assumes a population of seismic sources accelerating towards instability with a distribution of initial slip speeds such that they would produce earthquakes steadily in the absence of any perturbation to the system. This assumption may not be valid in typical intraplate settings where most examples of induced seismicity occur, since these regions have low stressing rates and initially low seismic activity. The goal of this paper is twofold. First, to derive a revised Coulomb rate-and-state model, which takes into account that seismic sources can be initially far from instability. Second, to apply and test this new model, called the Threshold rate-and-state model, on the induced seismicity of the Groningen gas field in the Netherlands. Stress changes are calculated based on a model of reservoir compaction since the onset of gas production. We next compare the seismicity predicted by our threshold model and Dieterich's model with the observations. The two models yields comparable spatial distributions of earthquakes in good agreement with the observations. We find however that the Threshold model provides a better fit to the observed time-varying seismicity rate than Dieterich's model, and reproduces better the onset, peak and decline of the observed seismicity rate. We compute the maximum magnitude expected for each model given the Gutenberg–Richter distribution and compare to the observations. We find that the Threshold model both shows better agreement with the observed maximum magnitude and provides result consistent with lack of observed seismicity prior to 1993. We carry out analysis of the model fit using a Chi-squared reduced statistics and find that the model fit is dramatically improved by smoothing the seismicity rate. We interpret this finding as possibly suggesting an influence of source interactions, or clustering, on a long timescale of about 3–5 yr.

Key words: Europe; Instability analysis; Earthquake hazards; Earthquake interaction, forecasting, and prediction; Statistical seismology; Dynamics and mechanics of faulting.

1 INTRODUCTION

Many prominent examples of anthropogenically induced seismicity occur away from tectonically active regions in intraplate settings where strain rates and background seismic activity is low. Two well-known examples are the waste-water injection-induced seismicity in Oklahoma (Ellsworth 2013) and the extraction induced seismicity in the Groningen gas field in the Netherlands with, remarkably, no detected historical seismicity (Dost *et al.* 2017). These two examples, have in common that the onset of induced seismicity occurred at a significant time-lag after the start of injection or production and stress changes in the crust became significant. In Oklahoma the onset of an anomalous seismicity rate occurred about 13 yr after injection started (Zhai *et al.* 2019), but gas was extracted for about 25 yr from the Groningen gas field before any detected earthquake occurred (Bourne *et al.* 2014; Smith *et al.* 2019, Fig. 1a).

In order to understand the interplay of injection or extraction and the observed induced seismicity, a number of recent studies have coupled mechanical models of crustal stress changes and the

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An integrated framework for surface deformation modelling and induced seismicity forecasting due to reservoir operations

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Abstract: Induced seismicity and surface deformation are common observable manifestations of the geomechanical effect of reservoir operations whether related to geothermal energy production, gas extraction or the storage of carbon dioxide, gas, air or hydrogen. Modelling tools to quantitatively predict surface deformation and seismicity based on operation data could thus help manage such reservoirs. To that effect, we present an integrated and modular modelling framework which combines reservoir modelling, geomechanical modelling and earthquake forecasting. To allow effective computational cost, we assume vertical flow equilibrium, semi-analytical Green's functions to calculate surface deformation and poroelastic stresses and a simple earthquake nucleation model based on Coulomb stress changes. We use the test case of the Groningen gas field in the Netherlands to validate the modelling framework and assess its usefulness for reservoir management. For this application, given the relative simplicity of this sandstone reservoir, we assume homogeneous porosity and permeability and single-phase flow. The model fits the measured pressure well, yielding a root mean square error (RMSE) of 0.95 MPa, and the seismicity observations as well. The pressure residuals show, however, a systematic increase with time that probably reflects groundwater ingression into the depleted reservoir. The interaction with groundwater could be accounted for by implementing a multiphase-flow vertical flow equilibrium (VFE) model. This is probably the major factor that limits the general applicability of the modelling framework. Nevertheless, he modelled subsidence and seismicity fit very well the historical observations in the case of the Groningen gas field.

The increasing demand for energy and the need to mitigate the impact on climate is driving various industry operations that involve either injecting or extracting fluids from the sub-surface. These operations include the storage of carbon dioxide, air, gas or hydrogen, gas extraction or geothermal energy production. They imply pressure changes and geomechanical deformation which can lead to measurable surface displacements and seismicity (Rutqvist *et al.* 2016). There is now abundant literature on this topic. For example, Vasco *et al.* (2018) report surface deformation and seismicity at sites of carbon dioxide injection in Algeria; Williams-Stroud *et al.* (2020) report seismicity triggered by CO_2 injection at the Illinois Basin – Decatur Project (IBDP); Li *et al.* (2021) document surface deformation and seismicity induced by groundwater extraction from a sedimentary aquifer at the Raft River geothermal field; and Shirzaei *et al.* (2016) document surface deformation and seismicity induced by wastewater injection in Texas. Seismicity is a concern because of the hazard posed to infrastructures and residents, but also because it could jeopardize the mechanical integrity of the reservoir in case of caprock fracturing. Surface deformation might or might not be a major liability, but it can be in any case a valuable source of information about pressure changes in the reservoir. For these reasons, there is most value in computationally effective methods to relate reservoir operations (well flow rates and pressures) to surface deformation and seismicity.

A number of studies have proposed computationally efficient methods for either reservoir modelling (Cowton *et al.* 2018; Jenkins *et al.* 2019), geomechanical modelling (Kuvshinov 2008; Bourne and Oates 2017; van Wees *et al.* 2019; Jansen and Meulenbroek 2022) or seismicity modelling (Dieterich 1994). Along these lines, we present here a computationally efficient modelling framework which consists of different modules: a simplified reservoir model based on the vertical flow equilibrium (VFE) approximation, a Green's function approach to calculate poroelastic stress changes and surface subsidence and a simple earthquake nucleation model to relate stress changes to seismicity. We use the well-documented example of the Groningen

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Induced Seismicity Forecasting with Uncertainty Quantification: Application to the Groningen Gas Field

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Abstract

Reservoir operations related to natural gas extraction, fluid disposal, carbon dioxide storage, or geothermal energy production, are capable of inducing seismicity. Modeling tools have been developed that allow for quantitative forecasting of seismicity based on operations data, but the computational cost of such models and the difficulty in representing various sources of uncertainties make uncertainty quantification challenging. We address this issue in the context of an integrated modeling framework, which combines reservoir modeling, geomechanical modeling, and stress-based earthquake forecasting. We use the Groningen gas field as a case example of application. The modeling framework is computationally efficient thanks to a 2-D finite-element reservoir model which assumes vertical flow equilibrium, and the use of semi-analytical solutions to calculate poroelastic stress changes and predict seismicity rate. The earthquake nucleation model is based on rate-and-state friction and allows for an initial strength excess so that the faults are not assumed initially critically stressed. The model parameters and their uncertainties are estimated using either a Poisson or a Gaussian likelihood. We investigate the effect of the likelihood choice on the forecast performance and we estimate uncertainties in the predicted number of earthquakes as well as in the expected magnitudes. We use a synthetic catalog to estimate the improved forecasting performance that would have resulted from a better seismicity detection threshold. Finally, we use tapered and non-tapered Gutenberg-Richter distributions to evaluate the most probable maximum magnitude over time and account for uncertainties in its estimation. We show that the framework yields realistic estimates of the seismicity model uncertainties and is applicable for operational forecasting or to design induced seismicity monitoring. It could also

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Geophysical Research Letters

RESEARCH LETTER
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Earthquake Nucleation Characteristics Revealed by Seismicity Response to Seasonal Stress Variations Induced by Gas Production at Groningen

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Abstract Deterministic earthquake prediction remains elusive, but time-dependent probabilistic seismicity forecasting seems within reach thanks to the development of physics-based models relating seismicity to stress changes. Difficulties include constraining the earthquake nucleation model and fault initial stress state. Here, we analyze induced earthquakes from the Groningen gas field, where production is strongly seasonal, and seismicity began 3 decades after production started. We use the seismicity response to stress variations to constrain the earthquake nucleation process and calibrate models for time-dependent forecasting of induced earthquakes. Remarkable agreements of modeled and observed seismicity are obtained when we consider (a) the initial strength excess, (b) the finite duration of earthquake nucleation, and (c) the seasonal variations of gas production. We propose a novel metric to quantify the nucleation model's ability to capture the damped amplitude and the phase of the seismicity response to short-timescale (seasonal) stress variations which allows further tightening the model's parameters.

Plain Language Summary Earthquakes are difficult to predict with certainty, but progress in forecasting their likelihood using probabilistic models based on stress changes has been made. However, challenges remain in understanding how earthquakes start and the initial conditions of faults. Here, we analyzed induced earthquakes in the Groningen gas field, where production is seasonal and seismic activity began 34 years after gas production started. By studying how the earthquakes respond to rapid changes in stress, we could better understand how they start and develop models to forecast their temporal occurrence. By considering factors like the initial strength of the faults, the duration of earthquake initiation, and seasonal variations in gas production we could accurately match the observed seismic activity. We introduced a new measure to evaluate how well the models captured the dampened strength and timing of seismic activity in response to short-term stress changes (such as seasonal variations), which helped refine the model's parameters.

Key Points:

- An improved reservoir, geomechanical, and seismicity modeling workflow is proposed for forecasting induced seismicity at various timescales
- Short-timescale stress variations allow constraining the characteristics of the earthquake nucleation process using Groningen as case study
- Initial strength excess and finite duration of the nucleation process allow reproducing long-and-short timescale characteristics of seismicity

Supporting Information:

Supporting Information may be found in the online version of this article.

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1. Introduction

Numerous activities related to the decarbonization, or security of energy production involve managing subsurface reservoirs (geothermal, CO_2 sequestration, hydrogen storage, conventional, and unconventional oil-and-gas extraction). Induced earthquakes are a major obstacle to these activities (Candela, et al., 2018; Ellsworth, 2013; Goebel & Brodsky, 2018; Grigoli et al., 2017; Kaven et al., 2015; Raleigh et al., 1976; Shirzaei et al., 2016; Walsh & Zoback, 2015; Zhai et al., 2019) raising the need for improved methods to forecast induced seismicity. The modern understanding that earthquakes result from unstable frictional fault slip (Scholz, 2019) provides a foundation to forecast changes of earthquake rate in response to stress changes, ΔS (Bourne & Oates, 2017a, 2017b; Bourne, et al., 2018; Dahm & Hainzl, 2022; Dempsey & Suckale, 2017, 2023; King et al., 1994; Kühn et al., 2022; Langenbruch et al., 2018; Richter et al., 2020; Zhai et al., 2019). The approach requires a model of earthquake nucleation and knowledge of the stress change needed to initiate it (strength excess). At its simplest, the standard Coulomb friction model, CF, assumes that unstable fault slip initiates instantaneously when the ratio of shear stress to effective normal stress exceeds the static friction coefficient. In this context, the often-observed lagged response of the seismicity to stress changes can be modeled through an initial strength excess (Bourne & Oates, 2017a, 2017b). While the CF approach has been found satisfying in several case studies (Bourne & Oates, 2017a, 2017b; Bourne, et al., 2018; Dempsey & Suckale, 2017, 2023; Smith et al., 2022), this model

Seismological Research Letters

Bursts of fast propagating swarms of induced earthquakes at the Groningen gas field

--Manuscript Draft--

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Full Title:	Bursts of fast propagating swarms of induced earthquakes at the Groningen gas field
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Abstract:	Gas extraction from the Groningen gas reservoir, located in northeastern Netherlands, has led to a drop in pressure driving compaction and induced seismicity. Stress-based models have shown success in forecasting induced seismicity in this particular context and elsewhere, but they generally assume that earthquake clustering is negligible. To assess earthquake clustering at Groningen, we generate an enhanced seismicity catalog using a deep-learning-based workflow. We identify and locate 1369 events between 2015 and 2022, including 660 newly detected events not previously identified by the standard catalog from the Royal Netherlands Meteorological Institute. Using the nearest-neighbor distance approach, we find that 72% of events are background independent events, while the remaining 28% belong to clusters. The clusters are dominated by swarms (78% of the clustered events, 20% of total seismicity), with only a small fraction being aftershocks (~8% of total). Among these are five newly identified swarm sequences propagating at high velocities between 3 – 50 km/day along directions that do not follow mapped faults or existing structures and frequently exhibit a sharp turn in the middle of the sequence. The swarms occurred around the time of the maximum compaction rate between November 2016 and May 2017 in the Zechstein salt formation, above the anhydrite caprock, and well-above the directly induced earthquakes that occur within the reservoir and caprock. We suggest that these swarms are related to aseismic deformation within the salt formation rather than fluids. This study suggests that propagating swarms do not always signify fluid migration.
Suggested Reviewers:	Torsten Dahm Professor, GFZ German Research Centre for Geosciences, Physics of Earthquakes

Remote Sensing of Environment

InSAR monitoring of elastic and inelastic deformation in compacting reservoirs due to subsurface operations

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Abstract:	Surface deformation and induced seismicity due to subsurface operations needs to be managed to ensure a safe and sustainable energy matrix. Hydrocarbon and hydrogen extraction and storage are promising avenues but the uncontrolled deformation of subsurface reservoirs hosting the operations can stall the projects and generate significant economic losses. In this study, we analyze the time-dependent deformation of the two reservoirs in northeastern Netherlands using comprehensive geodetic datasets, including InSAR (RADARSAT2, TerraSAR-X, Sentinel-1), GNSS, and optical leveling, to investigate the mechanics of reservoir compaction. Our approach utilizes Independent Component Analysis (ICA) to isolate deformation signals of various origins. We find that surface deformation within the Groningen reservoir is dominated by decadal subsidence, with spatially variable subsidence rates dictated by local compressibility. Remarkably, ICA revealed distinct seasonal fluctuations at Norg Underground Gas Storage (UGS), closely mirroring the gas storage operations. This signal, with an amplitude of approximately 20 mm over a 5x5 km area, is obscured in the raw InSAR time series due to various noise sources. By comparing the observed long-term subsidence within the Groningen reservoir and the seasonal oscillations at Norg from a linear poroelastic compaction model, we can quantify the percentage of inelastic deformation of the reservoir in space and time. Such inelastic compaction is highlighted in an increase of apparent compressibility over time in Groningen. The Norg UGS does not present any sign of inelastic deformation. This study offers important insights for refining seismicity forecasting models in the Groningen context. More generally, it provides a methodology to monitor and calibrate models of the subsurface deformation and surface subsidence induced by fluid pressure changes in the subsurface related to geo-energy operations or aquifer management.
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