Study Plan for Induced Seismicity in Groningen during the Pressure Equilibration Period

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Executive Summary

On 14th April 2022, SodM requested NAM to prepare a plan to study the development of seismicity in Groningen during the pressure equilibration phase, after production has been reduced to relatively low levels and ultimately has ceased. This report contains a proposal from NAM to carry out these studies.

The studies cover the forecasting of reservoir pressure, compaction and seismicity and focus on potential causes of delay between gas production from the reservoir and the occurrence of the earthquakes.

1 Introduction

The Study and Data Acquisition Plan

Start of the NAM-led research programme

Immediately following the Huizinge earthquake on 16th August 2012, NAM prepared a 'Study and Data Acquisition Plan' (ref. 1) describing activities to study the consequences of induced earthquakes in Groningen. After discussions with the regulator, SodM, and the Ministry of Economic Affairs, the plan was made public by the minister in January 2013.

The Study and Data Acquisition Plan has been updated and expanded several times. Major updates of the plan were prepared in 2014, 2016 (with Winningsplan 2016) and early 2019 (ref. 2 to 8). The most recent update of the Study and Data Acquisition Plan was issued in July 2020 (ref. 9 to 12).

Studies into time- and rate-dependent effects included in the Study and Data Acquisition Plan

Since 2014, studies into time- or rate-dependent effects in seismicity were carried out as part of the Study and Data Acquisition Plan. Statistical and machine-learning studies of the historical earthquake catalogue found that these effects are considerably smaller than volume dependent-effects. If these effects exist, they were at that time obscured by volume-effects (ref. 32 to 38).

While producing the Groningen gas field at relative higher production rates, the only other feasible option available to effectively study these potential effects was 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). These experiments indicate that the process leading to compaction in the Groningen gas field is relatively fast-acting and should not lead to significant long time-effects (ref. 39 to 43).

Based on these studies of the earthquake catalogue and laboratory experiments time-delay effects were expected to be relatively small in the Groningen gas field. However, production at a much lower level and cessation of production offers the opportunity to revisit and try to better quantify these effects.

Placing NAM at a distance

As a consequence of the widely shared desire to avoid the appearance of influencing decision making by NAM, the research programme led by NAM was stopped. After 2018, no further studies were initiated and on-going studies were finalised. The July 2020 edition of the Studies and Data Acquisition Plan (ref. 9 to 12) contained an overview of the projects that had been completed and those still to be finalised. These last studies primarily focussed on the further development of the methodology to predict ground motions and a workshop to estimate the maximum magnitude of earthquakes in Groningen based on the latest studies results. Twice SodM requested NAM to prepare an addendum to the Studies and Data Acquisition Plan to provide further detail on the studies in progress (ref. 13 to 17). After having been postponed twice, due to Covid related travel restrictions, the Mmax-workshop was held in Amsterdam from 13th to 17th June 2022 (ref. 18). This completed the last remaining activity of the Study and Data Acquisition Plan.

Subsurface studies into induced seismicity in Groningen will be continued by the DEEPnl programme (led by NWO) and the KEM programme (led by the Ministry of Economic Affairs and Climate Policy and the regulator SodM). The DEEPnl programme and the KEM programme commenced 5 years ago in July and October 2017 respectively. NAM made financial contributions to DEEPnl programme (€ 15 mln). Research into building damage and building risk was ceased with closing down of the Study and Data Acquisition Plan.

Surveillance after cessation of production

NAM will maintain the knowledge and capabilities to carry out the seismic monitoring in support of the surveillance of the field. A surveillance plan has been prepared to ensure continued monitoring of the field after gas production has ceased (ref. 19 and 20). As part of the support for continued seismic surveillance, after the field is closed-in, NAM supported studies into the further evolution of seismicity. These were primarily carried out in a collaboration between the Shell Technology Centre in Amsterdam and 'The Centre for Geomechanics and Mitigation of Geohazards (GMG)' at Caltech led by prof. Jean-Philippe Avouac. Results of these studies have been published in open access peer-reviewed journals (ref. 21 to 23).

SodM request for this study

In October and November 2021, NAM published reports on the earthquake swarm near Zeerijp from 4th to 6th October 2021 and the Garrelsweer earthquake on 16th November 2021 (ref. 24 to 28). The review of these reports by SodM identified a requirement for further studies into seismicity during the pressure equilibration phase of the Groningen gas field (i.e. while producing at relatively low production rates and after gas production from the field is closed in). In the letter by SodM to the minister of EZK, a structure was proposed for this study, in line with the principle that NAM should be at a distance from the studies into seismicity[1] (ref. 29).

> *"I therefore advise you to have TNO, as manager of the public SDRA and responsible for further model development, formulate and carry out a study into the validity of the seismological model and the possible causes of the observed deviation and to involve NAM in this – the latter given their legal obligation to investigate. I advise you to have this investigation submitted to you by NAM before 1 July 2022, to the satisfaction of the Inspector General of Mines."*

In a letter "Recente ontwikkelingen aardbevingen Groningen" (Recent developments earthquake Groningen) of 16th December 2021 to the House of Representatives (Tweede Kamer) (ref. 30) the minister writes on this study[2]:

> *"SodM indicates the number of earthquakes is near the upper limit of the forecast and advises to carry out further research into this. The research fits with TNO's ongoing activities in the context of the model development of the public hazard and risk assessment. I accept the advice and will incorporate the research with the current activities in the assignment for development of the model."*

In a letter of 14th April 2022 (ref. 31) SodM requested NAM to carry out additional studies into the seismicity in the Groningen gas field. Objective is to improve the forecasting of the seismicity during the pressure equilibration phase with a focus on time-dependent effects like creep. The scope of the studies is broad and includes:

- A dynamic reservoir model (calibration during pressure equilibration phase).
- A compaction model (time-dependent compaction as used in subsidence modelling).
- A seismological model (rate dependent and creep effects).
- Alternatives for the extreme-threshold model.

On 30th May 2022, a meeting was held between NAM and SodM to to share expectations and discuss the activities that could potentially be included in the current study plan.

This report

In this document, NAM will provide a short discussion of the mechanisms that potentially could lead to a time-delay between gas production and seismicity. This will be followed by a description of the studies NAM proposes to better understand the time-delay. Together these studies form the studies

plan NAM proposes in response to the request of SodM to improve the forecasting of seismicity during the pressure equilibration phase (when gas production is low or has been terminated).

2 Description of activities in the Study Plan

Discussion of mechanisms for a time-delay in seismicity

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, 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.

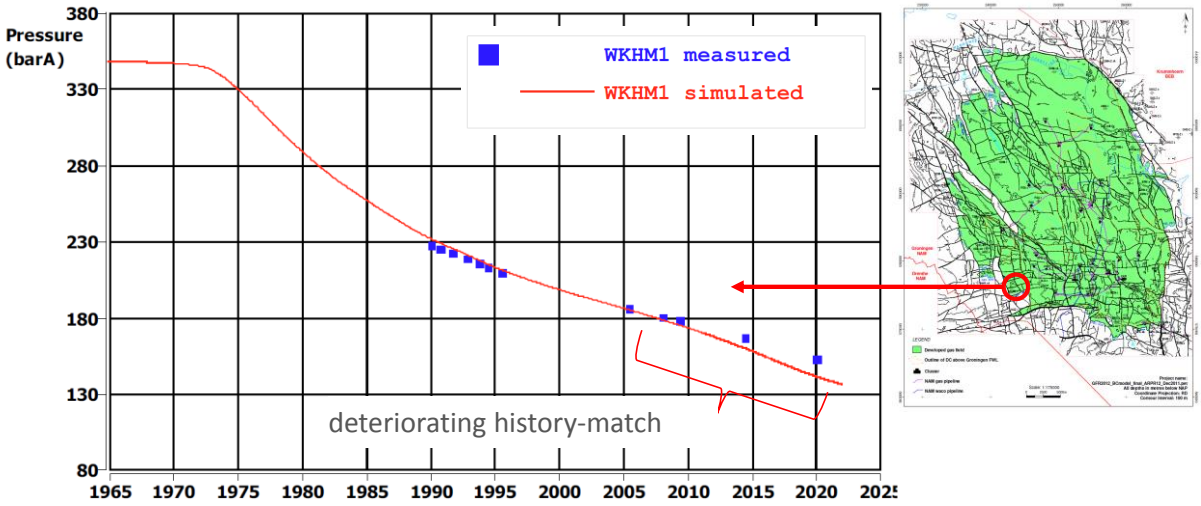
Activities to study each of these possible causes of a delay in seismicity affecting the decline of the seismicity following cessation of production are discussed below.

Reservoir Pressure

History-match reservoir model

Pore pressure diffusion causes a delay between gas production rate changes and reservoir pore pressure changes that increases with the distance from the production well. This mechanism is captured by the dynamic reservoir model used to forecast reservoir pressure changes given well production rates and is included in the seismological model. To include the latest pressure-data, a recalibration of the dynamic reservoir model will be carried out.

A revisit of the history match of the dynamic model for the Groningen gas field is currently carried out by NAM as part of the continued monitoring of the Groningen gas field. One focus of this study is an improvement of the pressure match in the Kolham area. Kolham-1 is one of 10 selected long-term pressure monitoring wells. The KHM-1 pressure history-match has gradually deteriorated over the last ten years to an 11 bar mismatch in 2020. This resulted in lower modelled reservoir pressure and a potential overestimation of forecasted subsidence and seismic hazard in the Kolham area. Kolham is not located in the seismically active area and the contribution of earthquakes from this area to the hazard is small.



Starting point of the calibration is the new version of dynamic reservoir model version 7, that incorporates several corrections and updates in both the static and dynamic part of the model compared to version 6 (ref. 46 to 48).

The quality of the pressure history-match will be assessed for the entire Groningen field. The re-calibration will incorporate new SPG and CITHP-to-BHP data up to May 2022 and focus on the seismically active area around Loppersum.

Compaction

Summarise findings experimental program

The experimental program of testing compaction of core samples has been carried out by researchers at the High Pressure and Temperature Laboratory in the Department of Earth Sciences (Faculty of Geosciences) at Utrecht University, the Shell laboratory in Amsterdam and the Upstream Research Centre of ExxonMobil in Houston. Especially the experiments performed at the University of Utrecht are relevant for time-delay processes like creep. This work and the results have been documented in a large number of scientific papers and dissertations (ref. 39 to 43). After NAM stopped their research program, this research was continued as part of the DEEPnl program led by NWO.

A status summary of the research will be prepared, including extension of this research under the DEEPnl project. A workshop will be held to inform SodM of the status and progress of this work and discuss future research.

Seasonal variations in geodetic observations of surface displacement

Inelastic creep potentially causes a delay between reservoir pore pressure changes and reservoir strain changes. Detailed analysis of the InSAR time series show no evidence of any significant inter-year delay between surface displacement rate changes and reservoir pore pressure rate changes, but instead are well-described on these time-scales by an instantaneous poro-elastic response (ref. 22 and 44).

There remains the possibility that the strain delay is non-zero and unresolved by the previous inter-year geodetic analysis. A further study will analyse the evidence for intra-year seasonal variations in geodetic observations of surface displacement rates and any phase delay in these seasonal variations relative to the historical seasonal variations in gas production rates and pore pressure rates. However, any intra-year delay between reservoir strain and reservoir pore pressure change will not affect the average annual seismic hazard or risk.

This activity will consist of:

- InSar, GPS post-processing and analysis,
- Reconciliation with pore pressure seasonal variations and any evidence for phase lags consistent with a compaction creep mechanism,
- Ensemble pore pressure model and coupling with alternative compaction models (poroelastic, viscoelastic, rate-type compaction models) for forward and inverse modelling of geodesy and seismicity.

This study will be carried out by 'The Centre for Geomechanics and Mitigation of Geohazards (GMG)' at Caltech led by prof. Jean-Philippe Avouac.

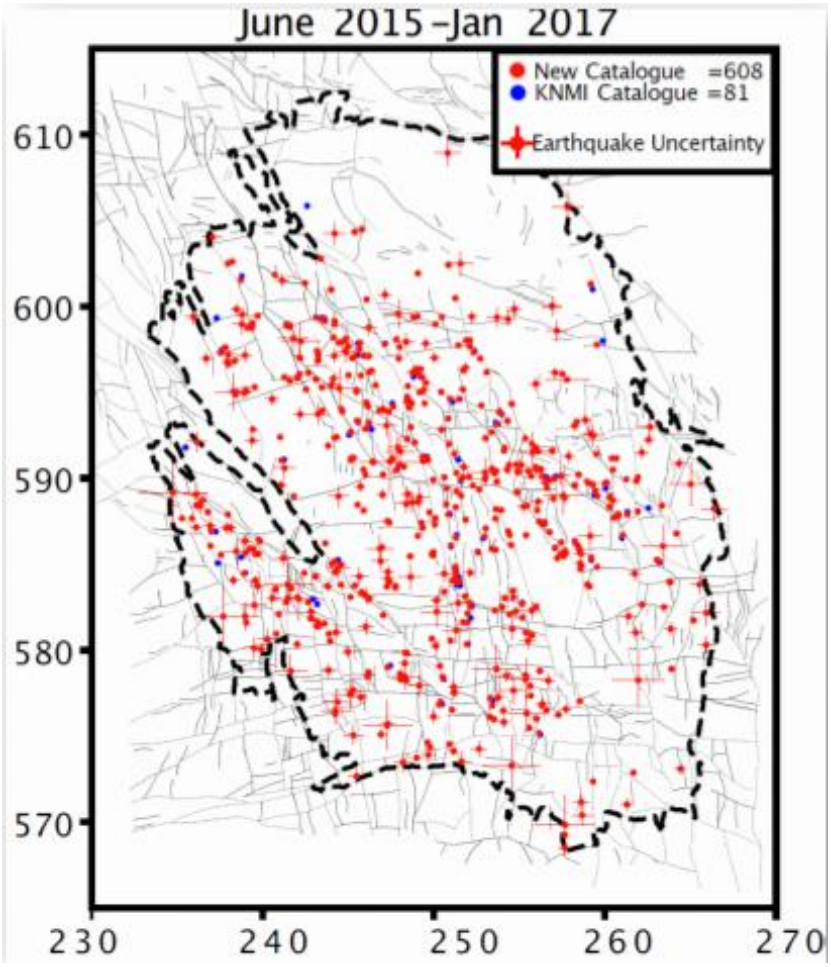
Seismic Event Rate

Revisit calibration of the seismological model

The seismological model has last been calibrated early 2021 using the earthquake catalogue up to 31 December 2020. The model calibration will be revisited using the earthquake catalogue covering two additional years, up to 31 December 2022. Since the previous calibration, 16 additional earthquakes with a magnitude $M_L \geq 1.5$ have been registered in Groningen. For comparison, the total number of registered earthquakes in Groningen with a magnitude $M_L \geq 1.5$ is 360.

Enrichment of the earthquake catalogue

In 2019 a study was published in which the earthquake catalogue for California was enriched using machine learning to identify smaller earthquakes (ref. 49). In 2018, a pilot study was carried out by Caltech University (research team of prof. Jean-Philippe Avouac) on the request of NAM to try these same techniques on the continuous seismic monitoring measurements of the KNMI network. The pilot study applied these methods to the 1 ½ year period from June 2015 to January 2017 and showed a potential increase of earthquake catalogue of 750 % by reprocessing of the existing waveform data. The earthquakes additionally identified were of small magnitude, below the current magnitude of completeness (ref. 50 and 51).

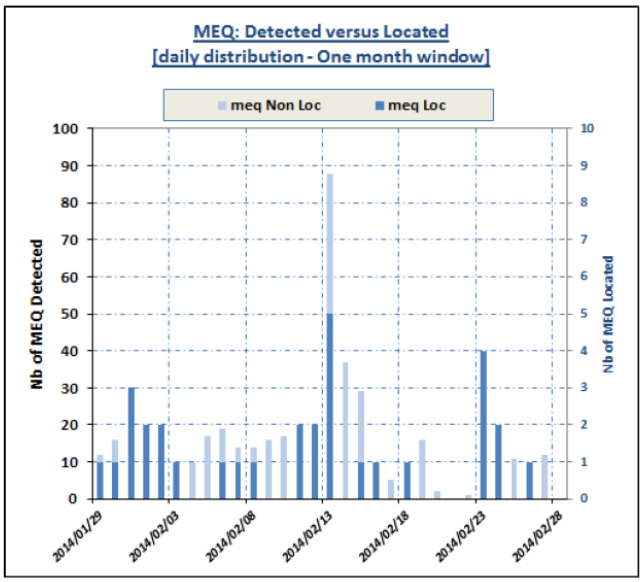


The current study will build on this pilot and aim to enrich the Groningen earthquake catalogue for the period June 2017 to December 2021. One of the benefits of an enriched earthquake catalogue is better insight into after-shocks and earthquake swarms and potentially an improvement in seismic event forecasting. The enhanced earthquake catalogue for Groningen will also be analysed for seasonal variations of induced stress rates and seismicity rates.

Investigation of after-shocks and earthquake swarms.

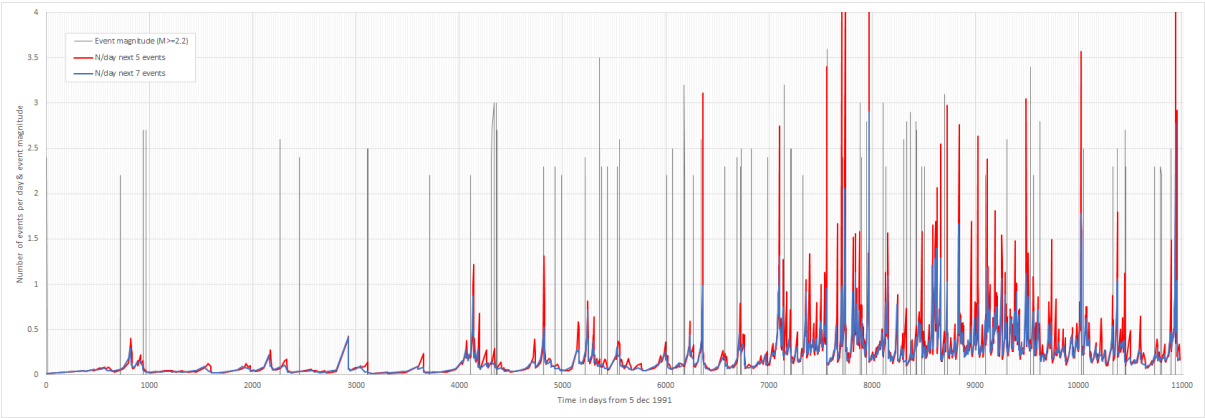
Aftershock sequences cause a delay between the parent earthquakes and their associated aftershock earthquakes. This is caused by delayed fault slip stress-transfers such as after-slip, and delayed aftershock nucleation after the stress transfer (rate and state friction). Detailed analysis of Groningen aftershocks indicates temporal clustering from a few days to months and is consistent with the Epidemic Type Aftershock Sequence (ETAS) model that is included in the Groningen seismological model (ref. 45).

Following the earthquake swarm near Zeerijp from 4th to 6th October 2021 (ref. 24 and 28), a study was initiated to investigate the presence of after-shocks in the Groningen earthquake catalogue. Statistical evidence of temporal and spatial clustering had already been observed in the calibration of the ETAS aftershock component of the Groningen seismological models. In the order of 20% of the located Groningen earthquakes should be regarded as aftershocks. Further examples of aftershocks have been observed in the downhole geophone-array. An aftershock sequence was seen on downhole array following the earthquake with magnitude M_L = 3 on the 13th February 2014.



(MEQ stands for micro-earthquakes)

The figure below shows the number of earthquakes during the 5- and 7-day period following an earthquake with magnitude $M_L \geq 2.2$, based on the KNMI earthquake catalogue for Groningen. It shows that in many cases large events coincidence with bursts of seismicity – foreshock-aftershock sequences. The results of an initial pilot study using the KNMI earthquake catalogue for Groningen have been presented at the Mmax-workshop from 13th to 17th June 2022 in Amsterdam.

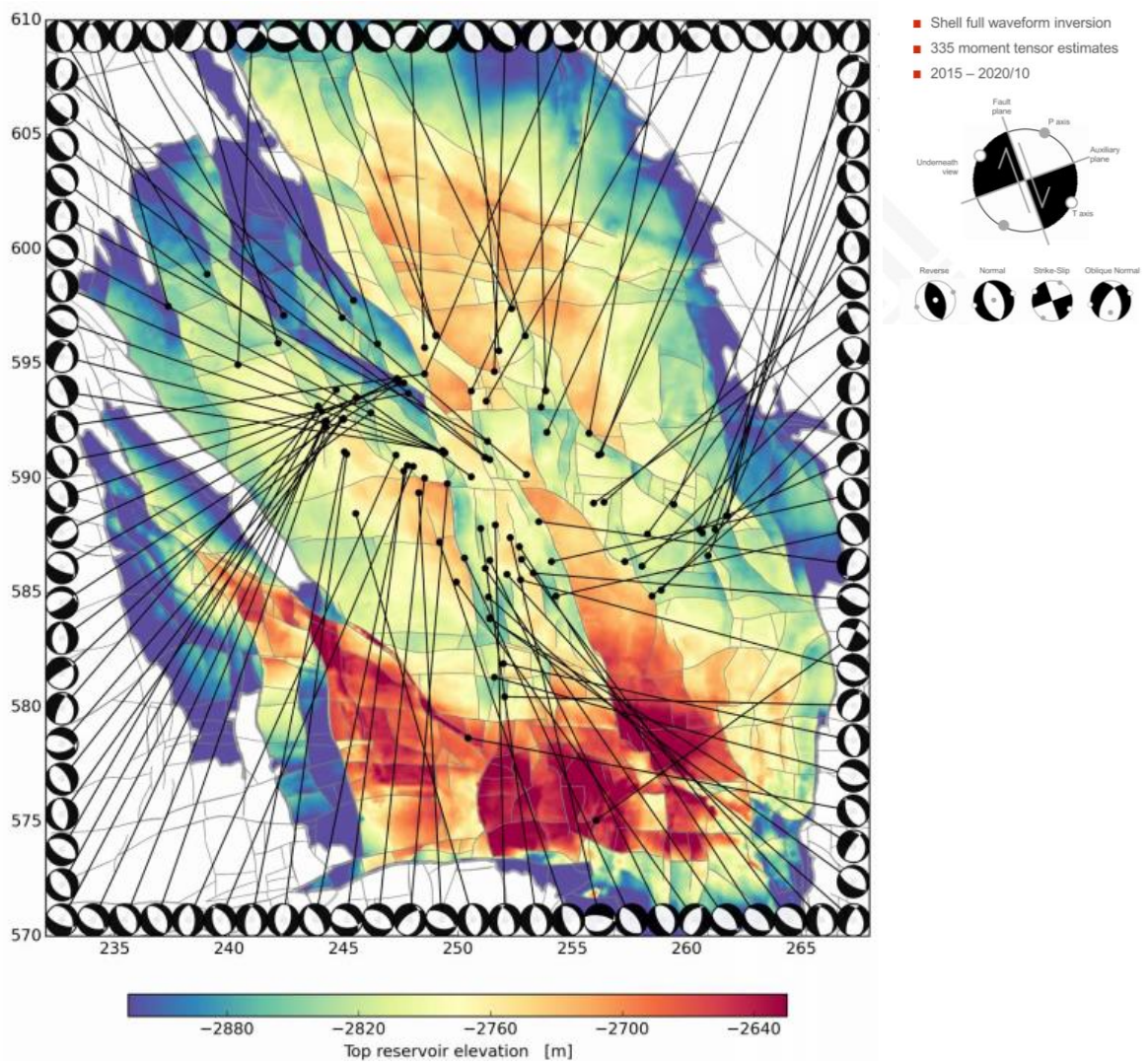


In the follow-up study, apart from the current earthquake catalogue for Groningen maintained by KNMI also the enriched earthquake catalogue will be used (see above).

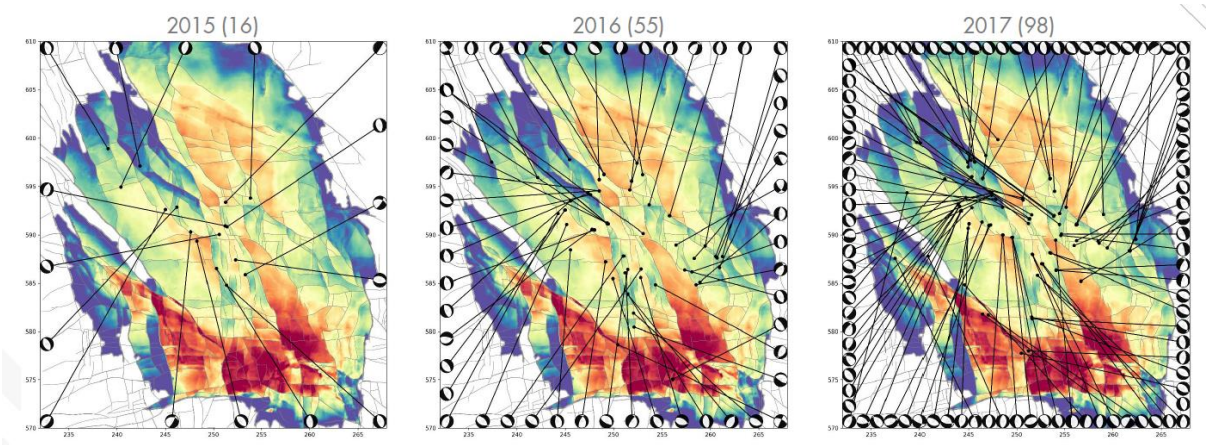
Focal mechanism and fault structure

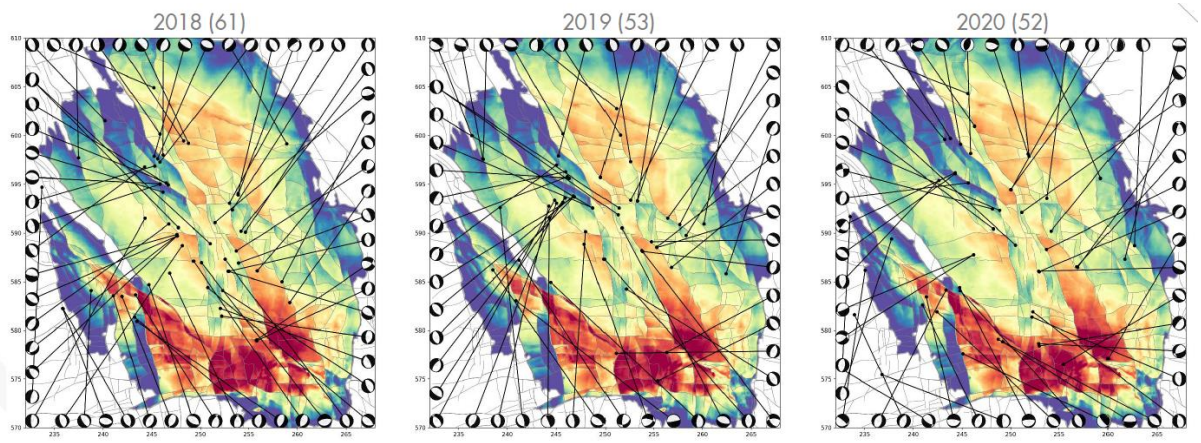
As part of the seismic monitoring program Shell has analysed data from the seismic monitoring network since 2017, using the automated full waveform Inversion (FWI) methodology (ref. 52 to 53). These efforts have resulted in a catalogue of more than 450 earthquake for which the event location (including depth) and the source characteristics have been established. Especially the orientation of the source mechanism allows for improved comparison with local faults.

The results of the automated method developed by Shell are used in monitoring the seismicity in Groningen and have been reported in several special reports for the regulator (Ref. 24, 27, 28, 54 and 55). In 2020, a pilot study was carried out to investigate the potential to use this data to further improve the seismological model.



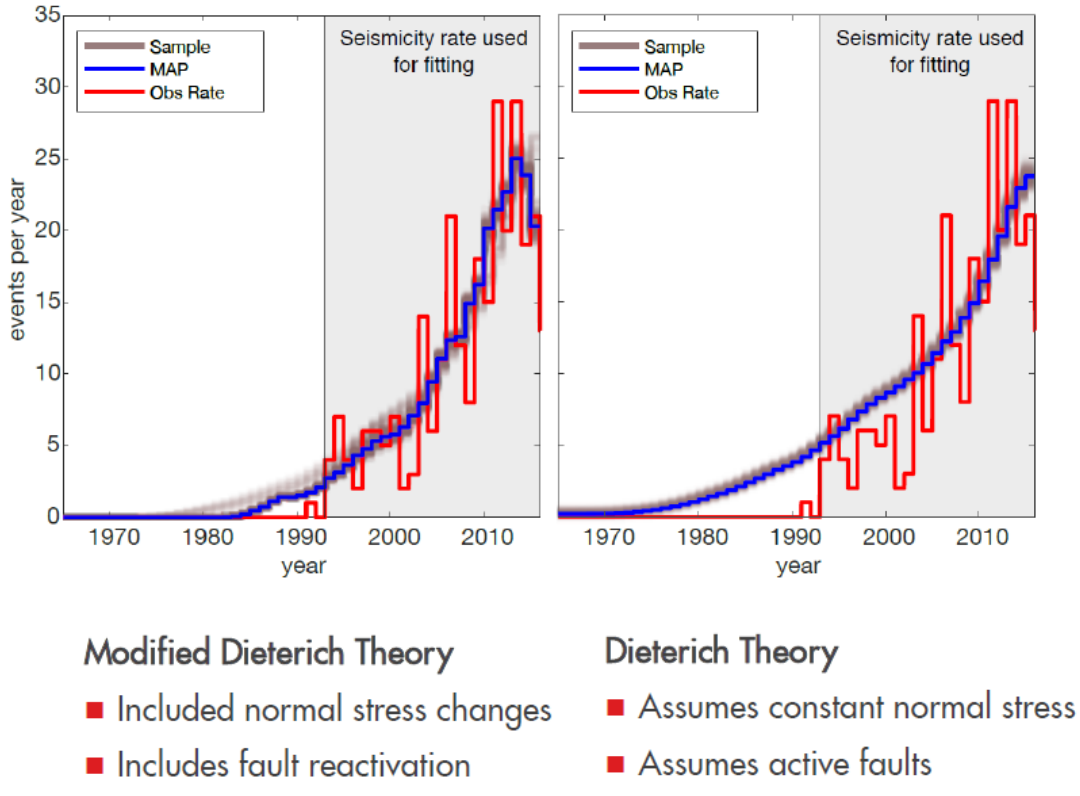
Incorporation of this source data could potentially improve the areal distribution of earthquakes in the event forecast. The current detailed analysis will be extended with more recent evaluations of earthquakes and potential for incorporation in the seismological model assessed.





Including Rate and State Seismicity Rate Theory into the Seismological Model

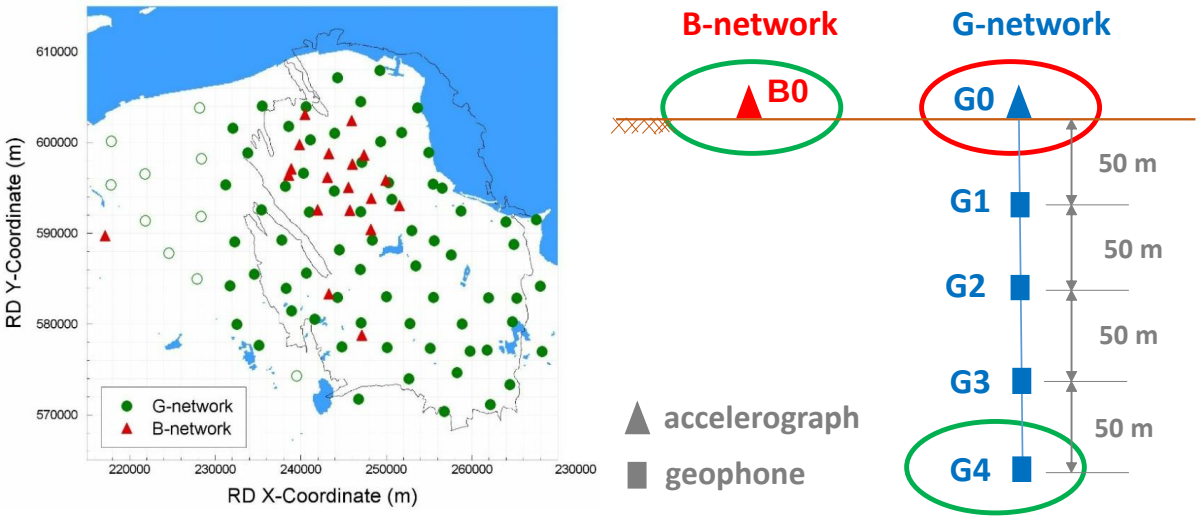
Slow fault creep during the earthquake nucleation phase potentially causes a delay between the fault stress changes induced by reservoir strains and seismicity rate changes on the fault. The leading theory for this mechanism is rate and state friction. Until recently seismological models incorporated rate and state friction assuming critical pre-stress, initially active faults (Dieterich 1994). This is not the case for the Groningen gas field (ref. 56). A further theoretical development of this model allowed the inclusion of sub-critical prestress, initially inactive faults, with successful application to Groningen seismicity (ref. 21). In this case the delay between stress rate and seismicity rate changes is sufficiently small to be indistinguishable from the instantaneous Coulomb failure model for forecasting annual average seismicity rates. A further study will enhance the existing earthquake catalogue to assess again any evidence for a lag between seasonal variations in seismicity rates, relative to seasonal variations in the induced stress rates.



Ground Motions

Introduction seismic monitoring network

The Groningen seismic monitoring network consists of stations with different designs (ref. 57 and 58). The B-stations consist of an accelerometer located at the base inside buildings. These buildings are predominantly light-weight structures. The first B-stations were installed in 1993. Currently, 18 B-stations are operational. The G-stations consist of an accelerometer located on a concrete slab together with a 200 m deep well with four geophones located at every 50 m. The G-stations were installed in the period 2014 to 2015. There are 69 G-stations operational. To the west of the Groningen gas field an additional nine G-stations were placed consisting of only an accelerometer on a concrete slab, without an accompanying well. In 2017 and 2018, four broadband stations have also been added to the network. The broadband sensors are located at the bottom of 120 m wells.



Investigations to date

Detailed comparison of the response of B-stations and G-stations showed differences in the short-period attenuation of the accelerometers of the B-stations and G-stations (ref. 59). Only for the dense seismic monitoring network installed in Groningen could such discrepancies have been noticed. The impact of this on the risk assessment for Groningen is likely very small. However, understanding of the cause of the differences might be relevant for other seismic networks placed on soft-soil areas. Further investigation of this is therefore of general interest. Several hypothesis have already been proposed and investigated to explain the differences:

- Differences in accelerometer instrumentation were tested at the shake-table of BuildinG (ref. 60).
- Detailed analysis based on modelling was carried out by Mozayk to investigate the impact of the building and cabinet on the earthquake measurements (ref. 61).
- Due to (a combination of) the weight of the building and vibrations in the building the properties of the soil below the building have been changed.

The first studies showed that neither differences in accelerometer type nor soil-structure interaction of the light-weight buildings (B-stations) compared to the cabinets on a concrete slabs (G-stations) could have caused the difference observed in the short-period attenuation. The third investigation was planned to commence on the 18th March 2020, but appointments to install geofoons near three B-station buildings (BHAR, braced-steel-frame barn/warehouse, BLOP small shed, BMD2 masonry-wall, timber-roof barn) were cancelled on 16th March 2020, after premier Rutte announced a hard lock-down for COVID-19 in a press conference on Dutch national television.

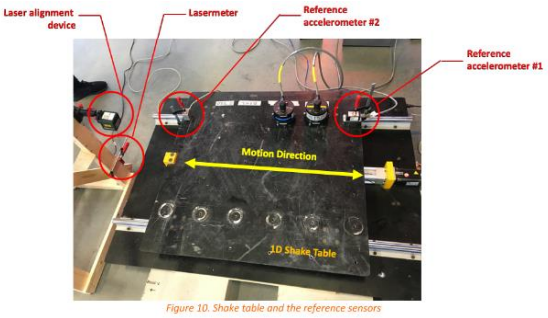


Figure 10. Shake table and the reference sensors

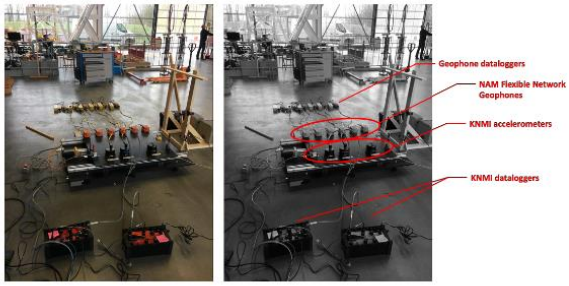


Figure 11. General view of the test setup, NAM geophones and KNMI sensors placed on the shake table

Feasibility Study

On 27th June 2022, a meeting was held at the NAM offices to explore the possibility of recommencing the measurement program to test the remaining hypothesis:

> Due to soil preparation making the soil ready for construction (in Dutch 'bouwrijp maken') the resulting densification has changed the properties of the soil beneath the building. This leads to a different local ground acceleration compared to when the soil had been undisturbed. This process causes the difference in the response of the B-stations (located at soil prepared for construction) and the G-stations (located at a concrete slab on undisturbed soil).

Representatives of Rossingh Geophysics, NAM, Eucentre, Julian Bommer, Eddie Siemerink, Rui Pinho and Michail Ntinalexis attended this meeting. Currently, an experimental program is being formulated with contributions from these parties.

Two avenues are being considered:

- Measurements of accelerometer response at selected B-stations and in the immediate vicinity of these stations. These will be more relevant to the observed differences in response in the Groningen seismic monitoring network.
- Measurements of accelerometer response at different locations with similar soil properties and geology, but with different levels of densification applied for the experiment. The experiment will be easier to control and potentially yield more general insights also of use elsewhere.

Elements of the experimental program are:

- Generation of a seismic signal (accelerated drop-weight, dynamite charges or small electro-magnetic vibrator).
- Design of the acquisition to obtain placement of 3C geophones and 'source locations'.
- Description of the local geology using hand-coring of top-soil layers, CPT and SPT.

Upon completion of the design of the experiments, these will be presented and discussed with SodM, before a decision on the final program is taken.

3 Study Management and Schedule

Introduction

Since 2018, NAM has been closing out studies of the 'Study and Data Acquisition Plan' in order to finalise the overall handover from NAM to the Government of handling and execution of the earthquake issues in Groningen (including the research program into induced seismicity in Groningen). This is referred to as 'NAM-at-a distance'. The last activity of this plan, the Mmax-workshop, was held in June 2022.

The current 'Study Plan for Induced Seismicity in Groningen during the Pressure Equilibration Period' in part continues on-going studies and builds on studies planned as part of the seismic monitoring of the Groningen gas field. These studies have been documented in reports available on the NAM web-page or in peer-reviewed papers.

The studies proposed in this report will be documented in scientific papers published in prestigious peer-reviewed journals. Any code developed as part of this research will be made available through a transferable GitHub.

Timeline

With the closing out of the 'Study and Data Acquisition Plan', NAM cancelled and finalised studies, reducing ties with the scientific community. The timeline presented in this plan is therefore still conditional on NAM being able to attract scientists to participate in this new research and agree a work schedule.

The two studies on seasonal variations in surface displacements and stress rates and seismicity rates respectively take longest time to complete. These are an extention of earlier studies (ref. 22 and 44). Their delivery date is mid 2023. Other studies proposed in this plan have completion dates in the fourth quarter of this year and the first quarter of next year.

Activity	Deadline
Complete History-Match and share new pressure forecast for potential use in risk assessment (SDRA).	31/12/2022
Workshop to discuss experimental program on compaction of rock samples performed at University Utrecht.	15/02/2023
Paper on seasonal variations in geodetic observations of surface displacement.	30/06/2023
Share new calibration of the Seismological Model for potential use in risk assessment (SDRA).	31/01/2023
Paper and enriched earthquake catalogue in support of other studies.	15/01/2023
Paper on investigation of after-shocks and earthquake swarms.	31/03/2023
Paper on seasonal variations in induced stress rates and seismicity rates.	30/06/2023
Paper on incorporating focal mechanism and fault structure in SM for discussions on activity to include in risk assessment (SDRA).	01/02/2023
Share feasibility study on investigation into the effect of soil-improvement.	01/04/2023
Make transferable GitHub with code available to reproduced results studies on seasonal variations.	01/08/2023

Study Plan for Induced Seismicity in Groningen during the Pressure Equilibration Period
August 2022

Activiteit	2022						2023						
	J	A	S	O	N	D	J	F	M	A	M	J	J
Reservoir Pressure													
History-match reservoir model													
Compaction													
Summarise findings experimental program													
Seasonal variations in geodetic observations of surface displacement													
Seismic Event Rate													
Revisit calibration of the Seismological Model													
Enrichment of the earthquake catalogue													
Investigation of after-shocks and earthquake swarms.													
Seasonal variations in induced stress rates and seismicity rates													
Include focal mechanism and fault structure in Seismological Model													
Ground Motion													
Investigation effect of soil-improvement									FR				
Project Deliverables													
Publish scientific papers													
Transferable GitHub with code to reproduced results													

Working
Discussing with SodM and finalisation

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End-Notes

[1] Translation of the text.

Original text:

> *Ik adviseer u daarom om TNO, als beheerder van de publieke SDRA en verantwoordelijke voor de verdere modelontwikkeling, een onderzoek naar de validiteit van het seismologisch model en de mogelijke oorzaken van de waargenomen afwijking te laten formuleren en uitvoeren en NAM hierbij te betrekken – dit laatste mede gegeven hun wettelijke onderzoeksplicht. Ik adviseer u dit onderzoek voor 1 juli 2022, ten genoegen van de Inspecteur-generaal der Mijnen, door NAM bij u in te laten dienen.*

Ik adviseer u daarom om TNO, als beheerder van de publieke SDRA en verantwoordelijke voor de verdere modelontwikkeling, een onderzoek naar de validiteit van het seismologisch model en de mogelijke oorzaken van de waargenomen afwijking te laten formuleren en uitvoeren en NAM hierbij te betrekken – dit laatste mede gegeven hun wettelijke onderzoeksplicht. Ik adviseer u dit onderzoek voor 1 juli 2022, ten genoegen van de Inspecteur-generaal der Mijnen, door NAM bij u in te laten dienen.

English translation:

I therefore advise you to have TNO, as manager of the public SDRA and responsible for further model development, formulate and carry out a study into the validity of the seismological model and the possible causes of the observed deviation and to involve NAM in this – the latter given their legal obligation to investigate. I advise you to have this investigation submitted to you by NAM before 1 July 2022, to the satisfaction of the Inspector General of Mines.

[2] Translation of the text:
Original text:

SodM geeft aan dat het aantal aardbevingen aan de bovenkant zit van de voorspellingen en adviseert om hier onderzoek naar te laten verrichten. Dit onderzoek past binnen de lopende activiteiten van TNO in het kader van de modelontwikkeling van de publieke seismische dreiging en risicoanalyse. Ik neem dit advies over en zal het onderzoek in samenhang met de lopende activiteiten opnemen in de opdracht voor modelontwikkeling.

English translation:

SodM indicates the number of earthquakes is near the upperlimit of the forecast and advises to carry out further research into this. The research fits with TNO's ongoing activities in the context of the model development of the public hazard and risk assessment. I accept the advice and wil incorporate the research with the current activities in the assignment for development of the model.