Hazard and Risk Assessment for Induced Seismicity Groningen

Study 1 Hazard Assessment

Update 1st May 2015

Contents

Introduction

The people living in Groningen have been confronted with increasing intensity of the effects of induced earthquakes. This has been the source of anxiety and frustration among the community. NAM, the ministry of Economic Affairs, and regulator SodM face the challenge of formulating an adequate response to the induced earthquakes. To that end, the currently existing instruments for assessing and mitigating these effects – as set down in mining regulations, risk policies and, for example, building codes – need to be extended and made fit-for-purpose.

Therefore, a new risk methodology was developed and initially used in the Winningsplan 2013. This new methodology combines NAM's own internal safety standards, including the important role of monitoring, national and international analogues. It will be progressed towards a dedicated risk assessment framework for the Winningsplan 2016. For this latter purpose the risk methodology has been shared with the Groningen Scientific Advisory Committee established by the Ministry of Economic Affairs (Ref. 17). This committee is tasked to develop a national policy on risks associated with induced earthquakes. This policy will be used, per decision on the Winningsplan 2013 (Ref. 19), to assess the Winningsplan 2016. Supporting elements, such as a national annex to the Eurocode 8 Building Code addressing the fragility of buildings.

This Study 1 on "Hazard Assessment" addresses the 'technical' hazard elements of the risk methodology, following the causal chain pictured in the subsequent paragraphs. This work has been well advanced since December 2013, with key deliverables such as a seismological model and compaction based on subsidence inversion now available. In Study 2 "Risk Assessment", the risk methodology is described, following the same causal chain as used in the current hazard study. This work covers for the first time a fully probabilistic risk assessment, which as yet can only be used qualitatively as it awaits quantitative calibration following studies such as site response measurements at the geophone network locations and a shake table test for a terraced house. The two studies can be read independently. The additive attributes for the full risk dimension, including the regional social impacts are to be merged into the composite 'equation' to evaluate the impact of gas production[1].

Data presented in this report should be read or interpreted with due caution taking into account the remaining scientific uncertainties and further calibration, refining of models, validation taking place in 2015 and 2016.

History of induced earthquakes in Groningen

Since 1986, relatively small earthquakes have occurred near producing gas fields in the provinces of Groningen, Drenthe and Noord-Holland. Over time, these events were considered to be a negative, but not an insuperable, consequence of gas production. Since the Huizinge earthquake, however, it is recognized that the earthquakes also pose a potential safety risk.

In the early 90's, a multidisciplinary study was initiated by the Ministry of Economic Affairs and guided by the above-mentioned Scientific Advisory Committee. This study focused on the relationship between gas production and earth tremors. It was concluded that the observed earth tremors were of non-tectonic origin and most likely induced by reservoir depletion (i.e., gas production). An agreement was set up with Royal Dutch Meteorological Institute (KNMI) to install a borehole seismometer network in the Groningen area. The network has been active since 1995 and

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[1] This report is the report as indicated in article 6-1 of the decision from the Minister of Economic Affairs of 30 January 2015

was designed to detect earth tremors, pinpoint their locations and quantify their magnitudes. Additional accelerometers were installed in areas with highest earth tremor frequency.

1986	First induced earthquake observed (Assen M= 2.8)
Early ’90	Multidisciplinary Study (1993) concluded:
	• “Earthquakes in North-Netherlands are induced by gas production”
1995	Seismic network operational
1995	KNMI estimates a maximum magnitude for Groningen: M_{max}= 3.3
1995	Agreement between NAM, Groningen and Drenthe on damage claim handling
1997	Roswinkel earthquake with M= 3.4
1998	KNMI adjusts estimate of maximum magnitude: M_{max}= 3.8-4.0
2001	Legal regulations damage claim handling set established by Parliament
	Establishment of Tcbb (Technische commissie bodembeweging):
2003	Technisch Platform Aardbevingen (TPA) established
2004	KNMI adjusts estimate of maximum magnitude: M_{max}= 3.9
2004	First Probabilistic Seismic Hazard Analysis by TNO and KNMI
2006	Westeremden earthquake with M= 3.4
2009	Calibration study by TNO (Damage analysis)
2011	Deltares assesses the Building Damage in Loppersum and confirms M_{max}= 3.9
2012	Huizinge earthquake with M= 3.6

Figure 1 Sequence of main events until the earthquake of 16th August in Huizinge

Two factors triggered a renewed focus and widespread attention for the issue of seismicity induced by gas production in Groningen. First, the earthquake near Huizinge (16 August 2012) with magnitude M_w=3.6 was experienced as more intense and with a longer duration than previous earthquakes in the same area. Significantly more building damage was reported as a result of this earthquake compared to previous earthquakes. Second, a general realization and concern developed in society that seismicity in the Groningen area has increased over the last years.

NAM reacted to these developments by initiating a series of new initiatives to better understand the relationship between gas production and safety. These are described in the NAM “Study and Data Acquisition Plan”, issued in October 2012 in support of a new Winningsplan 2013. This is further described in the next section.

Study and Data Acquisition Plan

The Study and Data Acquisition Plan describes the relationship and goals of all study and research effort by NAM and was shared with SodM and the Ministry of Economic Affairs (Ref. 1) in November 2012 and made public early 2013. Regular updates of the study progress were reported to the advisory committee of the Minister of Economic Affairs (TBO), the regulator (SodM) and her advisors (TNO-AGE and KNMI) and the "Dialoogtafel Groningen". The most recent update was reported to SodM in March 2015 (Ref. 13).

The main objectives of the plan are to:

1. Understand the impact of the earthquake hazard on buildings and the safety of the community
2. Perform a fully integrated Hazard and Risk Assessment for the Groningen region, with all uncertainties fully and consistently recognised and quantified
3. Identify and develop mitigation options:
    - Production measures
    - Pressure maintenance options
    - Optimised Structural Upgrading program:
        - Identify highest risk buildings
        - Establish optimal structural upgrading methodology

Other objectives are to:

4. Address areas of different scientific views, and initiate additional studies or measurements to create consensus,
5. Effectively monitor subsidence and seismicity,
6. Continuously improve our understanding of the physical mechanism leading to induced seismicity and the resulting hazard and reduce the uncertainty in the hazard and risk assessment.

To achieve these objectives, NAM has sought the assistance and advice from external experts for each expertise area from academia and knowledge institutes. The total cost of the study and data acquisition program for the period 2014 – 2016 is estimated to be almost € 100 mln. This program is reviewed every 6 months and adjusted if necessary.

Some of the activities in the Study and Data Acquisition Plan are not expected to directly support the Hazard and Risk Assessment of Winningsplan 2016. They rather serve to increase the understanding of physical processes and therefore lend support and physical background to the hazard and risk assessments. These activities are not expected to reach a level of maturity in the short term where they can be used to lend support to predictions. Examples are, the planned laboratory experiments on the Zeerijp core to investigate rupture and compaction processes in reservoir rock.

Winningsplan 2013

Intermediate results of the studies into induced seismicity carried out in 2013 were shared with the technical advisory committee of the Ministry of Economic Affairs (TBO) at three two-day workshops held in May, July and August 2013, and in several intermediate technical meetings focusing on specific technical issues. The study results were reported to the Minister of Economic Affairs and SodM in November 2013 in the “Technical Addendum to the Winningsplan - Groningen 2013” (Ref. 3, 4 and 5). This report also contained a probabilistic Hazard Assessment complemented by a deterministic Risk Assessment.

- Probabilistic analysis is based on chance incorporated in all uncertainties
- Deterministic analysis is based on specifically defined scenarios

In addition to the Winningsplan 2013, NAM also issued a Borgingsprotocol and a Monitoringplan in December 2013, enabling regular revisits of the risk assessment on the basis of acquired monitoring data.

The aforementioned “Technical Addendum to the Winningsplan - Groningen 2013” (Ref. 4 and 5) gives a full overview of the results of the studies carried out by NAM by the end of 2013.

Winningsplan 2016

The work done during 2013 provided new insights and received generally positive comments from peer reviewers and the TBO, but was by no means conclusive or complete. Many technical questions remained unresolved (Ref. 8 and 9), while uncertainties in the geomechanical parameters and in the estimated seismic hazard were still large. Some of the remaining uncertainty stems from lack of knowledge and data (epistemic uncertainty) and is therefore prone to be further constrained with ongoing data acquisition and analysis. The “Study and Data Acquisition Plan” was therefore continued in 2014 and 2015 and will be continued in the years thereafter.

The “Study and Data Acquisition Plan” is considered to be ambitious and comprehensive:

- It involves many external entities: commercial parties, academics, university laboratories and independent experts (Appendix A)
- The scientific work is subjected to an extensive voluntary and compulsory assurance program, through independent peer-review (Appendix B)
- Bases hazard and risk assessments on evidence and data, not solely on expert opinion or expert community consensus
- The Scientific Advisory Committee (SAC) appointed by the Minister of Economic Affairs provides independent oversight of the studies for the Winningsplan 2016

With the limited data available in 2013 to support or reject the available theories and models, the hazard assessment in 2013 was intended to be conservative. With the ongoing acquisition of new data and the progress of the studies, the hazard assessment will gradually become more reliable. Consequently, the assessed hazard and its associated uncertainty are expected to decrease.

In January 2014, the Minister announced the intention to approve the Winningsplan Groningen 2013 subject to the condition that NAM would submit a new Winningsplan in 2016 based on further and emerging insights and study outcomes (Ref. 12). It was realized that the hazard could potentially increase (and there were more uncertainties for the longer period of time) and that new insights were to be gained from ongoing studies and monitoring. The final decision on the Winningsplan was made on 30 January 2015 (Ref. 19) with a number of conditions. For the purpose of this report, the conditions in article 6 and in article 4 of the final decision from February 2015, are most pertinent. Article 4 demands an assessment of the hazard and risks per relevant region within the Groningen Field by 1st of May 2015. Several other conditions, e.g. the risk methodology, production caps, monitoring requirements and mitigation measures in terms of structural upgrading, are related to this hazard and risk assessment (as input or output) but are not discussed here.

The current report presents the intermediate update for mid-2015 (1 May 2015) of the Hazard and Risk Assessment for Winningsplan 2016. Since these intermediate results are extracted from an on-going work plan designed for delivery in 2016, they should be interpreted with caution given that some elements of the models, which are currently significantly more advanced than those presented in the Winningsplan 2013, are still evolving and maturing further using newly available data and recognizing that other improvements to reduce the uncertainty and further data from the monitoring programme will only be incorporated in a next version as they are currently not yet complete/mature.

Hazard and Risk Assessment

An important topic in NAM's research program focuses on the assessment of the hazard and risk to which people and buildings in the immediate vicinity of the gas field are exposed. The research on hazard and risk has been split in two studies, as explained in the Introduction section. Study 1 discusses the hazard assessment. The hazard is defined as: *the annual frequency or probability, associated with different levels of ground motion, at which buildings and other objects are exposed to earthquakes induced by the production of gas*. A commonly used measure of the hazard is the Peak Ground Acceleration (PGA).

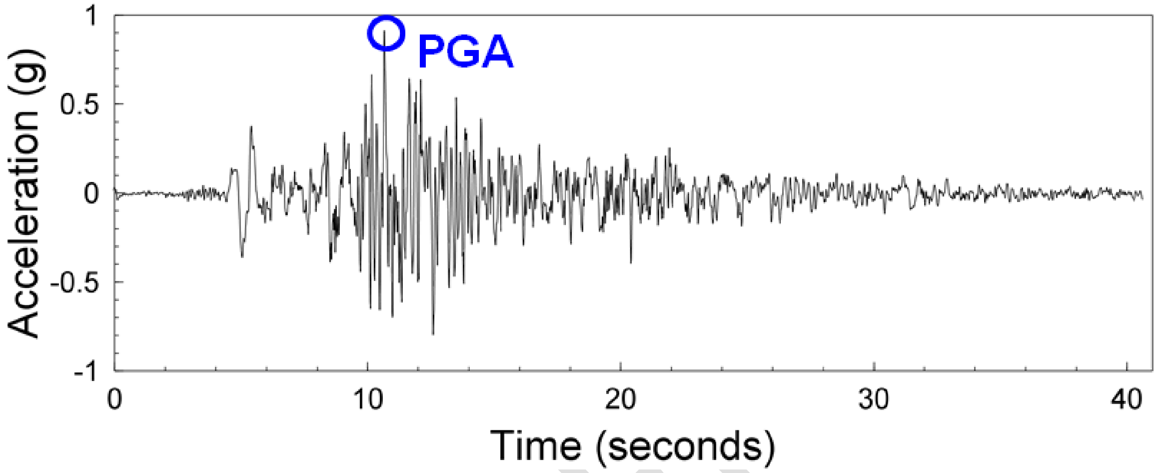

Figure 3 Acceleration record for a typical strong tectonic earthquake, with the PGA indicated.

Other important parameters for characterizing the hazard include:

- the spectral acceleration;
- the duration of earthquake accelerations;
- and the number of cycles.

A possible consequence of the seismic hazard is damage to, and in exceptional cases even collapse of, buildings and other objects. To date no buildings have collapsed due to an earthquake. Potential injuries or casualties for people located close to or inside these buildings can result from the shaking loose and falling of building elements or from the (partial) collapse of buildings.

The hazard and the risk of building collapse and the subsequent impact on people is assessed by a statistical methodology. The most widely used method is the Probabilistic Hazard and Risk Assessment or PHRA. The statistical Monte-Carlo method is used to perform the calculations for this hazard and risk assessment. This method entails repeated random sampling of the input variables to obtain numerical results for hazard and risk. This method is a common approach in solving physical and mathematical problems. It allows the uncertainties in all parameters to be consistently reflected in the PHRA, giving the full distribution of the hazard and risk and therefore also the hazard and risk at a given exceedance level.

Scope and Expertise Required

The hazard and risk assessment needs to span from the cause (gas production) to the effect (injuries and casualties). The uncertainties in each individual step need to be estimated and consistently incorporated in the total assessment.

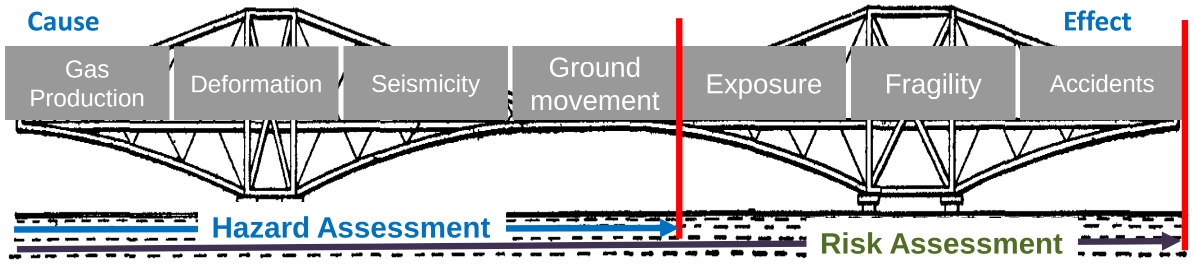

Figure 4 The Hazard and Risk Assessment requires a "bridge" to be built from the cause (gas production) to the effect (building collapse and potential casualties).

The causal chain starts with gas production, reducing the gas pressure in the reservoir and causing deformation of the reservoir rock. Deformation in turn can cause sudden movement in the subsurface, in other words: seismicity. This compartment of the "bridge" is addressing processes in the deep subsurface; the "geo-domain". This requires geological, geophysical and geomechanical expertise. The seismicity generated in the subsurface causes the ground motions or accelerations at surface which are affecting buildings and people. The prediction of ground motion is therefore the crucial link between the processes in the deep subsurface near the gas reservoir and the effects on buildings at the surface.

With sufficient knowledge of buildings, their structural strength, and of the presence of people in these buildings (the exposure), the risks can eventually be assessed. This is described in Study 2. Especially expertise in the civil engineering domain is vital to be able to carry out this assessment.

Progress Probabilistic Hazard Assessment

Based on the available earthquake catalogue and other data specific for the Groningen field, a probabilistic seismological and hazard model was built in 2013. Where observational data was sparse or did not exist, analogue data and methods from tectonic earthquake regions were used as the best available data in the absence of appropriate data. This model formed the basis of the probabilistic hazard assessment supporting the Winningsplan 2013. In this Winningsplan, hazard maps were presented that showed the PGA for a given period, and with a given probability of exceedance level.

Relatively sparse observational data from the Groningen area was available at that time. Both the number of earthquakes that had occurred and the number of observation sites were limited. From the start of monitoring in 1994 till August 2012, some 188 earthquakes with magnitude larger than M=1.5[2] had been recorded. For the prediction of the occurrence of larger events, NAM did not make an estimate of the hazard based on theoretical considerations, which would need to be supplemented with potentially biased expert judgment and the consensus views within the earthquake community. Instead, NAM prepared a hazard assessment based on the scarce evidence available from the Groningen area, complemented, where appropriate with evidence and methods derived from tectonic earthquakes (mainly in southern Europe). This is a conservative approach: for low exceedance levels, the hazard is more likely to be adjusted downwards than upwards, when updates are based on an expanding set of newly acquired acceleration data.

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[2] NAM is confident an earthquake with magnitude greater than or equal to $M \geq 1.5$ will be detected wherever the earthquake occurred in the field and irrespective of its timing. An earthquake of smaller magnitude might remain undetected, for instance, among the noise from activities at surface.

Hence, the acquisition of more data, the completion of more studies and the better quantification of uncertainties, are very important. This led NAM in 2012 to embark on a large program to acquire more and more relevant data. The main objective of this campaign is to make the hazard assessment more reliable. As assumptions used tended to be conservative, the assessed hazard and its associated uncertainty are likely to decrease. The various activities included in the data acquisition campaign are described below.

In 2013, geophone strings were placed in the two existing deep monitoring wells (Zeerijp-1 and Stedum-1) located in the Loppersum area, where seismicity is highest. With these two geophone strings placed at reservoir depth (some 3000 m), even small earthquakes could locally be monitored and their origin determined better relative to the interpreted fault system at reservoir level. Conclusions from the analyses of data retrieved from these geofoons are:

- The recorded micro-seismic events are in accordance with KNMI observations
- 98.3% of the analysed events originate from the gas reservoir
- Location of the events are in line with the known structural characteristics of the field

Early 2014, 10 additional GPS stations were placed to monitor subsidence better. In 2013 also a campaign started to extend the existing geophone and accelerometer network. In 2014 some 42 shallow (200 m deep) geophone wells were drilled with 4 geophones placed at 50 m intervals in each of these wells. In 2015, drilling continues. Phase I of this project consisting of almost 60 geophone stations is expected to be completed mid-2015. However, drilling will be continued with Phase II adding another 11 stations. At each of these stations also a surface accelerometer will be placed.

In 2014 the first dedicated deep well designed for seismic monitoring was drilled at the Zeerijp location to a depth below the Rotliegend reservoir. A second well will be spudded in May 2015. In this second well an extensive reservoir section will be cored. Three laboratories are awaiting arrival of sections of this core to perform rock experiments on both compaction and rupture processes. Mid 2015, NAM plans to install geophone strings in these dedicated wells. Additionally, a geophone string will be placed in the existing observation well Ten Boer-4, near the Eemskanaal cluster.

Each earthquake will now (depending on the magnitude) be recorded from multiple observation points. Based on studies of the geophone and accelerometer data collected and compaction data measured from experiments in laboratories, the hazard model can now, and will continue to be, improved. For each successive improvement of the hazard model, based on studies and monitoring, conservatism in the model will be reduced as conservative assumptions are replaced by constraints derived from actual field observations. This means we feel confident that the assessed hazard at low exceedance levels of 0.2%/annum or less is more likely to decrease than increase overall as a result of further data collection and studies.

Schedule

Early 2014, the progress of the various studies and the status of the hazard and risk assessment were reviewed. This underlined and clarified the interrelations between the various research activities and provided an opportunity to re-direct the research effort towards resolving the largest uncertainties and the most relevant research questions.

For each study domain, progress was envisaged with the hazard and risk model increasingly being refined and the model parameters improved.

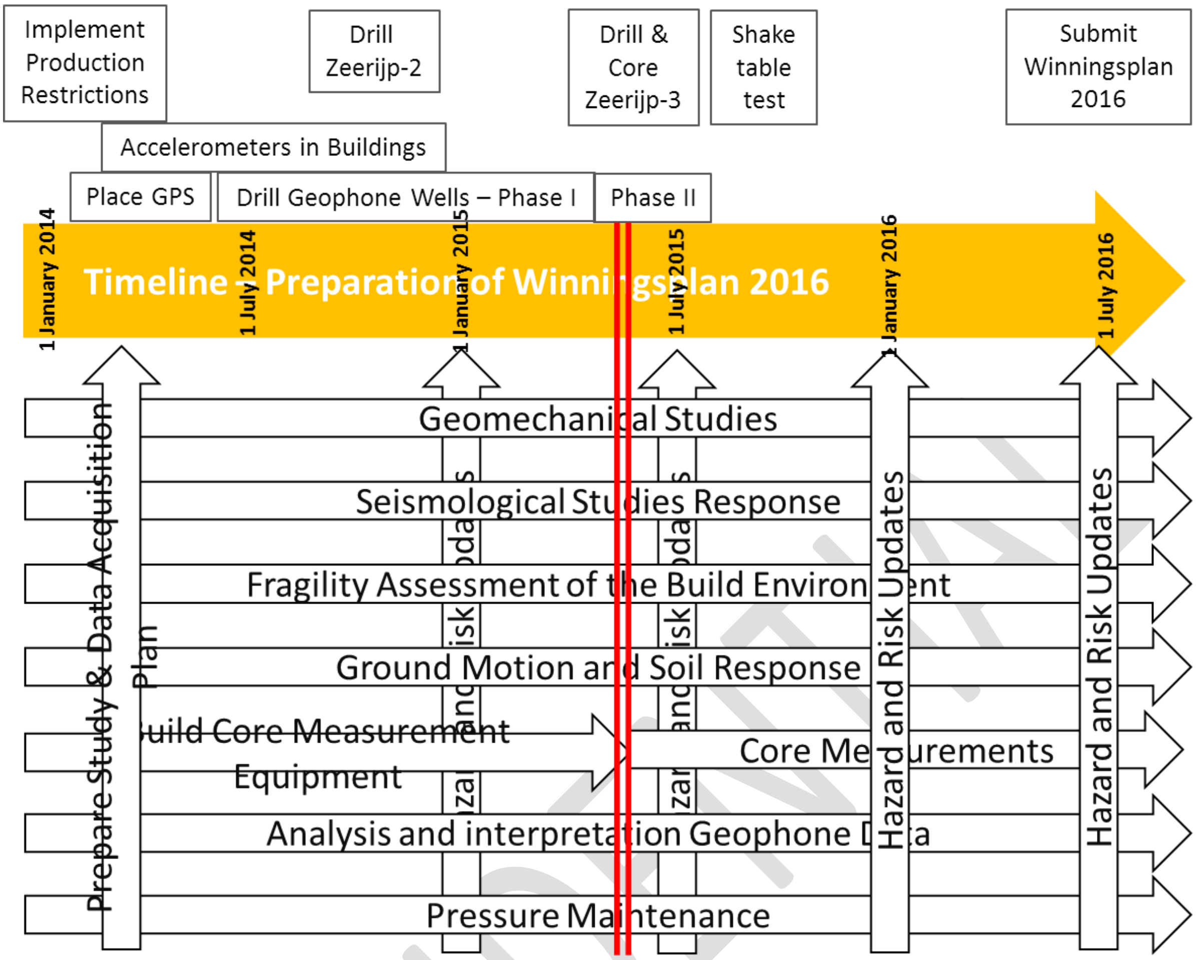


Figure 5 *Schedule for the research program for the Winningsplan 2016 as presented in the "Study and Data Acquisition Plan".*

Successive improvements at the half-yearly status reviews will be used to re-direct and optimise the research efforts. This is further discussed for each domain in the next sections. Note that the initial timeframe for the studies and half-yearly updates was different from the current timeframe as introduced by the February 2015 decision on the Winningsplan 2013 (Ref. 12).

Table 1 shows the current schedule for updates of the hazard and risk assessment in preparation of the Winningsplan 2016.

Target Date	Maturity Version	Status of Hazard and Risk Assessment
1st January 2015	0	Demonstrate capability to extend the probabilistic hazard assessment into the risk domain.
1st May 2015	1	First probabilistic Hazard and Risk Assessment. Important elements of the hazard assessment still in development (in particular site response). First version with probabilistic Risk Assessment for identification of most fragile buildings to optimise the structural upgrading program.
1st January 2016	2	Include site response into the ground motion prediction methodology. Hazard and Risk Assessment with most important input included.
1st July 2016	3	Final Hazard and Risk Assessment for Winningsplan 2016. The results of the full research effort is included in this assessment.

Table 1 Main deliverables for each inventory update of the hazard and risk assessment

Main new Elements Hazard Assessment – May 2015

This section presents the progress made in the probabilistic hazard assessment since the Winningsplan 2013 was submitted on 29th November 2013. The hazard assessment for Winningsplan 2013 was the first probabilistic hazard assessment for induced seismicity in Groningen. The current probabilistic hazard assessment builds on the work presented in the Winningsplan 2013 (Ref. 3) and the accompanying Technical Addendum (Ref. 4 and 5).

The further study work into induced seismicity in Groningen towards Winningsplan 2016 has been described in the "Study and Data Acquisition Plan" and the accompanying Study Catalogue. Below summarises the main improvements incorporated in the Hazard model for this assessment (mid 2015) and the expected improvements for the next assessment (late 2015) per category.

Rock Deformation – Compaction

Improvements for Version 1 (Mid 2015)

- Inversion from subsidence by using optical leveling survey data up to 2008.

Improvements for Version 2 (End 2015)

- Enhance inversion from subsidence by using additional optical leveling survey data 2013 and InSar data.
- Improved porosity model for the reservoir from detailed facies modelling and seismic inversion techniques for compressibility estimation.

Seismological Model

Improvements for Version 1 (Mid 2015)

- Activity Rate model for seismicity
- Integration between inversion from subsidence and activity rate model
- Confirmation from deep geophone wells that the hypo-centers of the earthquakes are in the reservoir with a small number of earthquakes possibly in the Zechstein.

Improvements for Version 2 (End 2015)

- Investigate evidence for potential changes in b-value – with time, space, strain, strain rate
- Investigate evidence for spatial-temporal bias in activity rates – scope for refining extended activity rate model
- Investigate evidence for rate or delay effects following production changes
- Establish Bayesian framework for ranking performance of alternative models
- Utilize data from the upgraded monitoring network
- Investigate influence of finite ruptures along mapped faults

Ground Motion

Improvements for Version 1 (Mid 2015)

- Groningen-specific equations for spectral accelerations as well as PGA
- Expanded dataset of Groningen ground-motion records
- Epistemic uncertainty in Ground Motion Prediction Equations (GMPEs), due to extrapolation to larger magnitudes, in logic-tree branches
- Sigma models for GMPEs calibrated to local data, with adjustments for point-source distance metric at larger M
- Preliminary model for prediction of durations, calibrated to Groningen recordings

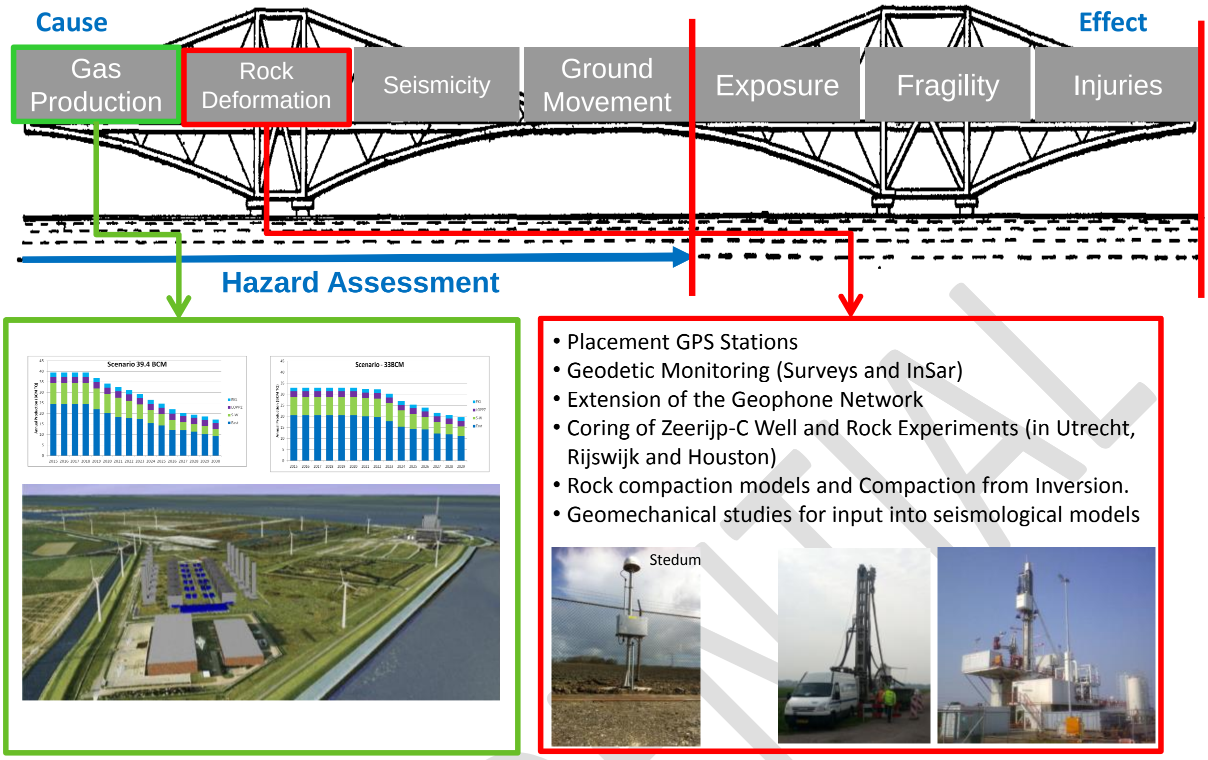
- Model for correlation of predicted values of spectral acceleration and duration

Improvements for Version 2 (End 2015)

- More accurate modelling of near-source attenuation of accelerations due to high-velocity layers above reservoir
- Improved model for durations, capturing very short durations in epicentral area and swift prolongation with distance, including enhanced model for the correlation of accelerations and duration
- Site-specific soil amplification terms giving more realistic spectral shapes and reduced sigma's in GMPEs
- Non-linear site response capturing reduced soil amplification with increased acceleration in base rock horizon
- Investigate strength limitations on maximum surface accelerations transmitted by very soft/weak soil layers
- Investigate influence of finite ruptures along mapped faults

The activities planned to further improve the hazard assessment are all discussed in the "Study and Data Acquisition Plan" issued early 2015 and the accompanying studies catalogue (Ref. 13). Progress will be reviewed twice a year and the research program re-directed if required. In case of a significant adjustment, an update of the "Study and Data Acquisition Plan" will be issued.

Gas production



- Placement GPS Stations
- Geodetic Monitoring (Surveys and InSar)
- Extension of the Geophone Network
- Coring of Zeerijp-C Well and Rock Experiments (in Utrecht, Rijswijk and Houston)
- Rock compaction models and Compaction from Inversion.
- Geomechanical studies for input into seismological models

Figure 6 The first section of the causal bridge starts with the cause, gas production, and the effect of the resulting pressure drop in the reservoir on the reservoir rock.

In both studies (hazard and risk assessments) two production scenarios are used to evaluate the hazard and risk. These scenarios are:

Scenario I The total gas production from the Groningen field in this scenario is limited to 39.4 Bcm/annum. Additionally, 4 regional production caps are imposed. These regional caps are imposed on the clusters in regions defined as East (24.5 Bcm/annum), LOPPZ (3 Bcm/annum[3]), South-West (9.9 Bcm/annum) and Eemskanaal (2.0 Bcm/annum). Together the regional caps sum up to the field production limit of 39.4 Bcm/annum. A consequence is a relatively imbalanced load-factor distribution over the field, highest on Eastern clusters and lowest on LOPPZ clusters. Operational flexibility is further limited by the Eemskanaal gas quality issue (Ref. 18), gas-distribution over the ring pipeline system connecting the production clusters with the custody transfer stations (overslagen) and filling up of the Underground Gas Storage in Norg during the summer months.

This scenario is based on the Ministerial decision of February 2015 (Ref. 19; article 5).

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[3] The ruling of the Council of State to further reduce LOPPZ to nil is not incorporated in this scenario given the limited time for modelling since the date of this ruling (14th April 2015) and because this ruling does not rule out that 3 Bcm may be produced if necessary for security-of-supply reasons. This scenario is therefore a conservative approach for the Loppersum area.

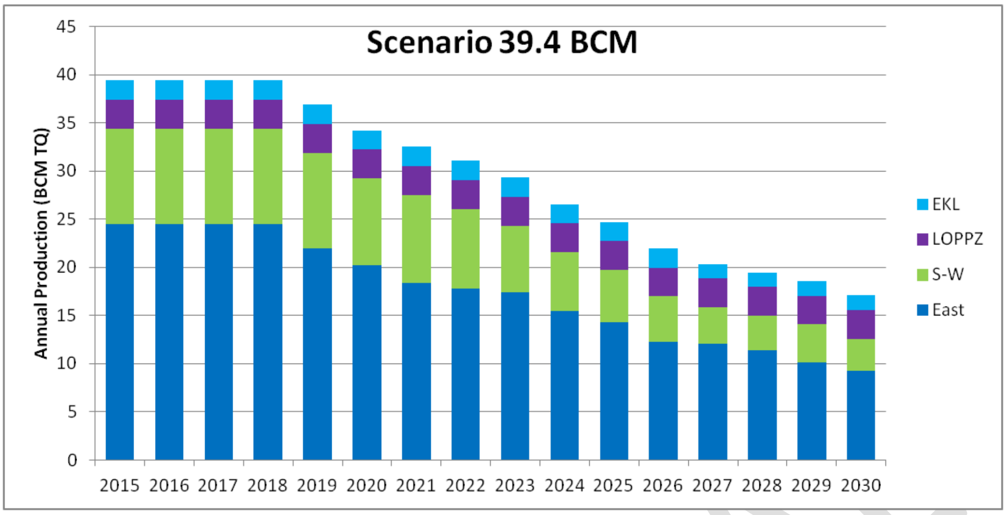


Figure 7 *An indicative gas production schedule for scenario I. Production is kept below 39.4 Bcm, until the natural decline of the production from the field sets in. No additional development wells are drilled.*

Scenario II In this scenario the field production is limited to 33.0 Bcm/annum, while the imposed regional caps remain unchanged and defined as East (24.5 Bcm /annum), LOPPZ (3 Bcm /annum), South-West (9.9 Bcm/annum) and Eemskanaal (2 Bcm /annum). The 33 Bcm annual gas production volume is the minimum volume to cover GasTerra's portfolio, with a pre-set monthly volume distribution. Operational flexibility is dictated by the Eemskanaal quality issue, filling up during the summer season of the Underground Gas Storage in Norg and gas-distribution in cooperation with GasUnie gas-quality management.

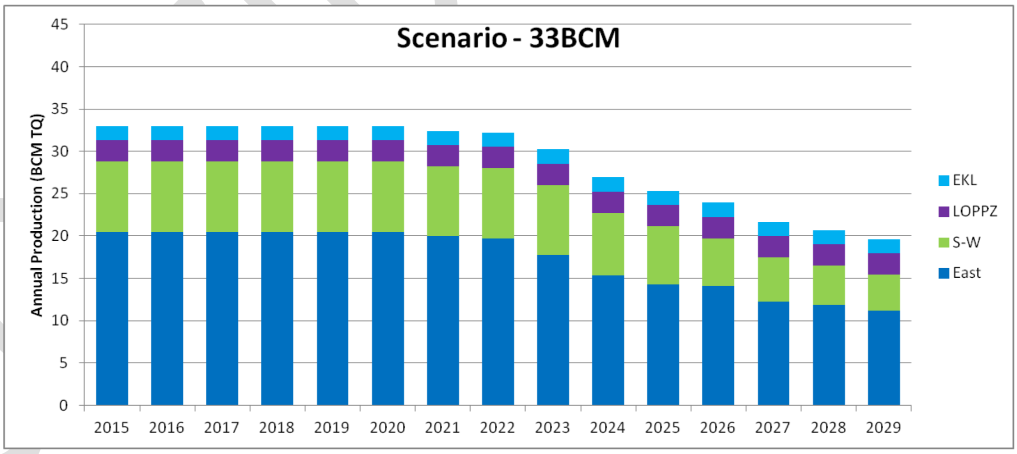
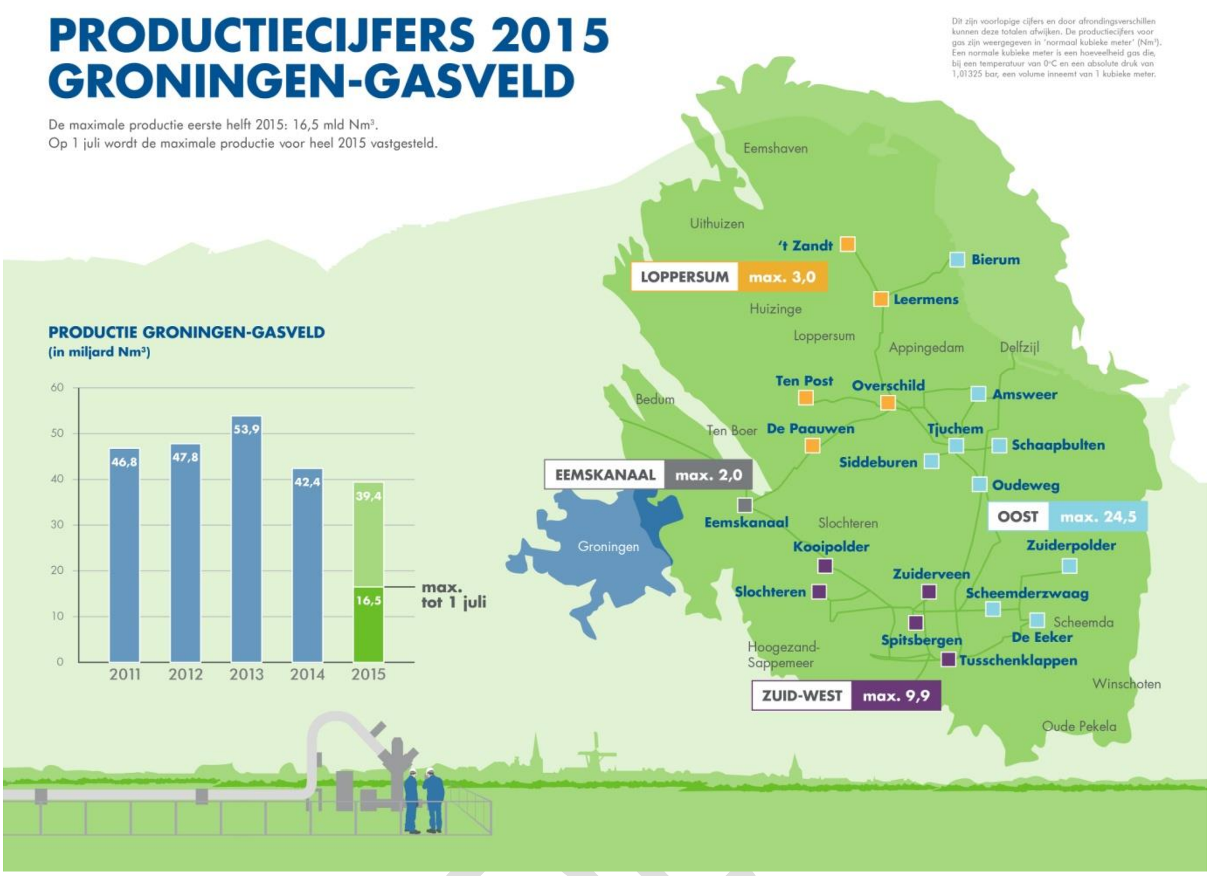


Figure 8 *An indicative gas production schedule for scenario II. Production is kept below 33.0 Bcm, until the natural decline of the production from the field sets in. No additional development wells are drilled.*

This scenario is based on the letter from the minister announcing his decision to reduce the production in the first half of 2015 to 16.5 Bcm. In this scenario, it is assumed that in the second half of 2015 the production will be limited to the same volume as in the first half.



PRODUCTIECIJFERS 2015 GRONINGEN-GASVELD

De maximale productie eerste helft 2015: 16,5 mld Nm³.
Op 1 juli wordt de maximale productie voor heel 2015 vastgesteld.

Dit zijn voorlopige cijfers en door afrondingsverschillen kunnen deze totalen afwijken. De productiecijfers voor gas zijn weergegeven in 'normaal kubieke meter' (Nm³). Een normale kubieke meter is een hoeveelheid gas die, bij een temperatuur van 0°C en een absolute druk van 1,01325 bar, een volume inneemt van 1 kubieke meter.

Figure 9 *Spatial and temporal production caps have been imposed. Production caps have been imposed on 5 groups of production clusters. Additionally, the production has been capped for the first and second half of 2015.*

Rock Deformation - Compaction Modelling

For the seismic hazard maps in the Winningsplan update 2013, three compaction models were used: bi-linear, time decay and isotach (Ref. 4). These models assume a relationship between compaction and porosity. These models produced local second order biased estimates of subsidence as evidenced by the spatio-temporal patterns in the residuals when compared to the levelling data. A direct inversion of the levelling data to compaction was identified as a useful alternative method to estimate the compaction grid of the Groningen field. It was demonstrated (Ref. 23) that it is indeed feasible to derive spatially smooth compaction estimates from the levelling on a course grid (2.5 X 2.5 km) using a homogeneous half space model with a Poisson's ratio of 0.25. Each block in the grid returns in this case a different compaction value (Fig. 10). The study showed that a basic ('first-order') forward simulation model with constant rates of compaction per unit of pore pressure decline per reservoir grid block performed well in its ability to explain the variation in subsidence measurements. This linear relationship was used for a base case compaction scenario to forecast the seismic hazard in the near future (2016-2021).

In addition, both the time decay and RTCiM compaction models (Ref. 4) were used as separate sensitivity scenarios to reflect the compaction model uncertainty in the hazard calculations. The RTCiM replaces the isotach model, mainly because TNO used the RTCiM as the base case compaction model in their latest reports (Ref. 7), thus allowing for better comparison.

The main difference with the compaction scenarios in the Winningsplan update 2013 is the decoupling of compressibility and porosity. Another main difference is that the compaction as calculated for the grid blocks in 2013, should be similar for all compaction models. All compaction models use a homogenous half-space model to estimate subsidence from compaction and vice versa rather than the rigid-basement model that was used in the Winningsplan 2013 update. This means that individual input parameters of the compaction models but also compaction values will not be one-to-one comparable.

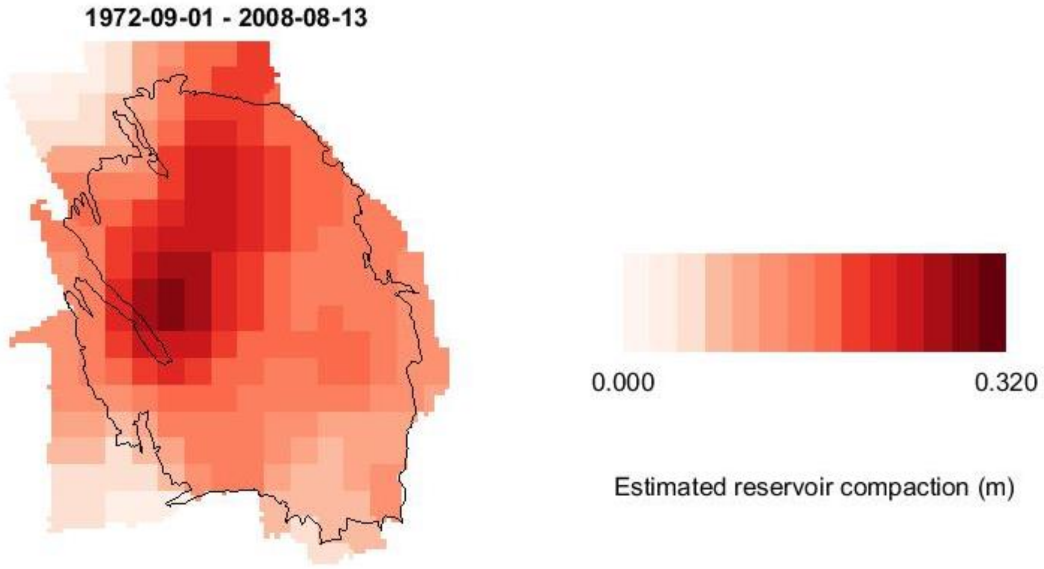


Figure 10 Example of a compaction grid calculated from the levelling surveys for the period 1972-2008.

Results

As a base case the linear compaction–pressure drop relation inferred by inversion from the subsidence measurements for the different blocks was used to predict the compaction for the period 1-7-2016 to 1-7-2021, using forecasted reservoir pressure grids for the two production scenarios. Also the effect of different compaction models was investigated (time-decay and RTCiM). Figure 11 shows the cumulative compaction from the start of production to 2021 for the two production scenarios using the linear compaction model. The impact of the two production scenarios on cumulative compaction is limited because of the short additional time period (5 years) compared to the time the field has been producing already. This is especially the case in the area of highest compaction.

Period: 1963-2021

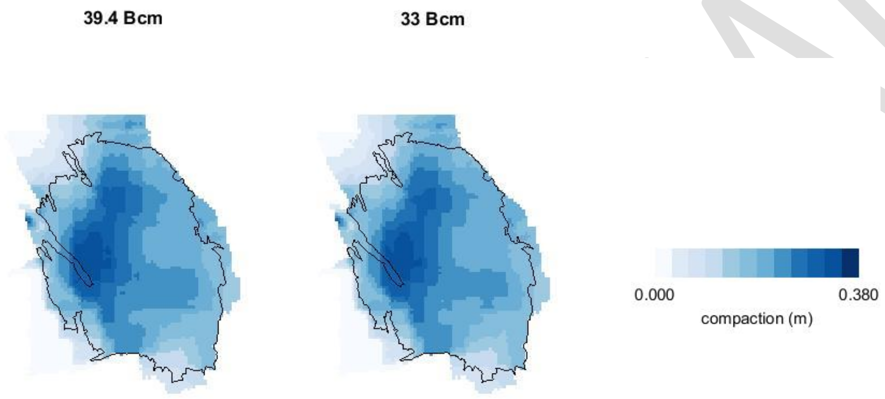


Figure 11 Cumulative compaction from the start of production to 2021 for both production scenarios based on the inversion of levelling data (linear compaction model)

Figure 12 shows the compaction for the period 1-7-2016 to 1-7-2021 for both production scenarios. AS the results show, the difference between both is small. These findings are in line with earlier published work on the impact of the Eemskanaal cluster on compaction assessment (Ref 18).

Period: 1-7-2016 / 1-7- 2021

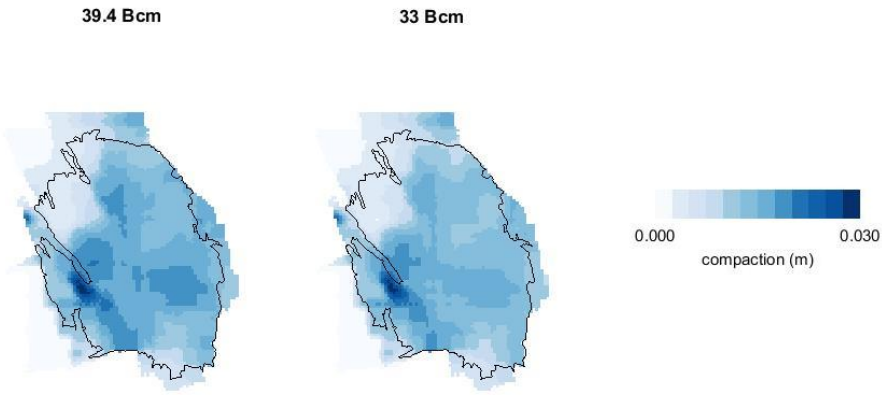


Figure 12 Compaction for the period 1-7-2016 to 1-7-2021 for both production scenarios using the linear compaction model

The impact on additional compaction in the period between 1-7-2016 and 1-7-2021, using alternative compaction models, is presented in Figure 13 for the 39.4 Bcm/annum scenario. This show that there is still uncertainty remaining in the compaction assessment. This is an important contributor to the uncertainty in the hazard and risk assessment.

Period: 1-7-2016 / 1-7- 2021

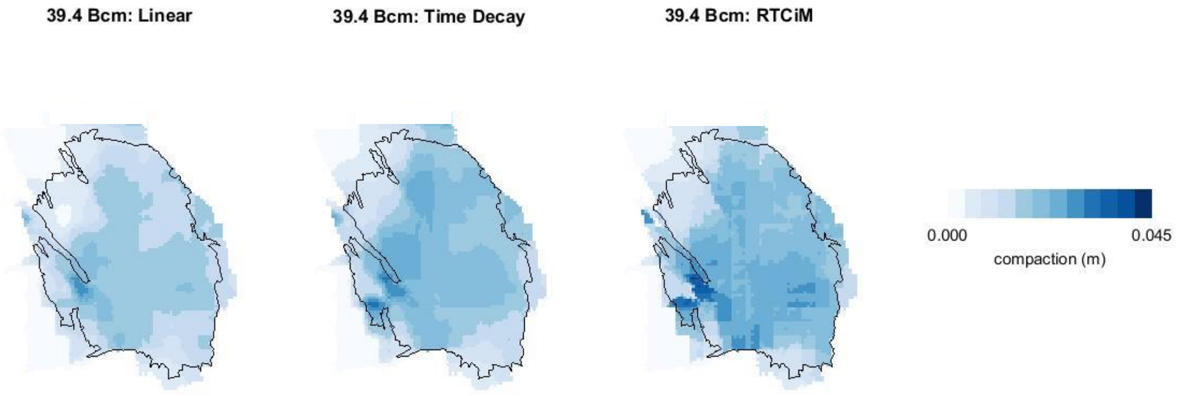
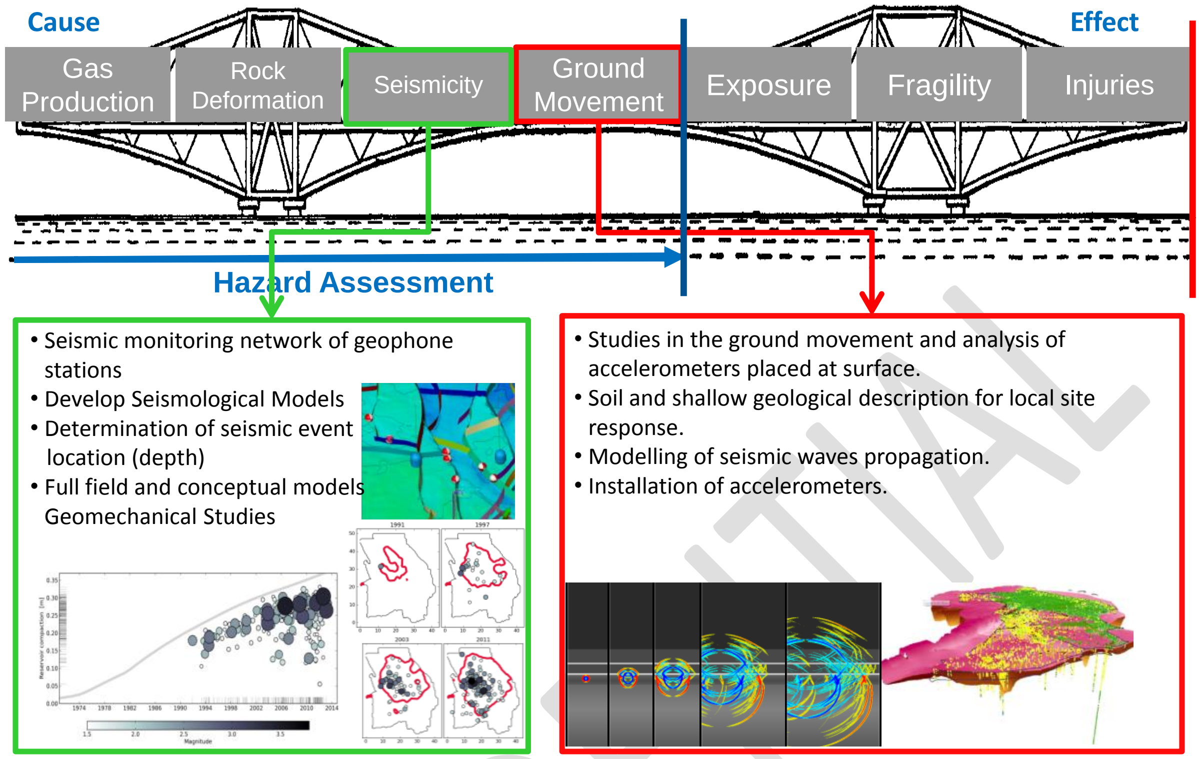


Figure 13 *Compaction for the period 1-7-2016 to 1-7-2021 for the three compaction models (39.4 Bcm production scenario)*

Seismological Model



- Seismic monitoring network of geophone stations
- Develop Seismological Models
- Determination of seismic event location (depth)
- Full field and conceptual models Geomechanical Studies

- Studies in the ground movement and analysis of accelerometers placed at surface.
- Soil and shallow geological description for local site response.
- Modelling of seismic waves propagation.
- Installation of accelerometers.

Figure 14 The causal bridge continues with seismicity resulting from the deformation of reservoir rock and the prediction of the ground motion (PGA).

The logical first step in the Probabilistic Hazard and Risk Assessment (PHRA) workflow is the Seismological Model - this is a model which allows synthetic earthquake catalogues, detailing event locations, occurrence times and magnitudes, to be calculated given their joint probability distributions based on a model of the underlying geomechanical process. In PHRA for naturally occurring tectonic earthquakes, the seismological model usually comprises an identified seismically active region with assumed parameter values specifying the expected level of seismic activity. In the Groningen case, reservoir compaction has been identified as the geomechanical process inducing the seismicity. The seismological models have been built on this basis. For the 2013 Winningsplan submission, the seismological model used in the PSHA calculations was based on earlier work by Kostrov and McGarr which linked the total seismic moment of a catalogue of events to the subsurface strains causing them. A strain partitioning factor was introduced to account for the observed division of strain into seismogenic and aseismic components.

An alternative to forecasting total seismic moment according to strain is to forecast the occurrence rate of events above a certain magnitude according to strain. Models of both types are seen in the literature and the choice between them is ultimately an empirical question: which type of model best fits the observed data? In the Groningen case, we see a more precise relationship between event rate and reservoir strain than we do for total seismic moment. Moreover, event rate based models can be naturally extended to incorporate after-shocks. This is particularly useful as it has already been shown that spatial and temporal clustering of events needs to be accounted for in the Groningen earthquake catalogue. For these primary reasons, an Activity Rate model incorporating an Epidemic Type Aftershock Sequence (ETAS) model has been developed as a second generation seismological model. The performance of this model was further improved by also accounting for the influence of pre-existing fault offsets. A simple geometric argument can be used to show that the induced strain on a pre-existing vertical fault in a compacting reservoir is proportional to the product of fault offset and reservoir compaction. Generalising this simplified geometry it can be shown that replacing compaction in the initial version of the Activity Rate model with a strain-thickness attribute accounts for reservoir compaction and reservoir dip including fault offsets.

As well as accounting for the variation of seismicity with the process of reservoir level compaction, the seismological model must also account for the observed statistics of earthquakes magnitudes, in particular the relative abundance of large and small magnitude events described by the Gutenberg-Richter b-value. Consideration of the Groningen catalogue as a whole gives a b-value very close to the value of 1.0, generally found for earthquake populations elsewhere. If, however, the catalogue is subdivided into smaller subsets according to the strain-thickness attribute, then potentially significant systematic variations of the b-value with strain-thickness become apparent with b tending to smaller values at larger values of strain thickness.

Although a systematic variation of the b-value is seen, the error bounds on the values obtained are large due to the reduced number of events considered in each subset. For this reason a constant b-value close to 1.0 calculated for the catalogue as a whole is taken as the base case scenario with an alternative upper bound scenario determined by taking the b-value as a stochastic function of the strain-thickness. The lower bound scenario was taken as having the constant b-value used for the base-case but maximum likelihood values of the Activity Rate and ETAS model parameters rather than samples drawn from the joint multi-parameter distribution.

Ground Motion Prediction

Peak Ground Acceleration

At the time of the preparation of Winningsplan 2013, relatively few earthquake acceleration records were available and therefore little data on which to base a ground motion prediction methodology. This was caused by the relatively low number of earthquakes causing measurable ground accelerations and the relatively low number of accelerometers placed over the field, recording these earthquake accelerations. Although the number of earthquakes with significant accelerations measured at surface increased from 8 to 12 from Winningsplan 2013 to this assessment, the number of recordings of these earthquakes increased from 40 to 85. This is mainly due to the increased number of recording sites as the first geophone sites with accelerometers of the network extension have now been taken into operation. Since the assessment was started two more earthquakes have occurred, each triggering 14 accelerometers and raising the number of recordings to 113.

The acceleration records currently available in the Groningen area are for low magnitude earthquakes (M≤3.6), which are capable of causing damage to buildings, but are considered to be too small to cause buildings to collapse. For the hazard and risk assessment the ground motion for larger magnitude earthquakes are important. To achieve this, the available data needs to be extrapolated to larger magnitude earthquakes. Within the available time for Winningsplan 2013, a model derived from recordings of tectonic earthquakes in southern Europe was used. Because equations were used that were intended for much stronger tectonic earthquakes, the hazard associated with larger magnitude earthquakes was in hindsight overstated in the first pass in the Winningsplan 2013 (Ref. 4; Chapter 7). The latest studies (Ref. 24) now show that for an earthquake of a given magnitude the ground accelerations are smaller at short periods (e.g. PGA).

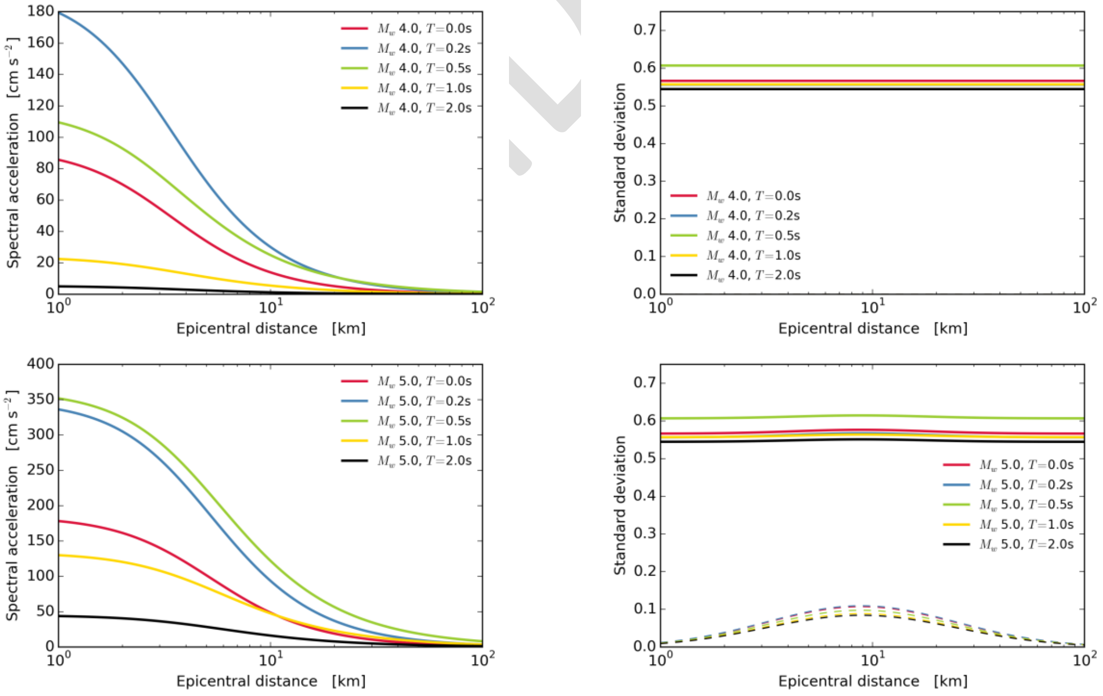


Figure 15 *Variation in the median GMPE with epi-central distance (left) and the associated variability (right) for a (top row) M4.0 and (bottom row) M5.0*

Due to the larger number of installed accelerometers in the field, more data is currently available for the preparation of a Groningen specific ground acceleration methodology. Using the additional acceleration records, first an assessment was made of the range of accelerations at surface that larger earthquakes could impose. This is based on a simulation approach. This resulted for the best estimate in a lower assessment of the hazard for earthquakes with a larger magnitude (Ref. 24).

In this update of the hazard assessment not only PGA is evaluated, but additionally spectral accelerations and the duration of the acceleration are evaluated. This is important for the risk assessment, as building response to the hazard critically depends on these parameters (see next section).

Spatial Variability

Apart from the average acceleration also the spatial variability of the acceleration resulting from a single earthquake is important. There are many reasons for the large variability in the accelerations measured by different stations, due to a single earthquake. Within the determining factors, the local soil conditions are very important. Accelerations at very soft sites, like peat areas, are in general higher than at less soft sites like sand areas. NAM has therefore asked Deltares to carry out a detailed study of the shallow geology of Groningen (Ref. 25 and 26). Together with experiments planned mid-2015 at the geophone locations and modelling of the site response, a basis will be created for the next update of the ground motion prediction methodology for the Groningen area, due by the end of 2015.

In the Winningsplan 2013, a database of tectonic earthquake recordings mainly in southern Europe and Turkey was used. Of course, the variability in the shallow geology over such a large area is much larger than that over the Groningen area. It is therefore likely that also the variability in the accelerations was overestimated for the Winningsplan 2013. The studies of the shallow geology of Groningen and the planned experiments at the geophone / accelerometer stations are expected to lead to a further reduction of the uncertainty in the assessment for the majority of soil types. The outcome of these experiments at the geophone / accelerometer stations, that are expected to commence late April 2015, are crucial to confirm this.

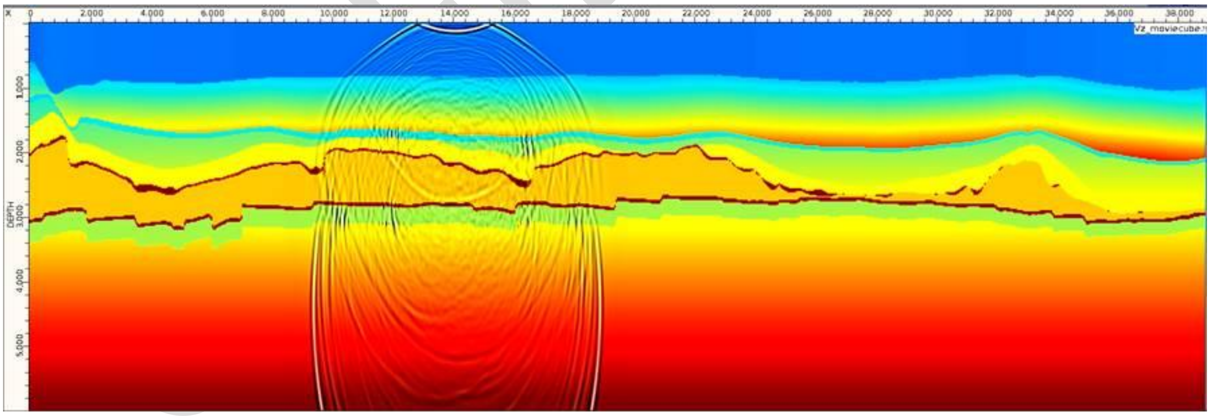


Figure 16 Results of a simulation of earthquake waves moving towards the surface.

Uncertainty

To reflect the remaining epistemic uncertainty in the final ground motion prediction, three methodologies are weighted (a low, mid and high case). These are combined to form the mean case using weight factors of 20%, 50% and 30% respectively. The high case is still based on tectonic earthquakes and is similar to the method used for the Winningsplan 2013, the mid and low case are based on simulation based extrapolation of the Groningen accelerometer data to higher magnitudes.

Hazard Assessment

Principles

For the probabilistic description of the ground accelerations (PGA) a hazard map is used. On this map for each location the acceleration is plotted that could, with a prescribed probability (exceedance level), be exceeded in a prescribed period. Hazard levels are shown using a gradual colour scales, with contours of equal hazard, i.e. PGA, added for convenience.

Hazard maps can be made for different production scenarios. An example are the two hazard maps prepared late 2014 (Ref. 18) using the updated model of the reservoir (Figure 17), the activity rate seismicity model and the RTCiM model to predict compaction. These maps were prepared for a probability of exceedance (exceedance level) of 2%/annum for the period 2017 to 2027.

The map on the left-hand side is based on the gas production as foreseen by NAM in the Winningsplan 2013, while the map on the right includes the production caps imposed early 2014 by the Minister of Economic Affairs. The yellow to red colour scale indicates the PGA as a fraction of g (the average free-fall acceleration in the gravitational field of the earth). Contours at intervals of 0.02 g are added.

Period: 2017 / 1-7- 2027

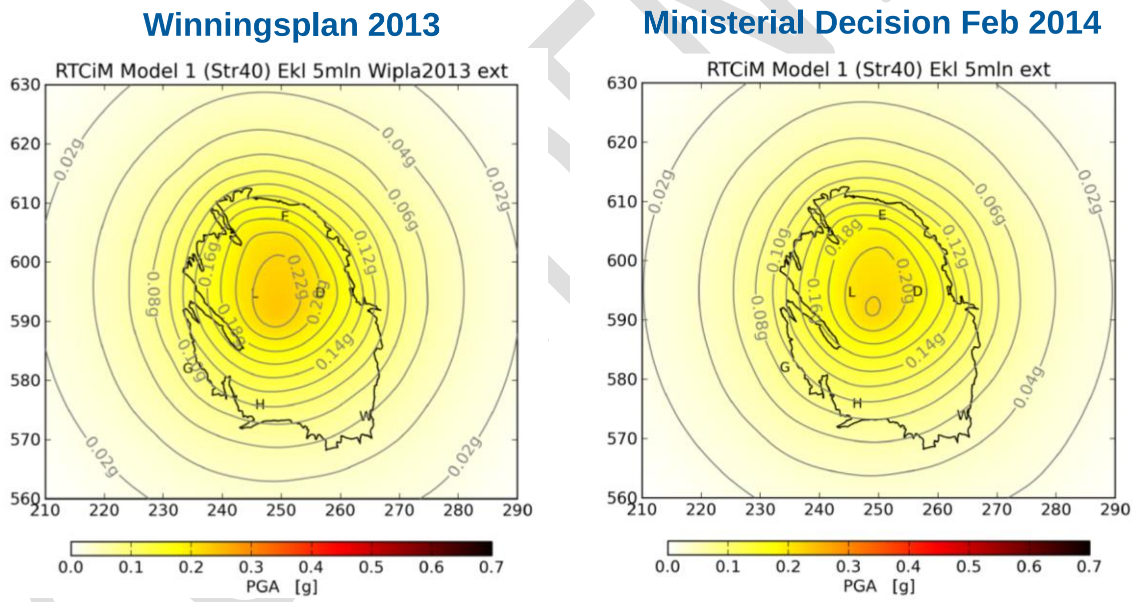


Figure 17 *Hazard map showing the peak ground acceleration (PGA) with 2 % average annual chance of exceedance from 2017 to 2027 and the Activity Rate seismological model. The contour interval is 0.02 g.*

Updates Hazard Assessment

The construction of the hazard maps shown in this section requires clarification. A location in the Groningen field during a period of 5 years is subjected to accelerations resulting from induced earthquakes. At some locations, e.g. near Loppersum, the chance of experiencing a large acceleration is higher than at the periphery of the field. The chance of experiencing an acceleration in excess of a certain peak ground acceleration value declines with larger accelerations. This is shown for a large set of locations in figure 18. Each declining line corresponds to a single location in the field.

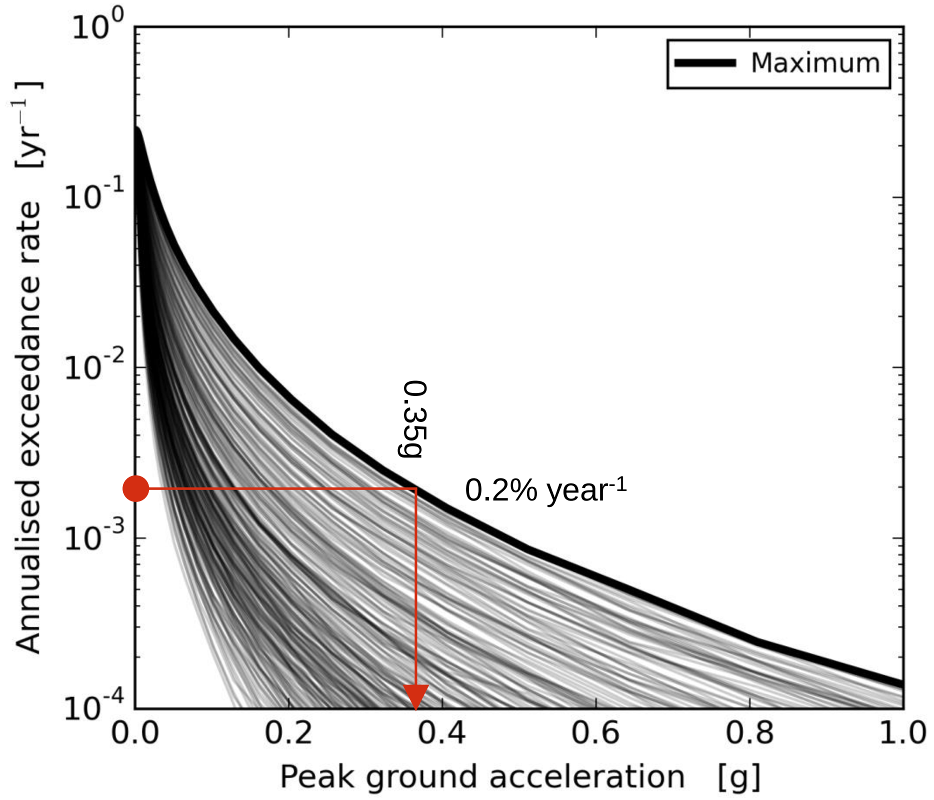


Figure 18 *Annual exceedance rate for peak ground acceleration at different locations in the field. This was assessed for the period 2016 – 2021 and the 39.4 Bcm production scenario. Each line corresponds to a location in the field. The bold line indicates the maximum PGA in the field for a given exceedance level (bounding envelope).*

How to read this figure: The red line indicates that for an exceedance level of 0.2%/annum the highest PGA felt in the field is 0.35g.

A weighted ground-motion prediction methodology was used to assess the hazard. A low, mid and high case GPME model were combined to arrive at the (weighted) medium ground motion prediction to create the mean hazard map. The resulting mean hazard map is shown below, in figure 19. This map is the basis for the risk assessment in Study 2.

Mean hazard map - period: 1-7-2016 / 1-7- 2021

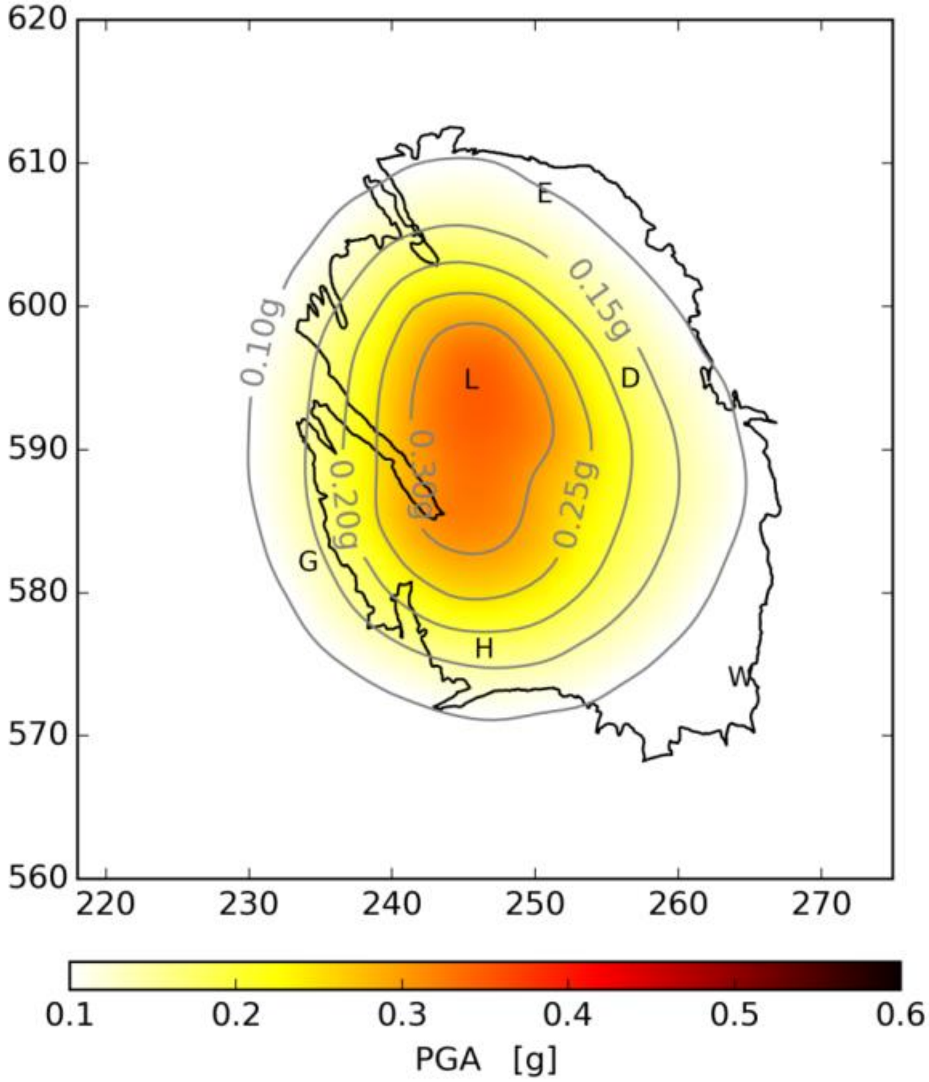
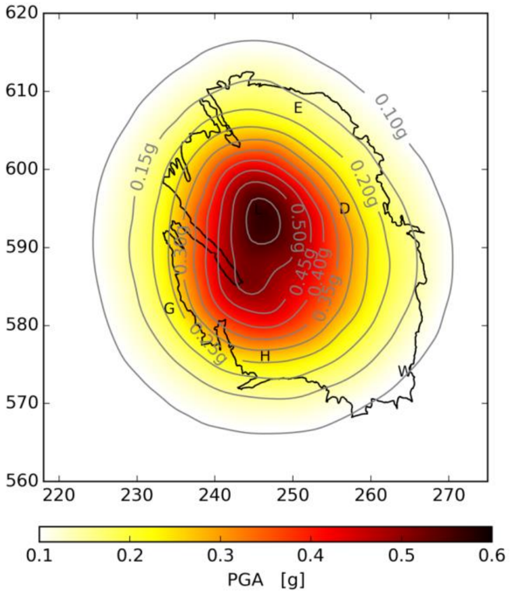


Figure 19 *Mean hazard map for period 1-7-2016 – 1-7-2021, Production: 39.4 Bcm/annum, Compaction: Inversion, Activity Rate: V1, M ≥ 3.5 Metric: 0.2%/year chance of exceedance (10% chance in 50 years).*

Comparison of Mean Hazard Map 2016 – 2021 with earlier Hazard Assessments

The current high case model was calculated using a methodology similar to the ‘mean case model’ of Winningsplan 2013, adjusted for the 39.4 Bcm production scenario. The difference between these maps gives an indication of the reduction in the hazard assessment achieved by the study and data acquisition in 2014 and early 2015. This shows a meaningful reduction of the assessed seismic hazard.



High - period: 1-7-2016 / 1-7- 2021

Figure 20 Hazard map for period 1-72016 – 1-7-2021, Production: 39.4 Bcm/annum, Compaction: Inversion, Activity Rate: V1, M ≥ 3.5 Metric: 0.2%/year chance of exceedance (10% chance in 50 years).

As a sensitivity, hazard maps for the mid case GMPE model are shown below, both for the 39.4 Bcm/annum and the 33 Bcm/annum production scenarios. As the production in the Loppersum area is reduced to a maximum of 3 Bcm/annum for in all production scenarios, the effect of the further reduction in production is minimal in the Loppersum area. The mid case GMPE model for the 39.4 Bcm/annum scenario shows markedly lower PGAs than the mean case model (Fig.19) as the mean case is heavily influenced by the high case.

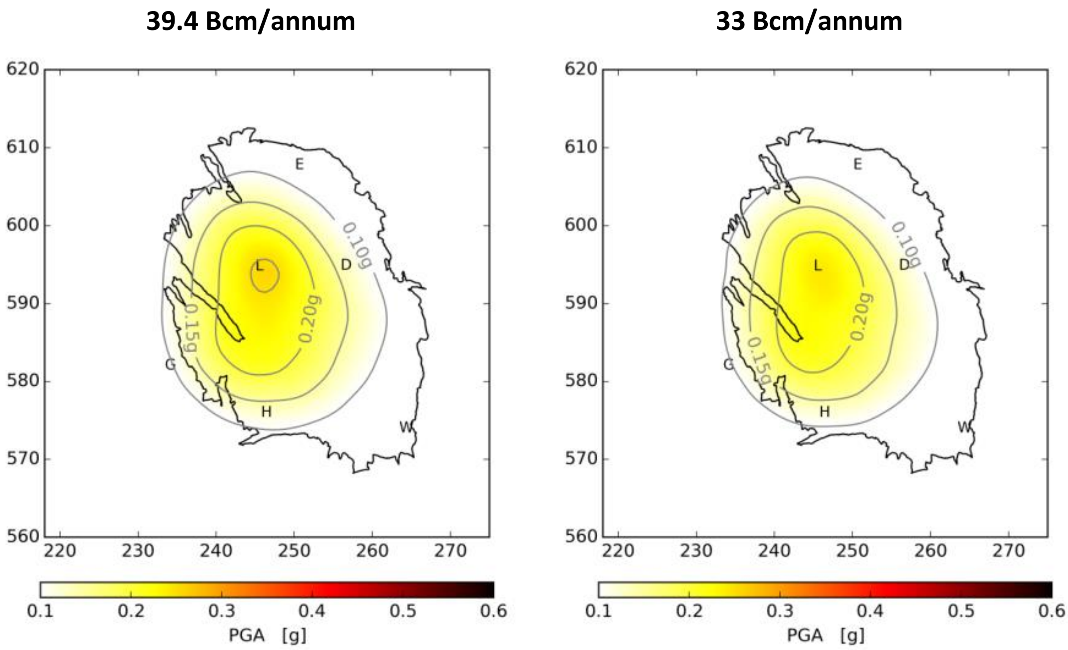


Figure 21 *Hazard map PGA hazard sensitivity to production rates. Period: 2016/7 – 2021/7, Production scenarios: 39.4, 33, 20 Bcm/annum, Compaction: Inversion, Activity Rate: V1, M ≥ 3.5, GMPE (central), Metric: 0.2% year-1 chance of exceedance (10% chance in 50 years)*

Conclusion

1. The Huizinge earthquake on August 16, 2012 was a watershed event for gas production in the Groningen field, causing NAM to launch a comprehensive Study and Data Acquisition Plan for induced seismicity in Groningen. This Plan builds on earlier seismic research and is a crucial building block for the *Winningsplan*, due July 1, 2016. The aim of the Plan is to deliver both a Hazard Assessment (i.e., ground motions) and a Risk Assessment (i.e., harm to people) for induced seismicity in the Groningen area.
2. The Hazard Assessment update presented in this study is an intermediate step in the execution of the Study and Data Acquisition Plan:
    a. Our understanding of the seismic hazard has benefited from fresh data obtained from the extended network of geophones and accelerometers, put in place in the second half of 2014. This has helped to refine our modeling of the seismic hazard.
    b. Compared with the results obtained for the 2013 Winningsplan, the current update shows a meaningful reduction of the assessed seismic hazard, translating into geographical maps with lower PGA hazard.
3. An important next step in the Study and Data Acquisition Plan is to further refine the Hazard Assessment by modeling the non-linear soil response using the recently completed Deltares description of the local shallow subsurface and new measurements of soil response.

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Note: For each document the link to the document on the web-site, where the document was issued has been provided. Some of these links might have become obsolete.

For those documents without a current link, a link to a www.namplatform.nl site will be provided in the next update of the report.

Appendix A - Partners

The main partners in the research program into induces seismicity in Groningen are listed below:

Partner	**Expertise**
Deltares	Shallow geology of Groningen, soil properties and measurements of site response/liquefaction.
University Utrecht (UU)	Measurements of rock compaction and rupture on core samples, understanding of physical processes determining compaction.
University Groningen (RUG)	Shallow geology of Groningen.
ARUP	Modelling of building response to earthquakes, management of the program to measure strength of building materials.
Technical University Delft (TUD)	Measure strength of building materials and building elements.
Eucentre, Pavia, Italy	Measure strength of building materials, building elements and shake table testing of full scale houses.
Mosayk	Modelling of building response to earthquakes.
Magnitude (A Baker Hughes & CGG Company)	Seismic Monitoring (determination of location results deep geophones)
TNO	Potential for earthquakes resulting from injection. Building sensor project.
Avelon	Supplier of geophone equipment permanent seismic observations wells.
Baker-Hughes	Supplier of geophone equipment temporary observation wells.
Anthea	Management of the extension of the geophone network.
Rossingh Drilling	Drilling of the shallow wells for the extension of the geophone network.

Appendix B - Experts

Apart from scientist, engineers and researchers in NAM and the laboratories of Shell (Rijswijk) and Exxonmobil (Houston), NAM has also sought the advice of internationally recognised experts. Some of the experts involved in the research program on induced seismicity in Groningen, led by NAM, are listed below.

External Expert	Affiliation	Role	Main Expertise Area
Gail Atkinson	Western University, Ontario, Canada	Independent Reviewer	Ground Motion Prediction
Sinan Akkar	Bogazici, University Istanbul	Collaborator	Ground Motion Prediction
Hilmar Bungum	NORSAR, Norway	Independent Reviewer	Ground Motion Prediction
Jack Baker	Stanford University, US	Independent Reviewer	Building Fragility
Julian Bommer	Independent Consultant, London	Collaborator	Ground Motion Prediction and Site Response
Tijn Berends	Student; University Groningen	Independent Reviewer	Site Response and Shallow Geological Model
Loes Buijze	University Utrecht	Collaborator	Rock Physics / Core Experiments
Fabrice Cotton	GFZ Potsdam, Germany	Independent Reviewer	Ground Motion Prediction
Helen Crowley	Independent Consultant, Pavia	Collaborator	Building Fragility and Risk
John Douglas	University of Strathclyde, UK	Independent Reviewer	Ground Motion Prediction
Ben Edwards	University Liverpool	Collaborator	Ground Motion Prediction
Paolo Franchin	University of Rome “La Sapienza”	Independent Reviewer	Building Fragility
Damian Grant	ARUP	Collaborator	Building Fragility
Michael Griffith	University of Adelaide, Australia	Independent Reviewer	Building Fragility
Russell Green	Virginia Tech, USA	Collaborator	Liquefaction Model
Brad Hager	Massachusetts Institute of Technology	Independent Advisor	Geomechanics
Curt Haselton	California State University, US	Independent Reviewer	Building Fragility
Rien Herber	University Groningen	Independent Facilitator	General
Rob van der Hilst	Massachusetts Institute of Technology	Independent Advisor	Geomechanics
Jason Ingham	University of Auckland	Independent Reviewer	Building Fragility
Adriaan Janszen	Exxonmobil	Independent Reviewer	Shallow Geological Model
Mandy Korff	Deltares	Collaborator	Site Response, liquefaction and Shallow Geological Model

Table continued:

External Expert	Affiliation	Role	Main Expertise Area
Marco de Kleine	Deltares	Collaborator	Site Response and Shallow Geological Model
Pauline Kruiver	Deltares	Collaborator	Site Response and Shallow Geological Model
Florian Lehner	University of Vienna	Independent Reviewer	Rock mechanics
Ger de Lange	Deltares	Collaborator	Site Response and Shallow Geological Model
Nico Luco	United States Geological Survey	Independent Reviewer	Building Fragility
Eric Meijles	University Groningen	Independent Reviewer	Shallow Geological Model
Guido Magenes	EUCentre Pavia	Collaborator	Building Fragility
Ian Main	University Edinburgh	Independent Reviewer	Seismogenic Model / Statistics
Piet Meijers	Deltares	Collaborator	Site Response, liquefaction and Shallow Geological Model
Michail Ntinalexis	Independent	Collaborator	Ground Motion Prediction
Barbara Polidoro	Independent Consultant, London	Collaborator	Ground Motion Prediction
Matt Pickering	Student; Leeds University	Collaborator	Seismic Event Location
Rui Pinho	University Pavia	Collaborator	Building Fragility
Adrian Rodriguez - Marek	Virginia Tech, USA	Collaborator	Site Response Assessment
Emily So	Cambridge Architectural Research Ltd	Collaborator	Injury model
Robin Spence	Cambridge Architectural Research Ltd	Collaborator	Injury model
Chris Spiers	University Utrecht	Collaborator	Rock Physics / Core Experiments
Joep Storms	TU Delft	Independent Reviewer	Shallow Geological Model
Jonathan Stewart	UCLA, California, USA	Independent Reviewer	Ground Motion Prediction
Peter Stafford	Imperial College London	Collaborator	Ground Motion Prediction
Peter Styles	Keele University	Independent Advisor	Geomechanics
Tony Taig	TTAC Limited	Collaborator	Risk
Dimitrios Vamvatsikos	NTUA, Greece	Independent Reviewer	Building Fragility
Brecht Wassing	TNO	Collaborator	Geomechanics

Table continued:

External Expert	Affiliation	Role	Main Expertise Area
Ivan Wong	AECOM, Oakland, USA	Independent Reviewer	Ground Motion Prediction
Stefan Wiemer	ETHZ Zurich	Independent Advisor	Geomechanics
Teng Fong Wong	University Hong Kong	Independent Reviewer	Rock mechanics
Bob Youngs	AMEC, Oakland, USA	Independent Reviewer	Ground Motion Prediction
Mark Zoback	Stanford University	Independent Reviewer	Seismological Model and Geomechanics