Study and Data Acquisition Plan Induced Seismicity in Groningen

Update Post-Winningsplan 2016

Progress and Schedule

1 Contents

1 Management Summary

1.1 Summary

With the Winningsplan (Ref. 50) in April 2016, NAM published an update of the "Studies and Data Acquisition Plan for Induced Seismicity in Groningen" (Ref. 62 and 63). The update was a directional plan with implicit reporting deadlines, conditional to the ministerial decision on future production in Groningen. Following the ministerial decision (Instemmingsbesluit), a schedule of activities in the Studies and Data Acquisition Plan was further defined, as presented in this report.

This schedule report follows the same structure as the Studies and Data Acquisition Plan and should be read in conjunction. Both reporting and publication dates are presented for each field of study, as well as the timing of the next updates of the full hazard and risk assessment in which the, at that time, latest results will be incorporated.

The ministerial decision also stipulated that NAM should develop a methodology to predict levels of building damage. The methodology will be shared before 1st February 2017. Subsequent milestones in this field of study are not yet included in the current report and will be added once the methodology is issued and agreed.

1.2 Samenvatting

Met de indiening van het Winningsplan Groningen 2016 (ref. 50) in april 2016 heeft de NAM tevens de meest recente versie van het Studie- en Data-aquisitieplan (S&D) aangeboden (ref. 62 en 63). Deze update is richtinggevend voor de studies, maar op het punt van het tijdschema nog niet in alle gevallen gelijkgeschakeld met de tijdlijnen zoals nu opgenomen in het Instemmingsbesluit op het Winningsplan. Dit schema is nu verder inzichtelijk gemaakt en gepresenteerd middels dit rapport.

Het schema volgt dezelfde opbouw als de meest actuele versie van het S&D-plan en dient in samenhang met dat plan te worden gelezen. Voor elk deelgebied is de rapportage- en publicatie-datum gegeven, als ook de doorwerking in de volgende versie van de Hazard and Risk Assessment. Deze laatste zal de alsdan bekende, meest recente inzichten omvatten.

Het Instemmingsbesluit vraagt de NAM tevens een methodologie te ontwikkelen om schade te voorspellen. De methodiek zal voor 1 februari 2017 worden ingediend. De voorbereidingen zijn momenteel in gang gezet, aanvullende studies binnen dit deelgebied zullen aan het S&D-plan worden toegevoegd wanneer de methodiek is overeengekomen.

2 Introduction

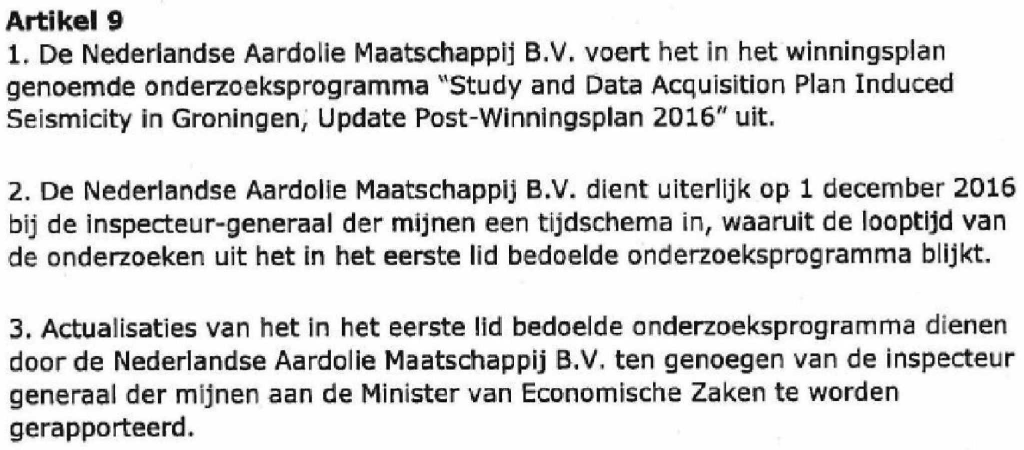
2.1 Study and Data Acquisition Plan – Winningsplan 2016

The first "Study and Data Acquisition Plan for induced seismicity in Groningen" was prepared in October 2012 (Ref. 4) and issued in January 2013. Following Winningsplan 2013 (Ref. 5) an updated study plan (Ref. 8) was issued early 2014. The latest update of the Study and Data Acquisition Plan (Ref. 62 and 63) accompanied Winningsplan 2016 and was issued on 1st April 2016. This update described the studies and data acquisition activities undertaken in 2016 and planned for the next 3 to 5 years in support of the assessments of hazard and risk resulting from induced seismicity in Groningen.

A schedule for the activities in the Study and Data Acquisition Plan was not included in the update of April 2016, because it was expected that later decisions might prompt a change in scope and specify milestone dates for updating the hazard and risk assessments. With the "Instemmingsbesluit Winningsplan Groningenveld" of 1st October 2016, both scope and schedule can now be finalised.

2.2 Instemmingsbesluit

Based on the milestone dates incorporated in the "Instemmingsbesluit Winningsplan Groningenveld" a revised schedule for the Study and Data Acquisition Plan for induced seismicity in Groningen was prepared and is presented in this current report, thereby following up on the actions stipulated in article 9[1].



Artikel 9

1. De Nederlandse Aardolie Maatschappij B.V. voert het in het winningsplan genoemde onderzoeksprogramma "Study and Data Acquisition Plan Induced Seismicity in Groningen, Update Post-Winningsplan 2016" uit.

2. De Nederlandse Aardolie Maatschappij B.V. dient uiterlijk op 1 december 2016 bij de inspecteur-generaal der mijnen een tijdschema in, waaruit de looptijd van de onderzoeken uit het in het eerste lid bedoelde onderzoeksprogramma blijkt.

3. Actualisaties van het in het eerste lid bedoelde onderzoeksprogramma dienen door de Nederlandse Aardolie Maatschappij B.V. ten genoegen van de inspecteur generaal der mijnen aan de Minister van Economische Zaken te worden gerapporteerd.

Figure 2.1 Article 9 from the "Instemmingsbesluit Winningsplan Groningenveld".

The "Instemmingsbesluit Winningsplan Groningenveld" also requires NAM to perform additional studies. In particular, article 7 asks to develop a methodology for the assessment of building damage states DS1, DS2 and DS3, using the building damage scale developed in the EMS-98 document. Currently, NAM is consulting academics and building damage experts on an extension of the Study

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[1] Translation:
Article 9
1 The Nederlandse Aardolie Maatschappij B.V. conducts the research program mentioned in the Winningsplan, "Study and Data Acquisition Plan Induces Seismicity in Groningen, update post-Winningsplan 2016".
2 The Nederlandse Aardolie Maatschappij B.V. submits, no later than December 1, 2016, a schedule to the Inspector-General of Mines in which the duration of the investigations of the research referred to in subsection 1 is shown.
3 Updates of the research referred to in the above paragraph must be reported Nederlandse Aardolie Maatschappij B.V. to the satisfaction of the Inspector General of Mines to the Ministry of Economic Affairs.

and Data Acquisition Plan, with increased focus on building damage. The damage assessment methodology (due by 1st February 2017) will be accompanied by the extension of the Study and Data Acquisition Plan, which will include a schedule for the associated activities.

This document should be read in conjunction with the "Study and Data Acquisition Plan Induced Seismicity in Groningen, update post-Winningsplan 2016". The scope of the study and data acquisition activities is described in the plan document, while the current report provides the schedule for these activities.

2.3 Overview Study and Data Acquisition Plan – Winningsplan 2016

This section provides a short overview of the "Study and Data Acquisition Plan Induced Seismicity in Groningen, update post-Winningsplan 2016". For more detail we refer to the document available at the studies page[2] of the website www.nam.nl.

- The main objectives of the Study and Data Acquisition Plan are to:
  1. Understand the impact of the earthquake hazard on buildings and other structures and the subsequent impact on 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, evaluate and develop mitigation options to reduce safety risk:
     - Production measures, i.e. changes in the areal distribution of the production from the field
     - An optimised Structural Safety Upgrading program:
       - Identify buildings and/or building elements that pose a safety risk
       - Establish optimal structural upgrading methodologies
     - Measures for industry and infrastructure.

Other important objectives are to:

4. Discuss the merits of alternative scientific views, and initiate additional studies and/or data acquisition to promote consensus amongst the knowledge institutes;
5. Monitor compaction, subsidence and seismicity;
6. Continuously improve our understanding of the physical mechanisms leading to induced seismicity and the resulting hazard;
7. Reduce the uncertainty in the hazard and risk assessment.
8. Hazard assessment tailored for infra-structure and industry.

Following the instemmingsbesluit a main objective has been added:

9. Prediction of levels of building damage (DS1, DS2 and DS3 on EMS-98 Scale).

- The research areas included in the Study and Data Acquisition Plan are:
  - Changing reservoir pressure (depletion) in response to gas production
  - Reservoir compaction in response to pressure depletion,
  - Generation of seismicity at faults (earthquakes) due to reservoir compaction,
  - Movement of the ground surface, due to earthquakes,
  - Response of buildings to the movement of the ground,
  - (Negative) impact on people in or near buildings, caused by damage or collapse of a building.

- The main activities initiated to improve monitoring of compaction, subsidence and seismic activity in the field have been:
  - Installation of 10 GPS stations,
  - Installation of 69 geophone wells and accelerometers (seismic monitoringstations),
  - Drilling and completion of 2 temporary monitoring wells with vertical geophone arrays, later replaced by,
  - Drilling and completion of 2 dedicated deep monitoring wells with vertical geophone arrays (Zeerijp-2 and Zeerijp-3A).
  - Installation of a real-time compaction monitoring fibre optic cable in ZRP-3A.

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[2] Link to this page: http://www.nam.nl/feiten-en-cijfers/onderzoeksrapporten.html

    - Gravimetric survey over full field.
    - Extensive wireline logging and pressure measurements in newly drilled wells.
    - Coring of a large section of the gas- and water-bearing part of the Rotliegend and Carboniferous formations in Zeerijp-3A.
    - Detailed mapping of the shallow subsurface and soils. Compilation of the map was followed by an extensive soil property measurement campaign.
    - Installation of more than 300 accelerometers in the foundations of buildings.
- Each research study carried out by or on behalf of NAM is subjected to both internal review and various types of external and fully independent reviews and verification. In this process, six layers of assurance were implemented:
    1. Internal NAM-assurance;
    2. Independent assurance requested by NAM;
    3. Independent assurance, requested by Ministry of Economic Affairs;
    4. Independent assurance by regulator SodM ;
    5. Independent assurance, requested by regulator SodM ,
    6. Independent critics,
    7. Transparency.
- Data has been shared with reputable research institutes and universities to do their own research independently from NAM.

- NAM proposes the introduction of an assurance process modelled after the SSHAC level-3 process used for seismic hazard assessment for the siting of large projects (e.g. nuclear facilities and hydro-electric dams). This is seen as the 'gold standard' for technical oversights.

- The document describes various studies addressing research questions. The following study proposals are included:
    - Investigations into sub-salt faulting,
    - Cenozoic fault activity,
    - Updates to the Groningen Reservoir Model,
    - Additional subsidence data acquisition,
    - In-situ Compaction monitoring,
    - Core measurements of compaction,
    - Compaction constitutive models,
    - Flexible Seismic Monitoring System,
    - Network of broadband sensor geophone wells,
    - DAS seismic monitoring,
    - Determination of hypo-centre and magnitude,
    - Core measurements and models for rupture processes,
    - In-situ stress measurements,
    - Development of alternative seismological models,
    - Assessment of hazard changes due to swing production,
    - Measurements of Ground Motion and expansion of the database,
    - Measurement of site (local soil) response,
    - Refinements to the Ground Motion Prediction methodology,
    - Spatial correlation of Ground Motions,
    - Wave-field Simulation-based Event Characterisation,
    - Investigation into Swelling Clays and Peat,
    - Investigation into anthropogenic soil (e.g. wierden),
    - Investigation into Liquefaction,
    - Expansion and refinement of the Exposure Database,
    - Properties of building materials,
    - Experimental tests of Structural and non-structural elements of buildings,
    - Modelling and testing of Structural Components of buildings and Systems,

- In-situ dynamic testing of buildings,
- Modelling and testing of non-Structural Components of buildings,
- Assessment of Falling Objects,
- Modifications to the Monte-Carlo Risk Engine,
- Control Optimisation for Earthquake minimization,
- Comparing predictive performance seismological models,
- Next Generation PSHA

3 Schedule

In this section the current progress and schedule for the main activities listed in the "Study and Data Acquisition Plan – Winningsplan 2016" will be described. The text follows the same structure as the Study and Data Acquisition Plan and addresses the developments for each of the study areas. It is important to realise that these studies often involve fundamental research for which the outcome and/or timeline is impossible to predict, while follow-up studies depend on the results of earlier studies. As a result, the scope and timing of future studies may have to be adjusted depending on the outcome of precursor studies (or insights from other studies by other parties). The associated timelines will inherently carry significant uncertainty. In general, Data Acquisition can be planned with more confidence into the future than the studies.

3.1 Milestone Dates

Many of the study results will be incorporated in the updates of the seismic hazard and risk assessments. The schedule will therefore not only indicate the date when the results of the studies will be shared in reports, but also in which update version of the seismic hazard and risk assessment these will be incorporated.

Some of the studies aim at gaining a fundamental understanding of the physics of the origin, progression and effects at surface of the earthquakes. These are for instance the experimental studies on the reservoir core to better understand the compaction and rupture processes. NAM intends to share the progress and results of these fundamental studies also through academic symposia.

The overall overview of milestone dates is provided below:

Milestone	Date
Update of the Seismic Hazard Model, including Hazard Metrics for Building Damage	1st June 2017
Annual Symposium to share progress and status of research into induced seismogenic processes, including results of core experiments, geophysical/geomechanical studies into hypocentre location and source mechanism	September - October 2017 Date to be determined
Update of the Seismic Hazard and Risk Model, including application of the building damage assessment methodology	1st November 2017
Annual Symposium to share progress and status of research into induced seismogenic processes, including results of core experiments, geophysical/geomechanical studies into hypocentre location and source mechanism	September - October 2018 Date to be determined
Update of the Seismic Hazard and Risk Model, including application of the building damage assessment methodology	1st November 2018
Annual Symposium to share progress and status of research into induced seismogenic processes, including results of core experiments, geophysical/geomechanical studies into hypocentre location and source mechanism	September - October 2019 Date to be determined
Update of the Seismic Hazard and Risk Model, including application of the building damage assessment methodology	1st November 2019
Assurance workshops for the studies supporting the hazard, building damage and risk assessments for Winningsplan 2020.	January - June 2020 Date to be determined
Annual Symposium to share progress and status of research into induced seismogenic processes including results of core experiments, geophysical/geomechanical studies into hypocentre location and source mechanism	September 2020 Date to be determined
Winningsplan 2020 Update of the Seismic Hazard and Risk Model and application of the building damage assessment methodology	30th September 2020

Table 3.1 Milestone dates for the Study and Data Acquisition Plan covers hazard and risk assessments and events for sharing progress and results of fundamental research with academic community.

The date of 1st November of each year connects with article 5.3 of the instemmingsbesluit. Here NAM is tasked to deliver at the 1st of May and 1st of November of each year a report analysing the development of the seismicity and the effectiveness of the mitigating measures.

3.2 Groningen Reservoir Model

Further validation and calibration of the static and dynamic reservoir models of the Groningen field is an on-going effort. Section 6 of the "Study and Data Acquisition Plan – Winningsplan 2016" described the studies currently planned. Additional studies can in the future be identified based on further evaluation of the field behaviour in response to gas production. In this section we will discuss the schedule for delivery of those studies, focussing on their phasing and incorporation of their respective results in the update of the reservoir model and subsequent update of the seismic hazard and risk assessment.

3.2.1 Static Model Update

Two petrographic studies are in their final stages and will be completed before year end 2016. The titles of these two reports are (1) "Petrographic study of well Zeerijp-3A (ZRP-3A)" and (2) "Petrographic Aspects of the Rotliegend of the Groningen Field". A **sedimentological study** investigating options to incorporate facies information in the Groningen reservoir model will also be completed. This report is titled "On the implementation of sedimentological data in porosity modelling for the Groningen field". We expect to be able to publish these study reports on the onderzoeksrapporten-page[3] of www.nam.nl before 1st January 2017.

The **interpretation and mapping of the Top Carboniferous surface** is currently in progress. This work is making use of the newly reprocessed seismic data and aims to obtain a better understanding of fault patterns within the Carboniferous. The work is expected to be closed out and reported on the onderzoeksrapporten site by 1st October 2017. The Top Carboniferous surface will be used to better constrain the base of the Rotliegend reservoir in future versions of the Groningen static and dynamic reservoir models.

Currently, additional data acquisition on the Carboniferous is under consideration. Especially, the **seismic velocities in the Carboniferous** are of interest. A first 2D trial line was shot mid-November 2016 using the flexible geophone spread located over the area north of Loppersum (see section 3.4.1 Flexible Geophone Network). Depending on the result, this will be repeated when the geophone spread has been relocated to a different part of the Groningen field. This is the first step of the **new 3D data acquisition feasibility study**. Data acquisition will continue through 2017 and 2018, followed by processing of each new data set. Results will be reported and made available to other researchers when available.

The **interpretation of the Mesozoic and Cenozoic faults** in the Groningen area will commence early 2017 and is expected to be closed out with a report on the onderzoeksrapporten site by 1st October 2017.

3.2.2 Dynamic Model Update

A petrophysical study was initiated analysing the available logs from the wells partially drilled in the aquifer of the Groningen field, as part of the **investigation into the critical or trapped gas saturation in the aquifer**. A report describing the results is expected to be published to the onderzoeksrapporten site by 1st April 2017. The results of the study will subsequently be

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[3] Link to this page: http://www.nam.nl/feiten-en-cijfers/onderzoeksrapporten.html

incorporated in the model of the Groningen field that will be used for the update of the hazard and risk assessment for 1st November 2017.

The **gravity survey** done in the Groningen field in 2015 is subject to further detailed evaluation. A report is expected to be available 1st September 2017. Aim is to incorporate the results in the dynamic model for the update of the hazard and risk assessment for 1st November 2017. However, as this is very detailed and innovative work, delays in the delivery cannot be excluded. This same timeline also applies to the incorporation into the history matching process of the dynamic model of the **compaction measurements** based on the market bullets in observation wells.

Further advances in using the **tubing head pressure** data in the update of the dynamic model are in the final stages. This work is expected to be published 1st April 2017 and to impact the hazard update for 1st June 2017. The investigation into the **high permeability area in the central part of the field** is currently in progress. A report will be published 1st July 2017 and results be incorporated in the update of the hazard and risk assessment planned for 1st November 2017.

With the model directly calibrated and history matched to subsidence data, it is now also possible to further improve the modelling of compaction. This so-called **"closed-loop" compressibility – porosity relationship** is planned to be implemented by 1st September 2017 to be available in the dynamic model for the update of the hazard and risk assessment for 1st November 2017.

3.2.3 Schedule

The table below presents the schedule for further studies in support of enhancement of the Groningen Reservoir Model:

Study Activity	**Report available and published at Onderzoeks-rapporten site**	**Results incorporated in update of hazard and risk assessment**	**Description of the Activity in S&DAP. Section and Page number**
Petrographic study 1	1st January 2017	1st June 2017	Section 6, page 55
Petrographic study 2	1st January 2017	1st June 2017	Section 6, page 55
Sedimentological study	1st January 2017	1st June 2017	Section 6, page 55
Top Carboniferous mapping / Sub_Salt faulting	1st October 2017	1st November 2017 (preliminary) 1st November 2018	Section 6, page 55
Carboniferous velocities	Intermediate Report 1st November 2017	Long-term study effort	Section 6, page 55
Cenozoic faults interpretation	1st October 2017		Section 6, page 55
Gas in aquifer study	1st April 2017	1st November 2017	Section 6, page 55
Incorporate gravity survey results in dynamic model	1st September 2017	1st November 2017	Section 6, page 60
Incorporate compaction measurements in dynamic model	1st September 2017	1st November 2017	Section 6, page 60
Incorporate Tubing Head Pressure data in dynamic model	1st April 2017	1st June 2017	Section 6, page 58
High permeability area in Central part of field	1st July 2017	1st November 2017	Section 6, page 60
Closed-loop compressibility modelling in dynamic model	1st September 2017	1st November 2017	Section 6, page 59

Table 3.2 Milestone dates for further studies in support of enhancement of the Groningen Reservoir Model.

3.3 Subsidence and Compaction

3.3.1 Subsidence Data Acquisition, Interpretation and Visualization

Deployment of GNSS stations in Groningen has started recently. The purpose is to measure not only subsidence but also horizontal deformation (3D land deformation). After the deployment GNSS data will be processed using advanced scientific software. The ongoing high resolution InSAR monitoring for Groningen will continue by either using imagery from the same satellite (TSX) or Radarsat-2 imagery in fine resolution model (< 3 m). To cross validate GNSS and InSAR measurements artificial targets (corner reflectors or active transponders) will be deployed next to or near the GNSS stations. The comparison between the two will improve stochastic modeling of the error sources in the InSAR and GNSS measurements. Visualization tools for better presenting deformation measurements from various techniques will be developed and the modelled uncertainties of the deformation measurements will be integrated in the visualization.

3.3.2 Compaction monitoring in Observation Wells

Both wells TBR-4 and ROT-1A were surveyed in 2016 with the CMI tool from Baker-Hughes. Survey interpretations by Baker Hughes were however questionable (non-physical) and a re-evaluation of this data plus the data obtained in the STM-1 during the 2010 and 2013 surveys is requested by NAM. First results will be reported before 1st October 2017.

3.3.3 DSS data

A distributed strain sensing (DSS) fibre optic cable is installed in the ZRP-3A well. This well required a temperature and mechanical stabilisation period, before the strain measured was representative for the reservoir strain. A change out of the wellbore content (See section 3.4.3 Geophones placed over the Reservoir Section in Deep Wells) would induce temperature changes and therefore will be followed by another stabilisation period. Strains can be measured every 2 cm up to an accuracy of about 5 microstrain. First results will be reported before 1st October 2017.

3.3.4 Compaction data integration

The compaction data from both the GR markers as the DSS cable is to be integrated with the rock and pressure information, and will be described in a report after the re-evaluation of the CMI data by Baker Hughes.

3.3.5 Core Measurements

The geomechanical laboratory at Shell Global Solutions International B.V., Rijswijk, The Netherlands, has committed 8 to 12 triaxial cells, plus analytical equipment, to a geomechanical core testing program. Approximately ⅔ of the laboratory work has been executed and analyzed, and ⅓ is in progress. The experimental work performed so far includes 40 pore pressure depletion/cyclic loading tests to assess compaction and poroelastic properties, 16 triaxial compressive strength tests. All data suggest, for Groningen sample material, deformation during depletion is in the stable mechanically regime. Sample analysis in progress includes particle size analysis, Scanning Electron Microscopy, and CT scanning. Fault friction tests and being set up in collaboration with Utrecht University, and will focus on the effect of long-term healing in fault zones. An increased focus on acoustic properties of the material may allow correlation with wireline logs in the future. A full report is expected to be ready for release by Q4 2017.

A significant portion of the triaxial/uniaxial compaction and direct shear testing has been completed (70 experiments). UCS testing has not yet commenced. Limited testing and thin section information has also been collected on the uniaxial samples. Full report is expected for release by the end of the project. Intermediate results of these studies will be shared at the planned academic symposia.

3.3.6 Schedule

Study Activity	Report available and published at Onderzoeks-rapporten site	Results incorporated in update of hazard and risk assessment	Description of the Activity in S&DAP. Section and Page number
Densify existing GNSS network in Groningen by deploying between 10 and 30 GNSS stations.	Q4 2017	Data Acquisition will improve subsidence monitoring.	Section 7, page 63
Alternative GNSS processing with scientific software/EUREF	Q4 2017		Section 7, page 63
Continuation of high resolution InSAR	Q3 2017		Section 7, page 64
Deploy artificial target for InSAR based deformation monitoring	Q2 2018		Section 7, page 64
Supplemental research on the stochastic model of geodetic techniques	Q4 2017		Section 7, page 64
Visualization tools for subsidence measurements	Q3 2018		Section 7, page 64
DSS status report	Q2 2017	Data Acquisition will improve compaction monitoring.	Section 7, page 65
Re-evaluation of CMI data TBR-4, ROT-1A, STM-1	Q3 2017		Section 7, page 65
Compaction data integration	Q4 2017	1st November 2017	Section 7, page 65
Geomechanical core testing program report (with Shell Lab.)	Q4 2017	Intermediate results will be shared at academic symposia	Section 7, page 65-66
Geomechanical experiments report (with Exxonmobil Lab.)	Q2 2017		Section 7, page 65-66
Physics-based compaction and energy dissipation/storage models for implementation in macroscale modelling (with University Utrecht)	Q4 2017		Section 7, page 65-66
PhD thesis + published papers with integrated/refined, mechanism based compaction models, implications (with University Utrecht)	Q4 2018		Section 7, page 65-66

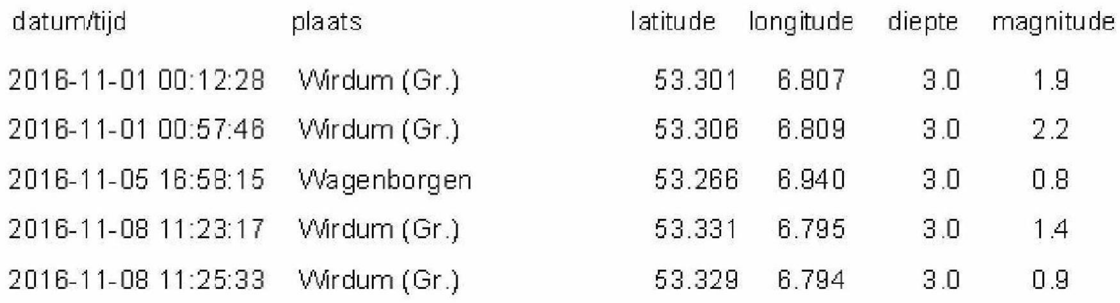
Table 3.3 Milestone dates for further studies in support of subsidence and compaction.

3.4 Seismological Model and Geomechanics

3.4.1 Flexible Geophone Network

The deployment of the flexible geophone network by Rossingh Geophysics BV from Gasselte has recently started. The network currently consist of 400 nodes with 3 recording channels each, allowing the use of 400 3-component geophones or 1200 single ones. As these nodes can be installed independently and consist of a separate battery pack, data logger and geophone these can be deployed very flexible, e.g. at variable distances from each other, in- and outside buildings, at different projects in parallel and for short and long (one year+) projects. There are a variety of data acquisition projects identified for the network. Most of these are in support of the development of the seismological model and the ground motion prediction methodology.

- Currently (November 2016) the network is laid out in a 7 by 7 km area north of Loppersum (Figure 3.3) by using all 400 nodes in a grid of 350 meters spacing. The main objective is the **assessment of the shear-wave (V_s) velocity in the shallow sub-surface**. The aim is to determine the shear-wave velocity for the interval down to 800 m depth ($V_{s,800}$). The outlook is promising, however as this part of the program is still in the experimental phase, processing of the data set will show whether determination to this depth can be achieved. The geophones have been collected in November 2016, and data is currently being retrieved from the data loggers. Processing is expected to take several months. The results are expected to be shared in a report by mid-2017. If this Loppersum data acquisition is successful, several other areas will also be covered by the network. Ultimately, measurements are expected to be done in 7 to 8 areas (depending on success of the Loppersum data acquisition). The next area selected for assessment of $V_{s,800}$ is located south of Delfzijl and the plan is to have that network ready in the field before X-mas 2016. Based on the first results of the processing of the data acquired over the area north of Loppersum, the design of the geophone set-up and duration of acquisition for the following spreads might be adjusted. It is expected this data acquisition will commence late January 2017 to early March 2017. It is currently expected that the 3rd $V_{s,800}$ data acquisition will commence late March 2017 and that following areas will each take some 2 months to carry out the data acquisition followed by an average 2 months for data processing. Reports with early results are expected to be available some 5 to 6 months after retrieval of the data from the geophone data loggers.
- Although the geophone spread north of Loppersum did not cover the epicentre, the geophones did record the **earthquake sequence near Wirdum early November 2016**.



datum/tijd	plaats	latitude	longitude	diepte	magnitude
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2016-11-01 00:57:46	Wirdum (Gr.)	53.306	6.809	3.0	2.2
2016-11-05 16:58:15	Wagenborgen	53.266	6.940	3.0	0.8
2016-11-08 11:23:17	Wirdum (Gr.)	53.331	6.795	3.0	1.4
2016-11-08 11:25:33	Wirdum (Gr.)	53.329	6.794	3.0	0.9

Table 3.4 Earthquakes recorded near Wirdum (gr.) early November 2016. Table was taken from KNMI (www.KNMI.nl).

- During Q1 2017, a separate set of 75 3C-geophone nodes (similar to the ones currently in use for the $V_{s,800}$) will be located near and in **buildings currently equipped with TNO 3C sensors**.

The aim is to establish the ground motion near the building, the response of the foundations and of other elements and levels of the building. The results are useful for better understanding of and optimizing the use of the TNO sensors. However, this installation will require adaptations of the current geophone nodes. We expect to have received the necessary permits by early Q1 2017. These nodes will most likely need to remain in place for at least 12 months. Results are therefore expected to be published in the second quarter of 2018.

- After the second pick up of 400 $V_{s,800}$ geophone nodes this network is planned to be redeployed over Wierde **Groot-Maarslag**. Depending on earlier progress in the field, this is expected to commence February to March 2017.
- Next to the above mentioned two groups a third pool of 175 nodes will be used for acquiring the $V_{s,30}$, which campaign can fill at least two years. The $V_{s,30}$ projects will generally not take longer than 2 – 4 days, which makes planning of this set extremely flexible and therefore these can also be made available at short notice for a wide range of other surveys with high priority, e.g. there is an urgent request related to optimization of $V_{s,30}$ reliability nearby 17 KNMI stations.

Figure 3.2 Node of the flexible geophone network consisting of the battery pack (white), data logger (yellow) and three component geophone (green).

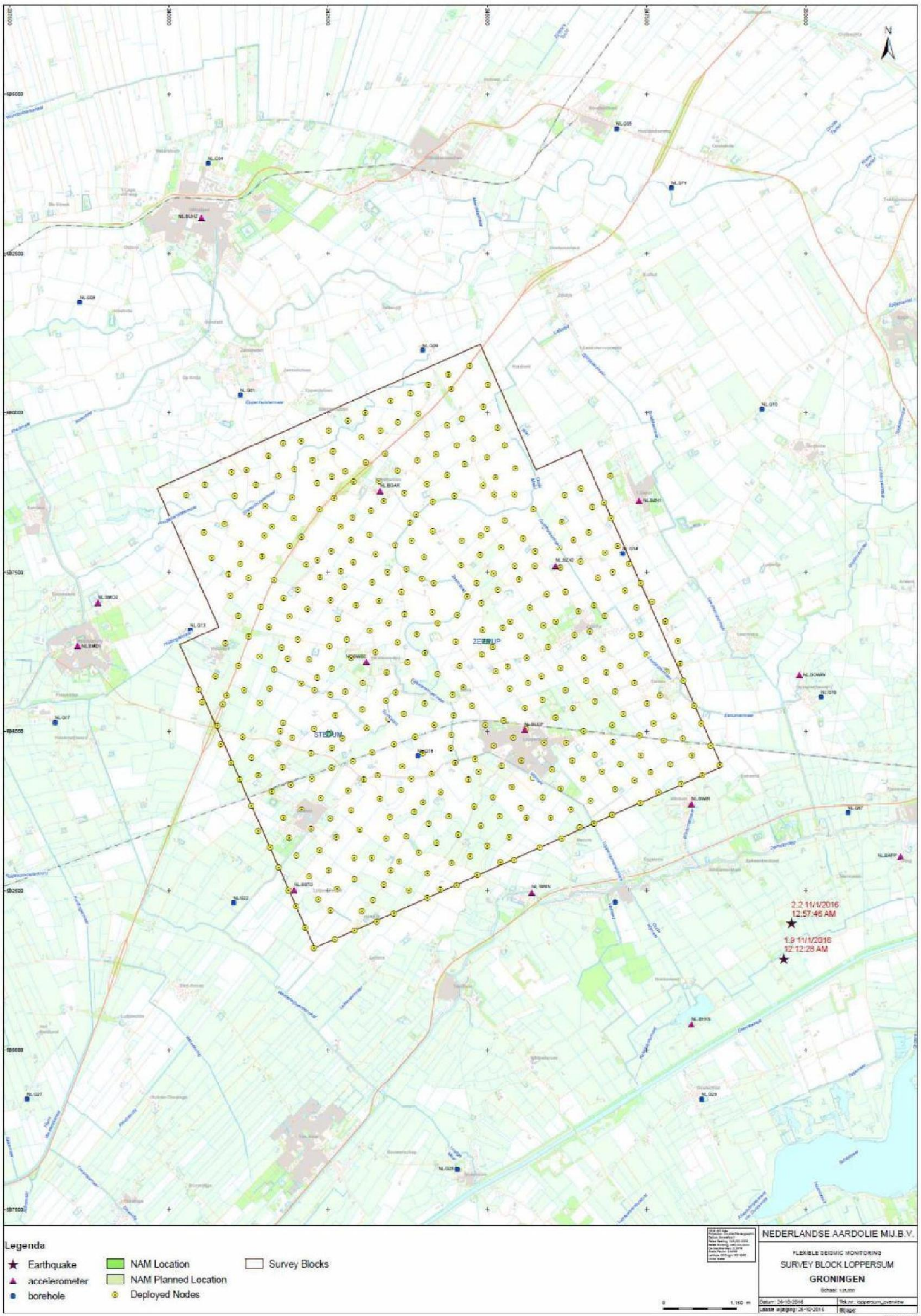

Figure 3.3 *Current spread of the flexible geophone network north of Loppersum. Area is roughly 7 X 7 km. The two epicentres of the earthquakes near Wirdum on the 1st November 2016 are indicated by red stars.*

3.4.2 Broadband Geophone Stations

Above the Groningen gas field a seismic monitoring network has been realized[4]. This monitoring network includes 70 monitoring stations, each equipped with 4 passive three component geophones installed at a depth of 200, 150, 100 and 50 meter, an at surface installed accelerometer and communication equipment. In addition to this monitoring network four additional **broadband stations** are foreseen, these broadband stations are scheduled close to the seismic monitoring stations G18, G44, G56 and G64, in order to be able to compare recorded data from both systems as well as taking advantage of available infrastructure.

Each broadband station will be equipped with one Kinemetrics STS-5A broadband sensor. The sensor will be installed at 100 meter depth in order to limit background noise to improve signal-to-noise ratio. In contrast to the above mentioned passive three component geophones, the broadband sensors have to be installed in a dry, cased borehole. A specific procedure has been developed to cement a Ø 225x199 mm class PN16 PVC casing in a 120 meter deep borehole. As the broadband sensor only functions in a dry environment, the main challenges are to avoid (rain - and ground) water encroachment, floating of the casing and obtain good bonding of the casing to the formation.

In the first half of November 2016, the first borehole has been drilled. After an observation period of at least two months, the borehole will be logged to prove absence of water and to measure the casing bond to the formation. When proven successful, the other three boreholes will be drilled early 2017, followed by installation of the broadband sensors, surface amplifiers and communication equipment. After installation, the recorded data is continuously communicated to the KNMI. Depending on the results of the drilling test and weather conditions during the drilling and construction period, this data communication is earliest expected 1st July 2017.

3.4.3 Geophones placed over the reservoir section in Deep Wells

Harkstede

A **temporary micro-seismic monitoring system** has been installed in the Harkstede-2a observation well (HRS-2a), an existing monitoring well in the field nearest the city of Groningen. An observation period of maximum 12 months is foreseen for this temporary system. Objective of the measurement is to gather information which serves as input to further improve our knowledge of hazard and risk estimations in the more densely populated area. The monitoring system includes an array of 9 three component geophones, and at surface recording and communication equipment. The array has been orientated using the seismic events (all with magnitude $M \geq 0.5$) recorded by both the HRS-2a array and the surface geophone network and interpreted by KNMI. Due to the relative high downhole temperature and pressure conditions failure of (a part of) the array might be expected. The geophone string is expected to be recovered from this well latest October 2017.

Stedum and Zeerijp

The deep-set geophone arrays in SDM-1 and ZRP-1 wells have been decommissioned after the **dedicated seismic monitoring wells ZRP-2 and ZRP-3A** were drilled. Unfortunately, the geophones installed in these new wells have suffered from various malfunctions, resulting in considerable downtime of the monitoring. The geophone strings from both wells have been recovered, repaired

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[4] Generally referred to as the KNMI network

and re-installed several times. The most likely failure mechanism seems to have been established through investigations of the geophone failures in a test well in the UK. Early next year the fluid in the two wells will be replaced with a potentially less corrosive fluid and the geophones re-installed. Once the fluid is changed out in both wells, their respective geophone strings will be re-installed for continuous recording. In a three months un-interrupted recording period at ZRP-3A prior to the failure, we saw that the longer geophone array length (spanning from the Carboniferous below the reservoir to well within the Zechstein above the reservoir) gave excellent results. Compared to the shorter arrays used at SDM-1 and ZRP-1, the longer arrays in ZRP-2 and ZRP-3A put us in a much better position to locate observed earthquakes with higher precision. As a consequence of these failures it was decided to extent the seismic monitoring from the existing observation well Stedum-1.

In order to get the geophone arrays to perform without failures in the future, hardware design changes have been proposed by the vendor, which are currently being implemented and tested. But also a change out of the fluid in the boreholes is planned. As from Q1, 2017, recording will commence in ZRP-2 again with the modified geophones, followed by ZRP-3A in Q2.

Due to the presence of a DTS temperature system in the Zeerijp-3 well, the change out of the fluid content of this well will also provide a useful **dataset for the evaluation of geothermal projects** in the Rotliegend reservoirs. Design of this data collection will be done in cooperation RUG, while the data will be shared with interested academic groups.

3.4.4 DAS Seismic Monitoring

In the Zeerijp-3A well, a fibre optic cable with multiple strands is fitted. Currently DTS (distributed temperature) and RTCM (compaction) are measured, but DAS (distributed acoustic sensing) is also possible. The well will be fitted with an array of 15 3-Component geophones (see section above), covering the lower 560 m of the borehole. The fibre optic cable however, runs all the way from TD to the top of the borehole, with a length of over 3800 m.

Particularly the lower SNR (signal to noise ratio) of the system makes the currently available recording instruments, usually deployed for VSP (Vertical Seismic Profile) measurements, less suitable for micro-seismic applications. However, OptaSense (aQinetiQ company, in collaboration with Shell) has developed an improved, 5th generation version of their instrument (called 'interrogator unit'), which is designed to be used for the micro-seismic applications.

The Zeerijp-3A well will be used to test this new hardware and benchmark it against the previous generation of interrogator units. Because of the experimental nature of the DAS cable deployment, we will be closely working together with the fiber optics and DAS specialists in Shell Rijswijk and Houston.

After a successful first test, planned for the January 2017, to establish whether the DAS cable and the interrogator unit perform as designed, we plan for an actual deployment of the DAS system in conjunction with the downhole geophones in Q2, 2017. Subsequently, a period of passive listening for micro seismicity will commence and results will be evaluated. Since this is an experimental setup, the results come with a considerable uncertainty.

3.4.5 Geomechanical Modelling

The geomechanical research is based on the understanding that all failure mechanisms are described by stress-based criteria. The geophysical work on the determination of the hypocentre locations using the geophone network and the two deep geophone wells over the last few years has provided evidence that the Groningen earthquakes are expressions of shear failure occurring along existing, geological fault planes. Fault slip is conventionally assumed to adhere to a Mohr-Coulomb shear failure criterion, which compares the actual shear stress on the fault plane with the local shear strength of the fault. However, realistic simulation of earthquakes is extremely complex, and involves modelling of 3D branched fault zones with asperities, reservoir offsets, non-linear (weakening) behaviour of formations and fault zones, possibly creep and other time-dependent hydrological processes, such as un-drained formation response near rupturing fault zones. The geomechanical research is aimed at continuous improvement of our understanding of the physical mechanisms leading to induced seismicity and the resulting hazard.

Since 2013, the geomechanical research follows a strategy of step-wise increase of the modelling complexity. The initial simple Mohr-circle approach was replaced by 2D static modelling approach to assess the onset of slip along faults with various throw. It was found that a Mohr-circle approach is inadequate to assess fault stability of faults with varied throws. Subsequently, the ideal slip law for the faults was replaced by a slip-weakening relationship, which led to understanding that both reservoir formation offset and slip-weakening determine whether or not a fault has seismogenic potential. Next, the 2D static fault stability model has been replaced by a 2D dynamic rupture model. This revealed three different rupture mechanisms: two basic mechanisms and a third that is the combination of the two other mechanisms. This allowed an assessment of the Moment Magnitude, the seismic efficiency, and other seismological parameters in relation to different geomechanical model parameters. Most importantly, the corner-frequencies of our simulated wave forms correspond well with those of actual seismic events in the Groningen field. This allows a direct comparison between geomechanical simulations and field data.

The next important question is: what determines the shape and size of the simulated rupture area, and what is the resulting displacement, the seismic efficiency, stress drop, Moment magnitude and wave forms (corner frequency). Currently, the 2D dynamic rupture model is extended to 3-dimensional analysis. Also, a detailed 3D geomechanical model of the Loppersum area has been built based on a local re-interpretation of the faults and the geology structure. The available post-processing is being extended for 3D dynamic rupture analysis, and sensitivity analyses will be conducted on the impact of asperity size on the rupture mechanism.

The following main focus areas are identified going forward:

- Development of a formation-offset dependent stress-path model, including probabilistic assessment of uncertainties and strength variability (asperities) (Q4 2017), with the ultimate aim to develop an alternative stress-based seismological model.
- Characterisation of fault strength in the Groningen field (2017-2018). The aim is to establish a relationship between available petrophysical and geological information of the Groningen faults on one hand and asperity size and properties (strength and post-failure behaviour) on the other hand. This should be input to work under the previous point.
- Simulation of asperities size and properties (2017-2018). This addresses fundamental questions about the impact of different and alternating patches of hard & brittle versus soft &

ductile fault gauge material on the moment magnitude. How large does a ductile patch need to be to arrest a rupture initiated elsewhere on a fault plane? This work should be informed by the characterisation conducted under the previous point.

- 3D rupture simulation and calibration against actual seismic events based on a comparison of wave forms and other location data. Currently, the focus is on the Loppersum area (2017).

3.4.6 Seismological Models

The **activity rate model** developed for Groningen uses strain data together with fault density to assess induced seismicity. The strain is evaluated from the rich subsidence data set. Since the deployment in Groningen and publication of papers, similar models that make use of the geodetic monitoring to understand the evolution of strain rate have been proposed for Oklahoma. One of the recent studies[5] shows that a complex mechanism of waste-water injection related seismicity is controlled by the changes in Coulomb stresses and background stresses. Using satellite geodetic data derived observations of the time-dependent stress field, these authors computed the evolution of strain rate and pore pressure to assess the triggering of the seismicity. This recent work highlights the value of observation of the time-dependent stress field and its role in the construction of the temporally-variable statistical framework used for earthquake operational forecasting.

The first seisomological model developed to describe Groningen induced seismicity within the PSHRA workflow was based on Kostrov's and McGarr's theoretical work which related strain to induced seismic moment. This was superseded by a model which related the seismic activity rate to the reservoir compaction. In addition to these models which have been implemented as an integral part of the PSHRA workflows, an **explicit fault based seismological model** has been developed by ExxonMobil. This has been complemented by dynamic fault rupture simulations performed for a number of representative scenarios by researchers in Shell and University of Utrecht. As possible alternatives to these models, **slider block models** and **models based on Eshelby's inclusion theory** are also being actively studied. We will continue to develop and advance the fault based seismological model as well as the alternatives just mentioned. Statistical methods (prospective testing) will be applied to determine which model provides the best fit to the observed seismicity.

The current 3D geomechanical models will be updated on the basis of new laboratory (variable fault friction, stress-strain behavior and rock creep) and field (in-situ stress and InSAR geodetic measurement) data and updated reservoir pressure models (new production scenarios and additional rock property data). Efforts to improve the understanding of the physical/geomechanical processes underlying the fault reactivation process will continue. For example, the extension of the 2D dynamic rupture simulations into the 3D domain will be considered. In this next phase, the following physical processes, which are important in fault reactivation, will be considered: undrained formation behaviour, salt creep, formation plasticity, rate and state fault friction laws, heat generation during rupture and inelastic reservoir strain. Such work will enable us to improve the correlation between geomechanical model attributes and the parameters describing the depletion-induced seismicity.

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[5] For instance in the paper: Manoochehr Shirzaei, William L. Ellsworth, Kristy F. Tiampo, Pablo J. González, Michael Manga, Surface uplift and time-dependent seismic hazard due to fluid injection in eastern Texas, Science, 23 SEPTEMBER 2016 • VOL 353 ISSUE 6306 sciencemag.org

The deliverables will be an updated 3D geomechanical model, an assessment of the relative goodness of fit for this and other alternative seismological models and the generation of appropriate model output attributes to enable us to determine the impact on seismicity of a range of production scenarios for the optimization of production.

3.4.7 Assessment of hazard changes due to swing production

Several exploratory studies using physics based, geomechanical and statistical approaches are in progress. Due to the complexity of the processes of seismic event initiation these studies have a fundamental research character. Results will be reported at the academic symposia.

3.4.8 Ongoing independent research projects

The raw, unprocessed seismological and subsidence data have been made available upon request to a variety of independent research groups worldwide with "no strings attached" to foster independent and autonomous research. The parties partaking in the data perusal include academic and non-academic groups such as university consortia, university research groups, non-government organizations, and knowledge institutes. The type of research done is academic in nature, solely guided by the groups themselves and as such fully independent of any NAM influence.

Data volume shared	Party data has been shared with	Time	Comments
Seismological data from temporary deep geophone wells	Mr. John Lanting Schokkend Groningen, The Netherlands	May 2014	
Seismological data from temporary deep geophone wells and VpVs velocity model	Gassnova Project, NORSAR, Norway	July 2014	Focus research: Locating hypo-centres of earthquakes.
VpVs velocity model and Geodetic Information.	Dr. Mike Fehler, Prof. Tom Herring and Prof. Brad Hager MIT (Massachusetts Institute of Technology), USA	August 2014	Focus research: (1) Analayis of historic seismic data and (2) Geomechanical and Geodetic investigation of seismic versus aseismic deformation.
VpVs velocity model and raw data deep geophones	Prof Gregory C. Beroza Stanford University, USA		Focus research: Ambient noise interferometry to infer shear wave Velocities
VpVs velocity model and raw data deep geophones	Dr. H. Paulssen, University Utrecht	December 2015	Focus research: Noise interferometry to infer changes in medium properties and Microseismicity
Subsidence measurements by InSar	Prof. Bob White Cambridge University, UK	December 2015	Focus research: Locating hypo-centres of earthquakes.
Seismological data from temporary deep geophone wells (update with recent data)	Gassnova Project, NORSAR, Norway	January 2016	Focus research: Locating hypo-centres of earthquakes.
Clarification of data request in progress	University of Bristol	March 2016	
Seismological data from the deep borehole arrays and KNMI shallow borehole network	Prof. Pablo Ampuero, Utrecht University	November 2016	Focus research: search for similar event waveforms (i.e. emprical Green's functions) to investigate source properties
Seismological data from the deep borehole arrays and KNMI shallow borehole network	Prof. Serge Shapiro, Free University Berlin	November 2016	Focus research: investigate source parameters using the emprical Green's functions
Seismological data from the deep borehole arrays and KNMI shallow borehole network	Prof. Doug Dreger, University of Claifornia at Berkley		Focus research: investigate source parameters using the emprical Green's functions

Table 3.5 Data packages shared with independent research institutes and universities.

An example of the independent nature and broad scope of research and the resulting applications is the project by NORSAR/Gassnova who are stewarding an effort to further improve downhole array detection, location, and characterizations of earthquakes, and improve the network design. Being an internationally recognized, independent, non-profit research foundation responsible for monitoring earthquakes and nuclear explosions, NORSAR will apply findings from the Groningen data sets to assessing the capabilities of the local (Norwegian) CO_2 storage.

Parallel efforts to characterize earthquake slip history, earthquake rupture size and rupture velocity for the microseismic events (smaller than M3), an unprecedented effort for events of such small magnitudes truly pushing the knowledge boundary of understanding the earthquake process, are steered by three universities: Free University of Berlin, Utrecht University and University of California at Berkley.

Recent and ongoing research at the NAM includes event location enhancement through usage of InSite software and a combination of downhole and shallow surface borehole network data. By scrutinizing the event location NAM is aiming to improve and fine-tune the existing P and S wave velocity model, and ultimately get a better understanding of the complex phase arrivals evident in a vast portion of the recoded data.

With the consideration that progress reporting is strictly voluntary, upon reaching an appropriate level of research results between different parties, a collaboration symposium will be planned (tentatively set for September - October 2017) to aid in overall knowledge sharing and agglomeration of findings to date.

3.4.9 In-situ Stress measurement

Determine the state of stress in the reservoir and in the Carboniferous. There will be variation throughout the field so multiple measurements will need to be made to capture the heterogeneity. This data can be used to better calibrate models to the current stress state of the field and to provide insight into the possibility of rupture out of the reservoir zone.

The objective of the study is:

1. Perform a feasibility study of new stress measurements in existing wells targeting RO and DC units;
2. In case of identified candidate wells, start executing a stress measurement campaign.

A feasibility study to obtain in-situ stress measurement in existing wells will be reported before 1st October 2017.

3.4.10 Schedule

Study Activity	Report available and published at Onderzoeks-rapporten site	Results incorporated in update of hazard and risk assessment	Description of the Activity in S&DAP. Section and Page number
First assessment shear-wave velocity $V_{s,800}$ with flexible geophone network	1st July 2017	1st November 2017 (preliminary results)	Section 8, page 69
Following assessments of $V_{s,800}$	2 to 3 months apart		Section 8, page 69
Additional geophone sensors near TNO sensors	1st July 2018	1st November 2018	Section 8, page 69
Wierde Groot Maarslag	1st September 2018	1st November 2018	Section 8, page 69
Broadband Geophone Stations	Earliest operational 1st July 2017		Section 8, page 70
Harkstede Deep Geophones	Operational until 1st July - 1st October 2017 (depending on performance)		Section 8, page 72
DAS Seismic Monitoring	Earliest operational 1st April 2017		Section 8, page 70
Report on development of a formation-offset dependent stress-path model	Q4 2017	Tbd	Section 8, page 79
Characterisation of fault strength in the Groningen field	Q2 2018	Tbd	Section 8, page 79
Report on the impact of asperities sizes and properties on the rupture mechanism	Q3 2018	Tbd	Section 8, page 79
Report on the simulation results and calibration against observed seismic data	Q1 2019	Tbd	Section 8, page 79
Seismological Models	Continuous effort to improve these models. Intermediate results will be shared at academic symposia.		Section 8, page 80
Assessment of hazard changes due to swing production	Intermediate results will be shared at academic symposia.		Section 8, page 81
Research into hypo-centre and source mechanism earthquakes	Ongoing Also independent from NAM.	Intermediate results will be shared at academic symposia.	Section 8, page 72
Improvements & enhancements to faulted 3D-geomechanical model	1st January 2018 1st July 2018	1st November 2018	Section 8, page 79
Alternative seismological model based on faulted 3D geomechanical model	1st January 2018 1st July 2018	1st November 2018	Section 8, page 81
Feasibility study in-situ stress measurement, Report	Q3 2017		Section 8, page 78
Start acquisition of stress data in case of positive outcome in the feasibility study.	Q2 2018		Section 8, page 78

Table 3.6 Milestone dates for further studies in support of the seismological Model and Geomechnics.

3.5 Ground Motion

3.5.1 Measurement of Shear Wave Velocity

Using the flexible geophone network (see above on section Seismological Model and Geomechanics) several campaigns to **assess the shear wave velocity** are planned. As described in this section, some 7 spreads will be used to obtain a detailed mapping of the shear wave velocity over the field. In areas of special concern, the shear-wave velocity will be assessed using bespoke design acquisition plans. For instance, the **acquisition on wierden** will be designed to obtain greater lateral granularity, while focusing on very shallow depth. The first wierde to be visited is de Groot-Maarslag wierde. The acquisition is planned to commence early 2017. After processing of the data a report will be published 1st September 2017.

Figure 3.4 Areal picture of the Groot-Maarslag wierde.

In 2015, geophysical measurements have been done in the direct **vicinity of the 18 KNMI accelerograph stations** active before 2012. For some of these stations the measurements could, for practical reasons, only be performed at some distance from the KNMI accelerometer. This could due to, for instance geological changes over short distances, lead to biased measurements for the location KNMI site. As the flexible geophone network is less intrusive some of these sites will be revisited later in 2017.

3.5.2 Ground Motion Database

In order to expand the database of available recordings over and above those retrieved from the permanent KNMI network and the newly-installed borehole network, work will be undertaken to establish which of the recordings from the TNO-installed Sensor Network can be reliably used. This will involve installing geophones from the flexible network at several locations where the TNO instruments may be contaminated by structural response. Additional insight will be obtained from installation of TNO Sensors on full-scale models of buildings to be tested on the LNEC shake-table in Lisbon.

Analyses will also be conducted to ascertain the usability of the recordings from the instruments installed within NAM's production facilities in the field.

3.5.3 Ground Motion Prediction

The development of the **next generation ground motion prediction methodology** (referred to as V4) is currently in progress. This methodology will not only further improve the methodology, use recently available earthquake data but also extend the methodology. The current methodology focussed on acceleration (PGA and PSA response spectra) and ground motion duration as the main metrics to describe the hazard in support of the seismic risk assessment. The updated methodology will additionally also present velocity metrics to describe the hazard, such as PGV (which is directly related to the V_{top} parameter). These velocity metrics are especially important for the prediction of building damage (DS1, DS2 and DS3 defined in EMS-98). The report on the development of the next generation Ground Motion Prediction methodology is expected to become available on 1st April 2017. The methodology will be used in the update of the hazard assessment for 1st June 2017.

The data collected with the flexible geophone network during earthquakes near Wirdum on the 1st November 2016 together with the data form the TNO Sensor Network, will be used in the development of a **spatial correlation model for ground motion**. This requires development of new methods and more fundamental research. The aim is to develop a preliminary methodology for the update of Hazard and Risk Assessment by 1st November 2017. The spatial correlation method for ground motion will be used to further refine the assessment of "Maatschappelijk Veiligheidsrisico". This will be the first time an explicit spatial correlation method for ground motion is developed for the assessment of Group Risk or "Maatschappelijk Veiligheidsrisico". However, whether this is feasible in this timeframe is uncertain. Further development of the methodology will be required in 2017 and the first half of 2018.

3.5.4 Wavefield Simulation-based Event Characterisation

Simulation of the **propagation of the wavefield** from the source through the rock to the surface is currently performed using the stochastic simulation code ExSIM. This study is currently in progress and the resulting spreading function is planned to be implemented in the next generation ground motion prediction methodology (V4). The results will be published in the report on the development of the next generation Ground Motion Prediction methodology, which is planned to become available on 1st April 2017. The methodology will be used in the update of the hazard assessment for 1st June 2017.

Additionally, studies are in progress to models wave propagation using finite difference simulations based on the Graves and Pitarka methodology for kinematic rupture models. Such **finite fault simulations, using more physical models** than the multiple-point source ruptures in ExSIM, may be used to refine the V4 GMPE. Such refinements, if found necessary, may be incorporated into the November 2017 version of the ground motion model.

3.5.5 Soil Description and Behaviour

To be able to obtain soil properties for **tidal flat deposits** consisting of a sequence thin sand and clay layers, a testing program of controlled cone penetration tests in artificially built layered deposits has been developed with Deltares. Apart from experimental tests this program also includes simulations of these tests. A report is planned to be available 1st September 2017.

In order to obtain an understanding of the response of soils in response to cyclic loading by an earthquake, Deltares has developed a test program for performing **cyclic test on undisturbed samples**. To obtain undisturbed soil samples freezing of the soil in the field with liquid nitrogen for transportation to the laboratory is proposed. Preparatory activities like a heave test are currently in progress at the Deltares laboratory. Results are expected to be published by 1st October 2017.

The investigation into **anthropogenic soils** is currently in the data acquisition phase with a program planned on the Groot-Maarslag wierde (see section 3.4.1 Flexible Geophone Network).

A program into the **effects of shallow swelling clays** on soil movement and basement / foundation stresses and movement is currently in development with Deltares. Prior to finalisation of this program and commencement of a pilot study, the comments and collaboration of various experts will be sought. As this is especially important for the development of a methodology to prepare a prognosis for building damage, this activity is currently planned as part of the extension of the "Study and Data Acquisition plan" for building damage. This will be submitted on the 1st February 2017 and will also include a time planning for this activity.

3.5.6 Liquefaction Studies

A study to describe the development of a **geological model for the Groningen field to gain more insight in the occurrence of loose, medium dense and dense sands related to the risk of liquefaction** has been completed recently. This liquefaction geological model is mainly based on CPTs and on the beta version of GeoTOP (from TNO). This report will be published on the onderzoeksrapporten-page of www.nam.nl before 1st January 2017.

A **general framework for evaluating liquefaction triggering** has been prepared. This is thought to provide a better liquefaction triggering assessment than the currently used methods for earthquakes in the magnitude range 4.0 to 5.5. This "unbiased" methodology was further developed for the Groningen specific soil situation. A pilot study has been completed and the methodology is currently being documented. This methodology will be further adapted to be able to implement it in the probabilistic framework of the hazard assessment.

To assess the impact of liquefaction on buildings and infrastructure the Liquefaction Damage Index (LPI) will be estimated. Based on the work of Ishihara (the Ishihara H1-H2 Chart) an improvement of the LPI was developed (LPI_{ISH}). It is planned to **implement the Liquefaction Damage Index - Ishihara (LPI_{ISH}) in a probabilistic framework** to assess the liquefaction hazard for the Groningen area. Currently, it is tentatively planned to incorporate this in the update of the Seismic Hazard Model planned for 1st June 2017. This would allow incorporation of the impact of the liquefaction hazard into the update of the Seismic Hazard and Risk Model including application of the building damage assessment methodology, planned for 1st November 2017.

It should be stressed that assessment of the potential for liquefaction damage within a probabilistic framework is in itself innovative. New methodologies have been developed and need to be implemented. The timeline for these studies therefore has a large uncertainty.

3.5.7 Schedule

Study Activity	**Report available and published at Onderzoeks-rapporten site**	**Results incorporated in update of hazard and risk assessment**	**Description of the Activity in S&DAP. Section and Page number**
Next generation ground motion prediction methodology (V4), including hazard metrics for building damage.	1st April 2017	1st June 2017 (hazard) and 1st November 2017 (risk)	Section 9; pages 92 to 98
Spatial correlation model for ground motion, in support of assessment of "maatschappelijk veiligheidsrisico"	1st November 2017	1st November 2017 (intermediary might be delayed) 1st November 2018	Section 9; pages 98
Propagation of the wavefield using ExSIM	1st April 2017	1st June 2017 (hazard) and 1st November 2017 (risk)	Section 9; pages 95
Finite fault simulations using more physical models, for spreading and/or durations	1st October 2017	1st November 2017 and 1st November 2018	Section 9; pages 95
Experiments and simulations to obtain soil properties for tidal flat deposits from CPT	1st September 2017	1st November 2017 (early results only)	Section 9; pages 99
Cyclic test on undisturbed samples	1st October 2017	1st November 2017 (early results only) 1st November 2018	Section 9; pages 99
Effects of shallow swelling clays	Scope of activity adapted for development building damage. Schedule to be submitted 1st February 2017		Section 9; pages 100
Sand map Groningen for liquefaction	1st January 2017	1st November 2017	Section 9; pages 103 and 104
General framework for evaluating liquefaction triggering, adaptation to Groningen specific soil situation.	1st April 2017	1st November 2017	Section 9; pages 104 and 105
Implementation of the Liquefaction Damage Index - Ishihara (LPI_{ISH}) in a probabilistic framework		1st November 2017	Section 9; pages 104 and 105

Table 3.7 Milestone dates for further studies in support of the Ground Motion Prediction.

3.6 Exposure of Buildings and People

There are 20.000 buildings inside the 0.2g KNMI contour. They are all included in the exposure database. For certain areas outside this centre of the earthquake area the Hazard & Risk Assessment Model (HRA) indicates specific typologies may also have an inside local personal risk above the acceptable norm of ILPR < 10^{-5}. It is also the objective to determine the addresses for the buildings of these typologies, by using image recognition techniques and inspection to search for these typologies in the specified areas outside the 0.2g KNMI contour.

The combination of risk per typology and estimated number of buildings to be upgraded is input into the strengthening effort led by the National Coordinator Groningen and described in his "Meerjarenplan". An exposure database with a unique typology assigned to each individual building, will help prioritizing of the strengthening effort of buildings in the region and will guide the development of the Expert System to focus on the buildings and typologies and location that have the highest priority.

The exposure risk database containing the typologies models is constantly updated as data comes available as a result of experiments, visual screening and studies of building response. The schedule of the typologies modelling and update of the exposure database synchronizes with the updates of the Hazard and Risk R Assessment and has a typical cycle of 10 months.

3.7 Building Response – Modelling Components and Systems

In 2015 a typical terraced masonry house was tested, whilst the start of 2016 saw the laboratory testing of a full-scale detached masonry house. As a result of the analyses of the data of the experiments new tests are defined for 2017. The current scheduled tests for 2017 contribute to further increase and **improve the capability to predict response, damage and losses from structural elements of buildings**, to formulate strengthening approaches and guidelines for assessment.

3.7.1 Structural System Tests

Section 11 of the "Study and Data Acquisition Plan Induced Seismicity in Groningen – Winningsplan 2016" described the studies currently planned. The schedule for delivery of those studies are focussing on the phasing of the **structural system tests**. The objective is incorporation of the results in enhancing numerical model for the prediction of the response of both structural and non-structural elements and subsequent update of the seismic Hazard and Risk Assessment.

The main structural system tests planned are:

- In Q1-2017 pseudo static testing is scheduled of cast-in-place one-store RC structure. The attention will be on the connections between walls and slabs in tunnel construction, considering external L and T joints and internal + joints and taking into account the different situation of a casting continuity or interruption, and, optionally, strengthening measures.
- In Q2-2017 two tests are scheduled: shake-table testing of one-storey URM terraced house and pseudo-static testing of precast two-store RC structure. The first test is a test in order to carry out shake table tests up to collapse and should be considered as complementary to the two-storey specimen shake table test performed at the EUCENTRE laboratory in September 2015. The full-scale specimen will be built with a geometry that represents a sub-structure of this typical two-storey terraced house with cavity walls, in particular its second floor and attic level. For this reason, the test data will also be used for checking the similarities or differences between this test and the one of the entire structure (e.g., shear/displacement curves, cracking patterns, flexibility of the roof, deformed shapes).
- The second test will again focus on the connections between walls and slabs in tunnel construction, considering external L and T joints and internal + joints and taking into account the different situation of a casting continuity or interruption, and, optionally, strengthening measures.
- In Q3-2017 shake-table testing of precast two-storey RC structure is scheduled. The test data will be used for checking the similarities or differences between this test and the one of the pseudo static test structure (e.g., shear/displacement curves, cracking patterns, flexibility, deformed shapes).
- In Q4-2017 shake-table testing of two-storey URM detached house is scheduled. The test addresses experimental campaign for the continuous updating of a more effective and reliable numerical models mimicking the Groningen building stock.

In the below table the tests are summarized and the expected timeline when each study report based on this phasing is available on the onderzoeksrapporten-page of www.nam.nl.

The scope of the **in-situ dynamic tests of structural systems** is being revised as part of the development of a methodology to prepare a prognosis of building damage. The schedule for this asctyivity isthereore being revisit. The new schedule will be included in the extension of the "Study and Data Acquisition Plan" for building damage, to be submitted 1st February 2017. However as this requires development and procurement of an innovative testing system, it is unlikely the first test will be performed before 2018.

3.7.2 Schedule

Study Activity	**Report available and published at Onderzoeks-rapporten site**	**Results incorporated in update of hazard and risk assessment**	**Description of the Activity in S&DAP. Section and Page number**
pseudo-static testing of cast-in-place one-storey RC structure	1st July 2017	1st November 2017	Section 11 Page 109, 110, 111, 112, 113, 118
shake-table testing of one-storey URM terraced house	1st October 2017	1st November 2017	Section 11 Page 110, 111, 112, 113, 118
pseudo-static testing of precast two-storey RC structure	1st October 2017	1st November 2017 (early results) 1st November 2018	Section 11 Page 111, 113, 118
shake-table testing of precast two-storey RC structure	1st December 2017	1st November 2018	Section 11 Page 111, 113, 118
shake-table testing of two-storey URM detached house	Q1 2017	1st November 2018	Section 11 Page 111, 113, 118

Table 3.8 Milestone dates for further studies in support of the Building Response .

3.8 Methodology Hazard and Risk Assessment

3.8.1 Monte Carlo Risk Engine

For the hazard and risk assessment supporting Winningsplan 2016, the risk resulting from falling objects and (partial or complete) building collapse were assessed separately, albeit that both play a role in decision making and prioritisation. These two elements of risk will now be combined in the probabilistic seismic risk assessment, due for 1st November 2017.

3.8.2 Optimisation of Production Distribution

In the instemminsbesluit (article 3.2) NAM is tasked to optimise the distribution of the production over the field to minimise risk. This is for several reasons a challenging task:

- There are many production constraints to be honoured in the optimisation:
    - Field production cap is set at 24 Bcm for an average year with variation depending on the weather (degree-days) and possible failure of gas distribution and blending facilities (article 2 and "bijlage bij het instemmingsbesluit").
    - Temporal even production over the months and seasons (article 4).
    - Additionally, there are practical constraints, due to limitations of the production system (e.g. limited production capacity of the clusters and limited capability to distribute production from the clusters over the custody transfer stations for export to the GTS gas transport system).
- The hazard and risk assessment uses a Monte Carlo approach, which is computationally very intensive. Combining such a computationally complex problem with optimisation is a challenge.
- Practicality of implementing the theoretical optimum needs to be assured. For instance, the requirement to do maintenance on the facilities, to allow for contingency around equipment failure, and to carry out inspections needs to be guaranteed.
- There is considerable uncertainty in any assessment of seismicity. As a result, establishing whether an adjustment in the distribution of production is effective in reducing seismicity will take considerable time.

For Winningsplan 2016, NAM investigated a practical alternative production distribution from the field. This was based on partial assessments combined with expert opinion and was documented in the Technical Addendum to the Winningsplan 2016.

Together with optimisation experts and mathematicians, NAM is currently developing an optimisation tool combining the reservoir simulation model with elements of the hazard and risk model. To ensure that the tool can be operated within the limitations of computer equipment and time schedule, proxies are being developed for some of the more complex calculations. A first prototype will focus on minimizing seismic event rate as the objective. Additional complexity will be added in subsequent stages to achieve a risk optimisation. The resulting optimised production distribution will be confirmed using the full detailed Monte-Carlo based risk engine, followed by an implementation review.

As per article 3.2 of the instemmingsbesluit, a concept-report will be delivered by 1st September 2017. This will be further worked to incorporate in the update of the hazard and risk assessment for 1st November 2018. Based on the hazard assessment to be delivered on 1st June 2017 (see table 3.9

with milestone dates), the optimisation activities will commence for a delivery on the 1st November 2017.

Prior to field implementation of the optimised distribution of the gas production, a consultation is planned.

3.8.3 Comparison of Predictive Performance of Seismic Models

Currently the hazard and risk assessment is based on the activity rate model to predict seismicity. Other modes like the slider block model have been proposed and developed. These models have resulted in gained understanding, but development of these modes lags behind that of the activity rate model.

Practical implementation of methods for the comparison of the predictive performance of seismic models would benefit of having at least a limited range of models available. Implementation of this activity in the hazard and risk assessment is therefore foreseen for the update of 1st November 2018.

3.8.4 Schedule

Study Activity	**Report available and published at Onderzoeks-rapporten site**	**Results incorporated in update of hazard and risk assessment**	**Description of the Activity in S&DAP. Section and Page number**
Incorporate Falling Hazards in probabilistic Risk Assessment	1st October 2017	1st November 2017	Section 11, page 120 and Section 12 , page 122
Optimisation of Production distribution – Initial Methodology	1st September 2017 Concept 1st November 2017 Final	1st November 2017	Section 12 , page 122
Optimisation of Production distribution – Improved Methodology	1st November 2018	1st November 2018	Section 12 , page 122
Comparison of Predictive Performance of Seismic Models	1st July 2018	1st November 2018	Section 12 , page 124

Table 3.9 Milestone dates for further studies in support of the development of the Methodology for Hazard and Risk Assessment.

4 Assurance

In section 4 of the "Study and Data Acquisition Plan – Winningsplan 2016" the assurance layers for the studies supporting Winningsplan 2016 are discussed. In section 5 of this report a proposal is made by NAM for the continued assurance of the studies carried out as part of the research program into the effects of earthquakes in Groningen, led by NAM.

NAM proposed to continue to work with the framework of 7 layers of assurance used for Winningsplan 2016, but to strengthen the entire assurance grid by subjecting all future studies to a rigorous assurance based on application of the SSHAC (Senior Seismic Hazard Analysis Committee) Level 3 process. This is the 'gold standard' for oversight. This would cover all scientific studies into induced seismicity in Groningen.

The SSHAC process for multiple-expert assessment of hazards was developed by the US Nuclear Regulatory Commission (USNRC), US Department of Energy (DOE) and Electric Power Research Institute (EPRI). Based on a review after 15 years of experience in applying the SSHAC guidelines, practical implementation guidelines by USNRC were issued in 2012. These are available through this link:

http://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr2117/

The SSHAC Level 3 process has been successfully applied to many seismic hazard assessments for critical infrastructure in western, central and eastern United States, Canada (British Columbia) and South Africa, and is currently being implemented in Japan and Spain. In addition to providing regulatory assurance, the SSHAC process accommodates the assurance needs of both scientific and academic experts (a key feature of the process is broad participation from members of the relevant communities), local communities and decision-makers. The clearly structured process of a SSHAC Level 3 study, subject to continuous independent peer review of both technical details and procedural adherence, is transparent, open to observation, extensively documented and widely viewed as the gold standard for multi-expert assessment of hazard (and perfectly amenable to extension to risk assessment as well).

This assurance process should, together with other stakeholders (e.g. NCG), be adapted to local circumstances and demands while respecting the basic requirements for compliance with the specifications of a SSHAC Level 3 study.

In 2017, NAM will engage with all parties involved including NCG and Ministry of EZ to ensure rigorous assurance of the study program.

Appendix A - Technical and Scientific Reports "Onderzoekrapporten" and Papers

A.1 Technical and Scientific Reports "Onderzoekrapporten"

1. Update of the Winningsplan Groningen 2003, Nederlandse Aardolie Maatschappij BV, 19th December 2003.
2. Update of the Winningsplan Groningen 2007, Nederlandse Aardolie Maatschappij BV, 31st May 2007.
3. Letter Actualisation Winningsplan Groningen, Nederlandse Aardolie Maatschappij BV, 21st December 2012
4. Study and Data Acquisition Plan Induced Seismicity in Groningen, Nederlandse Aardolie Maatschappij BV, Jan van Elk & Dirk Doornhof, January 2013, submitted in November 2012.
5. Update of the Winningsplan Groningen 2013, Nederlandse Aardolie Maatschappij BV, 29th November 2013.
6. Technical Addendum to the Winningsplan Groningen 2013; Subsidence, Induced Earthquakes and Seismic Hazard Analysis in the Groningen Field, Nederlandse Aardolie Maatschappij BV (Jan van Elk and Dirk Doornhof, eds), November 2013.
7. Supplementary Information to the Technical Addendum of the Winningsplan 2013, Nederlandse Aardolie Maatschappij BV (Jan van Elk and Dirk Doornhof, eds), December 2013.
8. Voortgangsrapportage Diepe Geofoons, Nederlandse Aardolie Maatschappij BV, September 2014.
9. Study and Data Acquisition Plan Induced Seismicity in Groningen for the update of the Winningsplan 2016, Nederlandse Aardolie Maatschappij BV, Jan van Elk & Dirk Doornhof, December 2014, submitted in March 2015.
10. Bierman, S, R. Paleja and M. Jones, Statistical methodology to test for evidence of seasonal variation in rates of earthquakes in the Groningen field, April 2015.
11. Risk Methodology; Back to the region, February 2015, Nederlandse Aardolie Maatschappij BV, (forwarded to the national committee on earth quake related risks in April 2015) (EP 201504200668).
12. Meet- en Regel Protocol - mei 2015, Nederlandse Aardolie Maatschappij BV, 1st May 2015.
13. Hazard and Risk Assessment for induced Seismicity Groningen, Part I Hazard Assessment, Nederlandse Aardolie Maatschappij BV (Jan van Elk and Dirk Doornhof, eds), 1st May 2015.
14. Hazard and Risk Assessment for induced Seismicity Groningen, Part II Risk Assessment, Nederlandse Aardolie Maatschappij BV (Jan van Elk and Dirk Doornhof, eds), 1st May 2015.
15. Voortgangsrapportage Diepe Geofoons, Nederlandse Aardolie Maatschappij BV, June 2015.
16. Meet- en Regel Protocol – juni 2015, Nederlandse Aardolie Maatschappij BV, June 2015.
17. In-situ compaction measurements using gamma ray markers, Pepijn Kole, June 2015
18. URM Modelling and Analysis Cross Validation – Arup, EUCENTRE, TU Delft, Reference 229746_032.0_REP127_Rev.0.03 April 2015.
19. Geological schematisation of the shallow subsurface of Groningen (For site response to earthquakes for the Groningen gas field) – Part I, Deltares, Pauline Kruiver and Ger de Lange.
20. Geological schematisation of the shallow subsurface of Groningen (For site response to earthquakes for the Groningen gas field) – Part II, Deltares, Pauline Kruiver and Ger de Lange.
21. Geological schematisation of the shallow subsurface of Groningen (For site response to earthquakes for the Groningen gas field) – Part III, Deltares, Pauline Kruiver and Ger de Lange.
22. Development of Version 1 GMPEs for Response Spectral Accelerations and for Strong-Motion Durations, Julian J Bommer, Peter J Stafford, Benjamin Edwards, Michail Ntinalexis, Bernard Dost and Dirk Kraaijpoel, March 2015.
23. De ondergrond van Groningen: een Geologische Geschiedenis, Erik Meijles, April 2015.
24. A re-estimate of the earthquake hypo-centre locations in the Groningen Gas Field, Matt Pickering, March 2015.

25. Mosayk, Report on software verification against experimental benchmark data, Deliverable D1, October 2014.
26. An activity rate model of induced seismicity within the Groningen Field, (Part 1), Stephen Bourne and Steve Oates, February 2015.
27. An activity rate model of induced seismicity within the Groningen Field, (Part 2), Stephen Bourne and Steve Oates, June 2015.
28. Regularised direct inversion to compaction in the Groningen reservoir using measurements from optical levelling campaigns, S.M. Bierman, F. Kraaijeveld and S.J. Bourne, March 2015.
29. Impact of various modelling options on the onset of fault slip and fault slip response using 2-dimensional Finite-Element modelling, Peter van den Bogert, July 2015
30. Computing the Distribution of Pareto Sums using Laplace Transformation and Stehfest Inversion Break, C. K. Harris and S. J. Bourne, May 2015.
31. Induced seismicity in the Groningen field - statistical assessment of tremors along faults in a compacting reservoir, Rick Wentinck, July 2015.
32. EUCentre Shaketable Test of Terraced House Modelling Predictions and Analysis Cross Validation, staff from ARUP, EUCentre (Pavia) and TU Delft, November 2015 [this document also includes; (1) Instruments full-scale test-house Eucentre Laboratory, (2) Protocol for Shaking Table Test on Full Scale Building (Eucentre) V_1, and (3) Selection of Acceleration Time-Series for Shake Table Testing of Groningen Masonry Building at the EUCENTRE, Pavia, all three by staff from EUCentre (Pavia)],
33. Development of Version 2 GMPEs for Response Spectral Accelerations and Significant Durations for Induced Earthquakes in the Groningen field, Julian Bommer et. Al, October 2015
34. Dynamic Geomechanical Modelling to Assess and Minimize the Risk for Fault Slip during Reservoir Depletion of the Groningen Field – 3-D Geomechanical Model, GMI, September 2015.
35. Experimental campaign on cavity walls systems representative of the Groningen building stock, Eucentre, October 2015.
36. Procedures of in-situ test, Eucentre, November 2015.
37. Report on structural modelling of non-URM buildings - v2 Risk Model Update - Deliverable D2 update, Mosayk, October 2015.
38. Report on soil-structure interaction (SSI) impedance functions for SDOF systems - Deliverable D3, Mosayk, October 2015.
39. Numerical and experimental evaluation of the seismic response of precast wall, connections, Eucentre, October 2015.
40. Neotectonic Stresses in the Permian Slochteren Formation of the Groningen Field, Rob van Eijs, November 2015.
41. Development of v2 fragility and consequence functions for the Groningen Field, Crowley H., Pinho R., Polidoro B., Stafford P., October 2015.
42. Impact of Production Shut-in on Inter-Event time in Groningen, A statistical perspective, Rakesh Paleja, Stijn Bierman, Matthew Jones, March 2016
43. Statistical methodology for investigating seasonal variation in rates of earthquake occurrence in the Groningen field, S. Bierman, R. Paleja, M. Jones.
44. Nederlandse Aardolie Maatschappij BV (Jan van Elk and Dirk Doornhof, eds), Hazard and Risk Assessment for induced Seismicity Groningen – Interim Update, 7th November 2015.
45. Groningen Pressure Maintenance (GPM) Study, Progress Report February 2016, Richard Hofmann and team, February 2016.
46. Groningen 2.0 Screening Study Alternatives to the base case approach of NAM to maintain pressure in the Groningen reservoir by nitrogen injection, with a focus on surface measures, Summary Report prepared by the Steering Committee, Chairman Prof. Dr W.C. Turkenburg Final Report February 2015.
47. Terp composition in respect to earthquake risk in Groningen, Dr. ir. E.W. Meijles, Dr. G. Aalbersberg and Prof. Dr. H.A. Groenendijk, March 2016.

48. Unbiased Cyclic Resistance Ratio Relationships for Evaluating Liquefaction Potential in Groningen, Russell Green, Julian Bommer, Adrian Rodriguez-Marek, Peter Stafford, April 2016.
49. Risk Assessment of Falling Hazards in Earthquakes in the Groningen region, Tony Taig and Florence Pickup (TTAC Ltd.), March 2016.
50. Risk Assessment of Falling Hazards in Earthquakes in the Groningen region (Appendices), Tony Taig and Florence Pickup (TTAC Ltd.), March 2016.
51. Winningsplan Groningen 2016, Nederlandse Aardolie Maatschappij BV, 1st April 2016.
52. Technical Addendum to the Winningsplan Groningen 2016 - Production, Subsidence, Induced Earthquakes and Seismic Hazard and Risk Assessment in the Groningen Field, PART I – Summary and Production, Nederlandse Aardolie Maatschappij BV (Jan van Elk and Dirk Doornhof, eds), 1st April 2016.
53. Technical Addendum to the Winningsplan Groningen 2016 - Production, Subsidence, Induced Earthquakes and Seismic Hazard and Risk Assessment in the Groningen Field, PART II - Subsidence, Nederlandse Aardolie Maatschappij BV (Jan van Elk and Dirk Doornhof, eds), 1st April 2016.
54. Technical Addendum to the Winningsplan Groningen 2016 - Production, Subsidence, Induced Earthquakes and Seismic Hazard and Risk Assessment in the Groningen Field, PART III - Hazard Assessment, Nederlandse Aardolie Maatschappij BV (Jan van Elk and Dirk Doornhof, eds), 1st April 2016.
55. Technical Addendum to the Winningsplan Groningen 2016 - Production, Subsidence, Induced Earthquakes and Seismic Hazard and Risk Assessment in the Groningen Field, PART IV - Risk Assessment, Nederlandse Aardolie Maatschappij BV (Jan van Elk and Dirk Doornhof, eds), 1st April 2016.
56. Technical Addendum to the Winningsplan Groningen 2016 - Production, Subsidence, Induced Earthquakes and Seismic Hazard and Risk Assessment in the Groningen Field, PART V - Damage and Appendices, Nederlandse Aardolie Maatschappij BV (Jan van Elk and Dirk Doornhof, eds), 1st April 2016.
57. Technisch addendum bij Winningsplan Groningen 2016 - Productie, bodemdaling, geïnduceerde bevingen en seismische dreiging en risicobeoordeling van het winningsveld in Groningen, DEEL I – Samenvatting en Productie, Nederlandse Aardolie Maatschappij BV (Jan van Elk and Dirk Doornhof, eds), 1st April 2016.
58. Technisch addendum bij Winningsplan Groningen 2016 - Productie, bodemdaling, geïnduceerde bevingen en seismische dreiging en risicobeoordeling van het winningsveld in Groningen, DEEL II - Bodemdaling, Nederlandse Aardolie Maatschappij BV (Jan van Elk and Dirk Doornhof, eds), 1st April 2016.
59. Technisch addendum bij Winningsplan Groningen 2016 - Productie, bodemdaling, geïnduceerde bevingen en seismische dreiging en risicobeoordeling van het winningsveld in Groningen, DEEL III - Dreigingsanalyse, Nederlandse Aardolie Maatschappij BV (Jan van Elk and Dirk Doornhof, eds), 1st April 2016.
60. Technisch addendum bij Winningsplan Groningen 2016 - Productie, bodemdaling, geïnduceerde bevingen en seismische dreiging en risicobeoordeling van het winningsveld in Groningen, DEEL IV – Risico Analyse, Nederlandse Aardolie Maatschappij BV (Jan van Elk and Dirk Doornhof, eds), 1st April 2016.
61. Technisch addendum bij Winningsplan Groningen 2016 - Productie, bodemdaling, geïnduceerde bevingen en seismische dreiging en risicobeoordeling van het winningsveld in Groningen, DEEL V - Schade en Bijlagen, Nederlandse Aardolie Maatschappij BV (Jan van Elk and Dirk Doornhof, eds), 1st April 2016.
62. Supplement to the Technical Addendum for Winningsplan Groningen 2016, Subsidence Development of Seismicity Maatschappelijk Veiligheidsrisico Epistemic Uncertainties, Nederlandse Aardolie Maatschappij BV (Jan van Elk and Dirk Doornhof, eds), 1st May 2016.
63. Study and Data Acquisition Plan Induced Seismicity in Groningen Update Post-Winningsplan 2016 -Part 1, Nederlandse Aardolie Maatschappij BV (Jan van Elk and Dirk Doornhof, eds), 1st April 2016.
64. Study and Data Acquisition Plan Induced Seismicity in Groningen Update Post-Winningsplan 2016 -Part 2, Nederlandse Aardolie Maatschappij BV (Jan van Elk and Dirk Doornhof, eds), 1st April 2016.

65. Oplegnotitie Winningsplan Groningen-gasveld 2016, Nederlandse Aardolie Maatschappij BV, 1st April 2016.
66. Meet- en Regelprotocol 2016 Nederlandse Aardolie Maatschappij BV, 1st April 2016.
67. Groningen Field Review 2015 Subsurface Dynamic Modelling Report, Burkitov, Ulan, Van Oeveren, Henk, Valvatne, Per, May 2016.
68. Groningen Earthquakes - Structural Upgrading LS-DYNA Validation Booklet, Arup Project, June 2016.
69. Groningen Earthquakes - Structural Upgrading, Laboratory Component Testing with Annex: Modelling Blind Predictions, Post-Test Predictions and Analysis Cross Validation, February 2016.
70. Tests for the Characterisation of replicated Masonry and Wall Ties, TU Delft, April 2016.
71. In-Plane Tests on Replicated Masonry Walls, TU Delft, April 2016.
72. Sensitivity study on the influence of the ground motion input components on the seismic response of Groningen URM buildings, EUCentre, April 2016.
73. Induced seismicity in the Groningen field - second statistical assessment of tremors along faults in a compacting reservoir, Rick M. Wentinck, May 2016.
74. A Database of Damaging Earthquakes of Moment Magnitude from 4.0 to 5.5, Cecilia Ines, Helen Crowley, Michail Ntinalexis and Julian Bommer, July 2016.
75. Summary and discussion of software benchmarking for Groningen PSHRA code, Stephen Bourne and Steve Oates, April 2016.
76. Report on Mmax Expert Workshop, Mmax panel chairman Kecin Coppersmith, June 2016
77. Material Characterisation – Version 1.3, Eucentre, P&P, TU-Delft, TU-Eindhoven, October 2015.
78. Local and Moment Magnitudes in the Groningen Field, Bernard Dost, Ben Edwards and Julian J Bommer, March 2016.
79. Independent Review of Groningen Subsurface Modelling Update for Winningsplan 2016, SGS Horizon, July 2016.
80. Human induced Earthquakes, Gillian Foulger, Miles Wilson, Jon Gluyas and Richard Davies, Durham University and Newcastle University, July 2016.
81. Geophysical Measurements of shear wave velocity at KNMI accelerograph stations in the Groningen field area, Deltares, Marco de Kleine, Rik Noorlandt, Ger de Lange, Marios Karaoulis and Pauline Kruiver, July 2016.
82. Measuring changes in earthquake occurance rates in Groningen – Update October 2016, Shell Statistics Group, Rakesh Paleja and Stijn Bierman, October 2016.
83. Meet en Regel Rapportage , NAM, November 2016.

A.2 Technical and Scientific Papers

This appendix contains a list of peer-reviewed and conference papers describing studies executed as part of the research program led by NAM. Conference papers, which have not been subjected to an external assurance review process by the journal, have also been included.

Title	Journal	Peer-reviewed or Conference paper
A Monte Carlo method for probabilistic hazard assessment of induced seismicity due to conventional natural gas production.	Bulletin of the Seismological Society of America	Peer-reviewed
A risk-mitigation approach to the management of induced seismicity	Journal of Seismology	Peer-reviewed
A seismological model for earthquakes induced by fluid extraction from a subsurface reservoir.	Journal of Geophysical Research: Solid Earth	Peer-reviewed
Liquefaction Mapping for Induced Seismicity in the Groningen Gas Field.	6th International Conference on Earthquake Geotechnical Engineering	Conference Paper
Developing an Application-Specific Ground-Motion Model for Induced Seismicity.	Bulletin of the Seismological Society of America	Peer-reviewed
Geomechanical Analysis to Evaluate Production-Induced Fault Reactivation at Groningen Gas Field	SPE Annual Technical Conference and Exhibition 2015	Conference Paper
Ray modelling for induced seismicity in piecewise linear (Vo-k) models	Meeting on active and passive seismics in laterally inhomogeneous media', Jun 8-12, 2015, Prague, Czech Republic	Poster
In-Well Distributed Strain Sensing	Society of Petroleum Engineers	Conference Paper
First Advance in Determining the regional site-response for induced earthquakes in Groningen, The Netherlands.	Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics	Conference Paper
Location results from a borehole micro-seismic monitoring experiment in the Groningen gas reservoir, Netherlands	6th EAGE workshop on Passive Seismic, Muscat (Oman), 31 Jan Feb, 2016	Poster
Experimental Characterization of Calcium-Silicate Brick Masonry for Seismic Assessment	16th International Brick and Block Masonry Conference.	Conference Paper
Out-of-plane shaking table tests on URM cavity walls	16th International Brick and Block Masonry Conference.	Conference Paper
Number of Equivalent Stress Cycles for Liquefaction Evaluations in Active Tectonic and Stable Continental Regimes	Journal of Geotechnical and Geo-environmental Engineering	Peer-review in progress
A New Stress Reduction Coefficient Relationship for Liquefaction Triggering Analyses	Journal of Geotechnical and Geo-environmental Engineering	Peer-review in progress
An Application of the SSHAC Principles to the Estimation of Maximum Magnitude in PSHA for Induced Earthquakes.	Seismological Research Letters	Peer-review in progress
An integrated shear-wave velocity model for the Groningen gas field, The Netherlands.	Bulletin of Earthquake Engineering	Peer-review in progress
Full Scale Shaking Table Test on a URM Cavity Wall Terraced house building.	16th World Conference on Earthquake Engineering, 16WCEE 2017	Conference Paper

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 collaborating in the research program on induced seismicity in Groningen, led by NAM, are listed below.

External Expert	Affiliation	Main Expertise Area
Damian Grant	ARUP	Building Fragility
Guido Magenes	EUCentre Pavia	Building Fragility
Rui Pinho	University Pavia	Building Fragility
Helen Crowley	Independent Consultant, Pavia	Building Fragility, Injury Model and Risk
Michelle Palmieri	ARUP	Building Fragility
Rinke Kluwer	ARUP	Building Fragility
Sinan Akkar	Bogazici, University Istanbul	Ground Motion Prediction
Ben Edwards	University Liverpool	Ground Motion Prediction
Michail Ntinalexis	Independent Consultant, London	Ground Motion Prediction
Barbara Polidoro	Independent Consultant, London	Ground Motion Prediction
Peter Stafford	Imperial College London	Ground Motion Prediction
Julian Bommer	Independent Consultant, London	Ground Motion Prediction and Site Response
Emily So	Cambridge Architectural Research Ltd	Injury model
Robin Spence	Cambridge Architectural Research Ltd	Injury model
Russell Green	Virginia Tech, USA	Liquefaction Model
Tony Taig	TTAC Limited	Injury Model and Risk
Loes Buijze	University Utrecht	Rock Physics / Core Experiments
Chris Spiers	University Utrecht	Rock Physics / Core Experiments
Bart Verberne	University Utrecht	Rock Physics / Core Experiments
Andre Niemeyer	University Utrecht	Rock Physics / Core Experiments
Matt Pickering	Student; Leeds University	Seismic Event Location
Marco de Kleine	Deltares	Site Response and Shallow Geological Model
Pauline Kruiver	Deltares	Site Response and Shallow Geological Model
Ger de Lange	Deltares	Site Response and Shallow Geological Model
Adrian Rodriguez -Marek	Virginia Tech, USA	Site Response Assessment
Mandy Korff	Deltares	Site Response, liquefaction and Shallow Geological Model
Piet Meijers	Deltares	Site Response, liquefaction and Shallow Geological Model
Jan Rots	TU Delft	Building Fragility

Table C.1 The most important expert collaborators.

The experts and academics on this list have worked for a considerable time on studies of this program.

To independently review the studies and assure their results the following experts and academics have been asked to familiarize themselves with the studies and provide their feedback in assurance workshops or reports:

External Expert	Affiliation	Main Expertise Area
Adriaan Janszen	Exxonmobil	Shallow Geological Model
Eric Meijles	University Groningen	Shallow Geological Model
Joep Storms	TU Delft	Shallow Geological Model
Tijn Berends	Student; University Groningen	Site Response and Shallow Geological Model

Table C.2 The assurance team for "Shallow Geological Model".

The assurance team for "Ground Motion Prediction" is shown in table C.3.

External Expert	Affiliation	Main Expertise Area
Gail Atkinson	Western University, Ontario, Canada	Ground Motion Prediction
Hilmar Bungum	NORSAR, Norway	Ground Motion Prediction and panel for the maximum magnitude of earthquakes
Fabrice Cotton	GFZ Potsdam, Germany	Ground Motion Prediction
John Douglas	University of Strathclyde, UK	Ground Motion Prediction
Jonathan Stewart	UCLA, California, USA	Ground Motion Prediction
Ivan Wong	AECOM, Oakland, USA	Ground Motion Prediction Member and panel for the maximum magnitude of earthquakes
Bob Youngs	AMEC, Oakland, USA	Ground Motion Prediction Member and panel for the maximum magnitude of earthquakes

Table C.3 The assurance team for "Ground Motion Prediction". Ivan Wong and Bob Youngs sit also in the panel for the maximum magnitude of earthquakes.

The assurance team for "Building Fragility" is shown in table C.4.

External Expert	Affiliation	Main Expertise Area
Jack Baker	Stanford University, US	Building Fragility
Paolo Franchin	University of Rome "La Sapienza"	Building Fragility
Michael Griffith	University of Adelaide, Australia	Building Fragility
Curt Haselton	California State University, US	Building Fragility
Jason Ingham	University of Auckland	Building Fragility
Nico Luco	United States Geological Survey	Building Fragility
Dimitrios Vamvatsikos	NTUA, Greece	Building Fragility

Table C.4 The assurance team for "Building Fragility".

The assurance teams have been informed by the extensive technical documentation and in workshops. The recommendations of the assurance teams have been incorporated in the details technical reports (section further work) and in this document. Because of their highly mathematical nature, the seismological models supporting the hazard and risk assessment have been reviewed by

Prof. Ian Main (of Edinburgh University). Prof. Main has prepared review letters, which have been shared. For the latest of these review letters see appendix J.

The studies on building fragility have additionally been review by Ron O. Hamburger of the consultancy Gumpertz & Heger. Also this report is attached to this report (as appendix I).

In a workshop conducted following the guidelines for a SSHAC level 3 process, a panel of experts has been asked to evaluate the distribution of Mmax values for the Groningen area, based on the current knowledge and uncertainty.

This panel consisted of:

External Expert	Affiliation	Role
Kevin Coppersmith	Geomatrix Consultants Inc.	Chaiman SHACC Committee
Ivan Wong	AECOM, Oakland, USA	Ground Motion Prediction and Member SHACC Committee
Bob Youngs	AMEC, Oakland, USA	Ground Motion Prediction Member and SHACC Committee
Jon Ake	US Nuclear Regulatory Commission	Member SHACC Committee
Hilmar Bungun	Norsar Norway	Member SHACC Committee
Torsten Dahm	GFZ Potsdam	Member SHACC Committee
Art McGarr	US Geological Survey	Member SHACC Committee
Ian Main	University Edinburgh	Seismogenic Model / Statistics and Member SHACC Committee

Table C.5 The panel for the determination of Mmax distribution.

Additionally the following independent external experts presented to the expert panel:

External Expert	Affiliation	Role
Serge Shapiro	Freie Universiteit Berlin	Independent Advisor
Emily Brodsky	University of California, Santa Cruz	Independent Advisor
Jenny Suckale	Stanford University, Department of Geophysics	Independent Advisor
Gilian Foulger	Durham University, Department of Geophysics	Independent Advisor
Gert Zöller	University of Potsdam Institute of Mathematics and Focus Area for Dynamics of Complex Systems	Independent Advisor

Table C.6 The experts presenting to the panel for the determination of Mmax distribution.

Appendix C – Universities and Knowledge Institutes

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.
Avalon	Supplier of geophone equipment permanent seismic observations wells.
Baker-Hughes	Supplier of geophone equipment temporary observation wells.
Antea	Management of the extension of the geophone network.
Rossingh Drilling	Drilling of the shallow wells for the extension of the geophone network.
China Earthquake Administration	Experiments for friction on moving fault surfaces and upscaling of small scale experiments. Research led by University of Utrecht.

Appendix D – List of Abbreviations

This list of abbreviations covers not only the abbreviations used in this document, but aims to include all abbreviations used in this dossier.

ALARA	As Low As Reasonably Achievable
ALARP	As Low As Reasonably Practicable
ARUP	Engineering Company named after founder: Ove Arup
Bcm	N.Bcm refers to a volume of a billion normal cubic meters. Normal means the volume is measured at a standard temperature (0 degree C) and pressure (1 bar)
BOA	Begeleidingscommissie Onderzoek Aardbevingen
CBS	Centraal Bureau Statistiek
CEA	China Earthquake Administration
CMI	Compaction Monitoring Instrument
CPT	Cone Penetration Test
CRR	Cyclic Resistance Ration (Liquefaction)
CSR	Cyclic Stress Ratio (Liquefaction)
CT	Coiled Tubing
CVW	Centrum Veilig Wonen
DAS	Distributed Acoustic Sensing
DS	Damage State
DSS	Distributed Strain Sensing
DTS	Distributed Temperature Sensing
EBN	Energy Beheer Nederland
EMS	European Macroseismic Scale
EZ	Ministerie van Economische Zaken
GR	Gamma-ray
GR	Group Risk
FDSN	Federation of Digital Seismograph Networks
Frl	Friesland
GBB	Groninger Bodembeweging
GMPE	Ground Motion Prediction Equations
GNSS	Global Navigation Satellite System
GPS	Global Positioning System

GR	Group Risk
GTS	Gas Transport Services B.V.
GWC	Gas water contact
HRA	Hazard and Risk Assessment
HRBE	High Risk Building Element
ILPR	Inside Local Personal Risk
I&M	Ministerie van Infrastructuur en Milieu
InSAR	Interferometric Synthetic Aperture Radar
KNGMG	Koninklijk Nederlands Geologisch Mijnbouwkundig Genootschap
KNMI	Koninklijk Nederlands Meteorologisch Institute
KU Leuven	Katholieke Universiteit Leuven (Catholic University Leuven)
LIDAR	Laser Imaging Detection And Ranging
LOFAR	Low Frequency Array
LPI	Liquefaction Potential Index
LPI_{ISH}	Liquefaction Potential Index - Ishihara
LPR	Local Personal Risk
LNEC	Laboratorio Nacional de Engenharia Civil (Lisbon)
M	Earthquake Magnitude
M_L	Local Earthquake Magnitude
MVR	Maatschappelijk Veiligheidsrisico
MASW	Multichannel Analysis of Surface Waves
MIT	Massachusetts Institute of Technology
MJP	Meerjaren Programma van de NCG
MSF	Magnitude Scaling Factor (Liquefaction)
NAM	Nederlandse Aardolie Maatschappij B.V.
NCG	Nationaal Coordinator Groningen
NGO	Non-governmental Organisation
NORSAR	Norwegian Seismic Array (Norwegian independent, not-for-profit, research foundation within the field of geo-science)
NTNU	Norges teknisk-naturvitenskapelige universitet (Norwegian University of Science and Technology in Trondheim)
OGP	Onafhankelijk Geologen Platform
OIA	Objectgebonden Individueel Aardbevingsrisico (Object related individual earthquake risk)
OIR	Object-bound individual risk (same as OIA)

OVV	Onderzoeksraad voor Veiligheid (Safety Board)
PGA	Peak Ground Acceleration
PGV	Peak Ground Velocity
PNL	Pulsed Neutron log
QRM	Quantitative Reservoir Management
RFT	Repeat Formation Tester
RGR	Reference Group Risk
RIVM	Rijksinstitute voor Volksgezondheid en Milieu
RTCM	Rate-Type Compaction Model
RTCiM	Rate-Type Compaction isotach Model
RVS	Rapid Visual Screening
RUG	Rijksuniversiteit Groningen
SAC	Scientific Advisory Committee (Winningsplan 2016)
SED	Schweizerischer Erdbebendienst (Swiss Seismological Survey)
SINTEF	Stiftelsen for industriell og teknisk forskning (Foundation for Scientific and Industrial Research)
SodM	Staatstoezicht op de Mijnen (also SSM State Supervision of Mines)
SPTG	Static Pressure and Temperature Measurement
SSHAC	Senior Seismic Hazard Analysis Committee
TBO	Technische Begeleidingscommissie Ondergrond (Winningsplan 2013)
Tcbb	Technische commissie bodembeweging
TK	Tweede Kamer (Dutch equivalent of House of Commons)
TNO	Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek, Netherlands Organisation for Applied Scientific Research
TNO-AGE	Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek – Advies Groep Economische Zaken
TU Delft	Technische Universiteit Delft
UU	Universiteit Utrecht
URM	Un-reinforced Masonry
USGS	United States Geological Survey
USNRC	United States Nuclear Regulatory Commission