NAM

**Nederlandse Aardolie Maatschappij B.V.**

# Study and Data Acquisition Plan

# for

# Induced Seismicity in Groningen

## *Planning Report*

**Date:** November 2012

**Issued by:** Jan van Elk & Dirk Doornhof

**Business Approval:**

| Name | Ref. Indicator | Role | Signature | Date |
|---|---|---|---|---|
| Johan de Haan, (DE) | UIE/P/G | Asset Manager Groningen | | |
| Jan van Elk | UIE/T/D | Cluster Development Lead Groningen | | |
| Dirk Doornhof | UIE/T/D | Geomechanics Lead | | |

**Version Control:**

| Version | Objective | Comment | Issue Date |
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| 1 | Inform NAM, Shareholders and Partner. | This version will be updated with comments from SodM. | 2/12/2012 |
| 2 | Inform NAM, Shareholders, Partner, SodM and EZ | Includes comments from the geomechanical workshop. | 20/12/2012 |
| | | | |

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# 1 Introduction

Since 1986 relatively small earthquakes occur in the vicinity of producing gas fields in the North Netherlands provinces Groningen, Drenthe and Noord Holland. In general these events only cause feelings of unease amongst residents, but in excess of a certain magnitude and intensity these tremors can also cause, mostly non-structural, damage to buildings.

In the early 90s a multidisciplinary study, EZ-initiated and guided by a Supervisory Committee, analysed the relationship between gas production and earthquakes, concluding that in view of the seismic pattern, the hypocentres location, difference with historical seismicity and the frequency-magnitude distribution, the earthquakes were of non-tectonic origin and were most likely induced by reservoir depletion (i.e. gas production). Following an agreement with Royal Dutch Metereological Institute, KNMI, a borehole seismometer network was installed since 1995 in Groningen to detect tremors, pinpoint their location and quantify their magnitude. Accelerometers were also installed in areas where tremors frequently occurred.

The recent earthquake near Huizinge (16/8/2012) with magnitude M=3.4 (moment magnitude $M_w$=3.6) was experienced as more intense and with a longer duration than previous tremors in the same area. An order of magnitude more building damage incidents were reported than for previous earthquake events. Also the public observation is that seismicity in the Groningen area seems to be increasing over the last years has triggered a renewed focus and attention for the issue of gas production induced seismicity in Groningen.

To better define the relationship between magnitude, duration, frequency, peak ground velocity and peak ground acceleration of tremors and potential damage to buildings, more extensive monitoring is planned. The existing accelerometer network in the Loppersum/Middelstum area will be extended with the objective of improving determination of the hypocentres and (surface) intensities of seismic events (“iso-intensity” maps). Installation of additional accelerometers has already been committed to KNMI. Additionally, it is planned to extend the monitoring activities to movement on buildings with tiltmeters on selected buildings. The damage information from the latest tremor will be compared with damage estimates from the “2009 Kalibratiestudie schade door aardbevingen” by TNO.

Apart from the desire to demonstrate prudent operatorship to a risk level that is “as low as reasonably practical”, NAM is also aspiring to reassure the people in the affected earthquake area that risks are managed responsibly. Especially since the last earthquakes, concern and anxiety is felt within the community. The public would also like to get insight into the expected frequency and intensity of earthquakes and what NAM can and will do to reduce their occurrence and/or impact.

# 2 Study Governance & quality assurance

In order to ensure technical quality and alignment with key stakeholders, the Groningen earthquake studies & data acquisition projects have both an internal and external governance structure.

## 2.1 Internal governance & quality assurance

- Project teams: Each study/project team will consist of the relevant NAM staff en where appropriate include geomechanics and seismology experts from Shell P&T and ExxonMobil
- Decision Executive: Johan de Haan, NAM Asset Manager Groningen
- Opportunity Manager Jan van Elk, NAM Cluster Development Lead Groningen
- Technical Council: Eilard Hoogerduijn-Strating, NAM Asset Development Lead Onshore
  Ibbel Ansink, Shell GM Quantitative Subsurface Evaluation
- NAM Technical Team: Dirk Doornhof, Geomechanics Discipline Lead
  Antony Mossop, Sr Geomechanics Specialist
  Steven Oates, Sr Geophysicist
  Stephen Bourne, Principal Geophysicist
  Rob van Eijs, Sr Geomechanics Specialist
- Decision Review Board: Jan van Elk, NAM Cluster Development Lead Groningen
  Jan Willem Resink, NAM Project Manager Huizinge earthquake response
  Josien Vegter, NAM Managing Counsel
  Margriet Kuijper, NAM SD & SP manager
  Hans Jansen, NAM Communications Manager

The Decision Executive and Opportunity Manager are accountable for the execution of the Study and Data Acquisition Plan. They are supported by the Technical Council and the Decision Review Board.

The Opportunity Manager for the Study and Data Acquisition Plan:

- Ensures the coordination and execution of the plan,
- Monitors its progress,
- Facilitates change management,
- Provides justification for the activities and
- Ensures approvals are in place.

Technical Council will provide advice to the Decision Executive by:

- Reviewing the content of the plan for Completeness; ensuring all opportunities for research in Groningen seismicity are included in the plan,
- Assessing whether quality control and assurance of study results are appropriate.

The Decision Review Board ensures that results are communicated responsibly and effectively with all stakeholders using the available communication media (presentations, exhibitions, web, etc.).

This communication involves relationship management with claimants, communities, municipalities, SodM, KNMI, TNO and Technische Commisie Bodem Beweging (TCBB) and will also cover other issues that are relevant for stakeholder management and an improved social performance of the Groningen Asset.

## 2.2 External governance & quality assurance

- Peer review with ExxonMobil, EBN and other external institutes as appropriate.
- The study plan and results will be discussed with an external Sounding Board with delegates from SodM, KNMI.

# 3 External Institutes

External institutes with relevant expertise and knowledge will be used to perform targeted studies and provide assurance for internally executed studies. A list of institutes that could provide services in these areas has been provided in appendix B.

Institutes that are presently considered to be approached are:

- Professor of Earthquake Risk Assessment; Julian Bommer of Imperial College London (through the ICCON agency). Professor Bommer's areas of exertise are: Engineering Seismology: earthquake ground-motion characterisation and prediction; definition of earthquake actions for seismic design; seismic hazard assessment; earthquake loss estimation.
- Professor of Seismology and Rock Physics, Ian Main of the University of Edinburgh. Professor Main's areas of exertise are: processes that lead up to catastrophic failure events, from earthquakes, rock fracture, and volcanic eruptions to failure of building materials and bridges, and in quantifying the resulting hazard.
- Professor of Geophysics, Torsten Dahm of the University of Potsdam (Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences). Professor Dahm is Head of the Section "Earthquake Risk and Early Warning" at GFZ Potsdam. His scientific interests include Earthquake physics: e.g. earthquake rupture process, triggering of earthquakes, fluid related earthquakes, seismicity, mining related seismicity.
- Professor of Geophysics, Serge A. Shapiro of the Freie Universität Berlin. His scientific interests include seismogenic processes, exploration seismology and rock physics. Since 2004 he has been the Research Director of the PHASE university consortium project, dealing with triggering mechanisms, modeling and imaging of induced seismicity.
- Professor Emeritus of Geophysics, M. Nafi Toksöz of Earth Resources Laboratory, Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology. Toksöz's research interests included earthquake seismology, plate tectonics and the structures of planetary bodies. Toksöz developed models of wave propagation in heterogeneous media, helped define the field of borehole acoustic logging, and advanced vertical seismic profile (VSP) and cross-well seismology. He retired from MIT in 2009 as the Robert R. Shrock Professor of Geophysics after 44 years on the faculty.

## 3.1 Role of KNMI

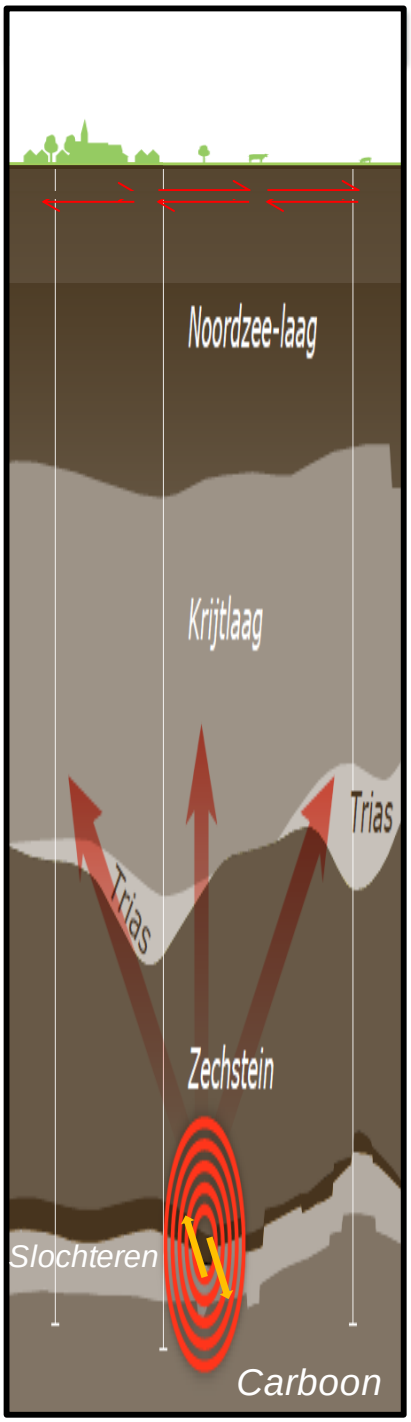
KNMI is the recognized authority on seismicity in the Netherlands. The institute has studied gas production induced seismicity in the Netherlands in detail since 1986 and has issued a number of reports and research papers on this subject. Many of the planned studies by KNMI will be of significance for NAM's operations and NAM's research program. Table 3 of Appendix B provides a summary of these KNMI studies. NAM has no governance over these studies except through NAM's participation in the TPA sounding board and NAM's funding of measurement and monitoring equipment around NAM's fields.

For the present study program, it has been agreed to avoid direct contact between NAM and KNMI to ensure KNMI's independence as an advisor to the Ministry of Economic Affairs. Any contact with KNMI, e.g. on data acquisition and monitoring programs, will be agreed with EZ prior to the engagement.

# 4 Study and Data Gathering Project Management

## 4.1 Research Questions

Objectives of the research on induced seismicity in the Groningen Field are to increase our understanding of the mechanism inducing the tremors and the resulting hazard of damage (e.g. to buildings) and if possible to define measures to minimize this hazard. This is part of NAM's responsibility as a prudent operator, to answer to queries from the regulator and inform the general public. To focus the research effort, these objectives have been translated into more specific questions that can be addressed by specific studies and research projects in NAM's plans.




These specific questions are:

1 What is the future trend of the seismic events:
   a. In terms of intensity;
      i. Will the magnitude of stronger earthquakes (M > 3) increase with time?
      ii. Will the number of stronger earthquakes (M > 3) increase?
      iii. Will the total energy of the earthquakes in a given time period increase?
      iv. What is realistically the largest magnitude of earthquake we could expect?
   b. In terms of area;
      i. Is the area subject to earthquakes changing through time?
      ii. Is the area where the stronger earthquakes occur changing through time?

2 Is there a relationship between the occurrence of seismicity and:
   a. geological structure (fault geometry and density),
   b. subsurface (paleo-)stress conditions
   c. reservoir parameters like porosity and compaction,
   d. gas production and production fluctuations and
   e. pressure differences over faults?

3 How does an earthquake at reservoir level translate into surface movement?

4 What is the relationship between surface movement and
   a. Damage to buildings "gebouwschade" and
   b. Safety of the general public?

5 Can a strategy be developed, based on a relationship possibly identified under item 2 , to reduce the occurrence of (high magnitude) earthquakes or their impact on the surface?

These specific questions will be considered in the studies and research plan, see Appendix B, where for each study the link with above specific questions has been indicated.

## 4.2 Previous Work

Since the nineties, it has become clear that production of gas can lead to earthquakes. In many cases these cannot be humanly perceived at surface and don't cause damage. However, there are three fields in the Netherlands, where earthquakes have been observed by the KNMI geophone network, with magnitude above M=3 on the Richter Scale.

The first tremor induced by gas production was observed in 1986 near Assen. The suspicion that this tremor and a tremor observed near Purmerend could potentially have been caused by gas production, led to the exploratory study "Multidisciplinaire onderzoek – relatie tussen aadbevingen en gas winning" (Multidisciplinary research – relationship earthquakes and gas production). This study (BOA, 1993) en later studies (e.g. Mulders), showed that pressure depletion resulting from gas production can lead to a higher stress on existing faults, which can lead to sudden movement of these faults and associated tremors. A list of reports condensing previous work has been included as Appendix A.

Prior to 1989 the detection limit for earthquakes was a magnitude of 2.5. Extension of the network in Assen lower this limit to 2.3. The installation of the borehole seismometer station in Finsterwolde lower the detection limit in the Groningen Field to 1.5 (De Crook et.al, 1998). In 1995 the KNMI network was extended with 8 borehole all equipped with 3 component geophones at 4 levels (50 – 100 – 150 – 200 m depth). This monitoring network has been extended since;

- in 2006, an accelerometer network with 8 accelerometers was put in place,
- in 2010 an additional 6 boreholes spread over the North Netherlands were added

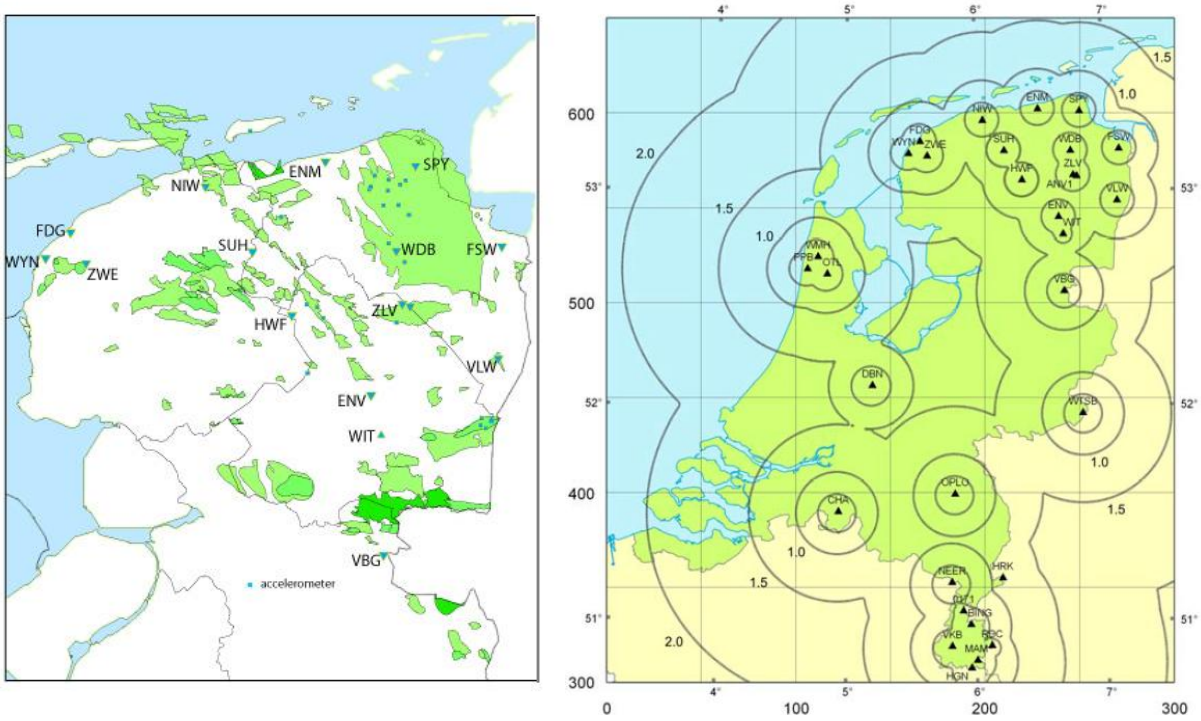



*Figure 1 Left: an overview of the KNMI network, triangles indicate locations of the borehole stations,; squares the locations of the accelerometers. Right: Detections limits of seismic event magnitude (Dost et. Al., 2012).*

The detection limit of the present network is magnitude M=1, with a number of limitations described in Eck et al (2004) and Dost et al (2012). The uncertainty in the location of the hypocenter is relatively large; horizontally 1 km and vertically several kilometers.

## 4.3 Groningen Field Review

During 2010 and 2011 the Groningen Field Review was carried out. During this study a very detailed model of the structure of the field was prepared. More than 1800 faults were mapped in the field. This field review will be the basis for further development studies and studies into the induction of earthquakes by gas production.

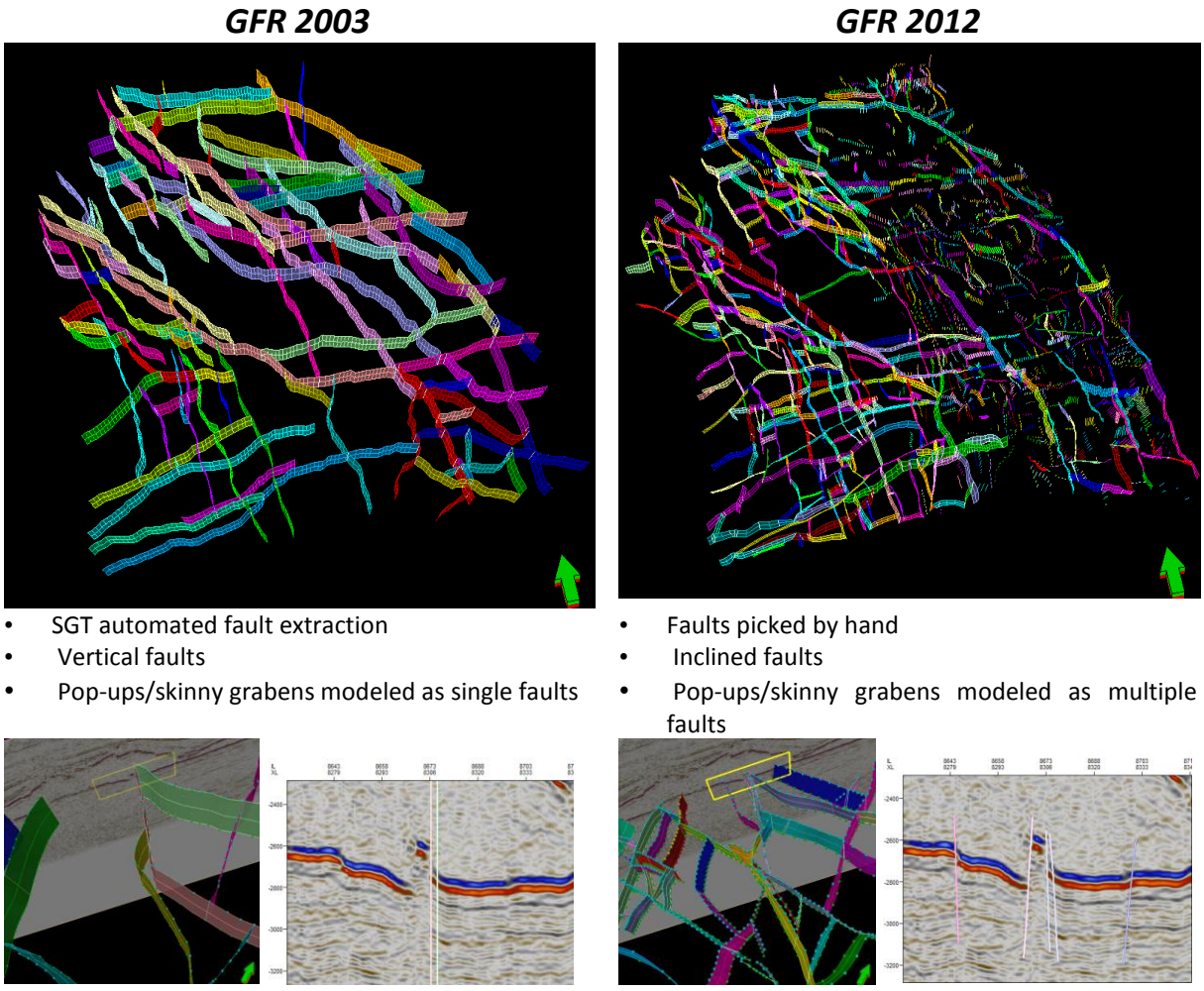



*Figure 2 Large improvement was made in the structural modeling during the Groningen Field Review 2012.*

## 4.4 Study Activities

A list of the activities in the study and data acquisition plan of NAM into induced Seismicity in Groningen, is attached as appendix B.

### 4.4.1 Data Acquisition Activities

#### Objectives of Data Acquisition

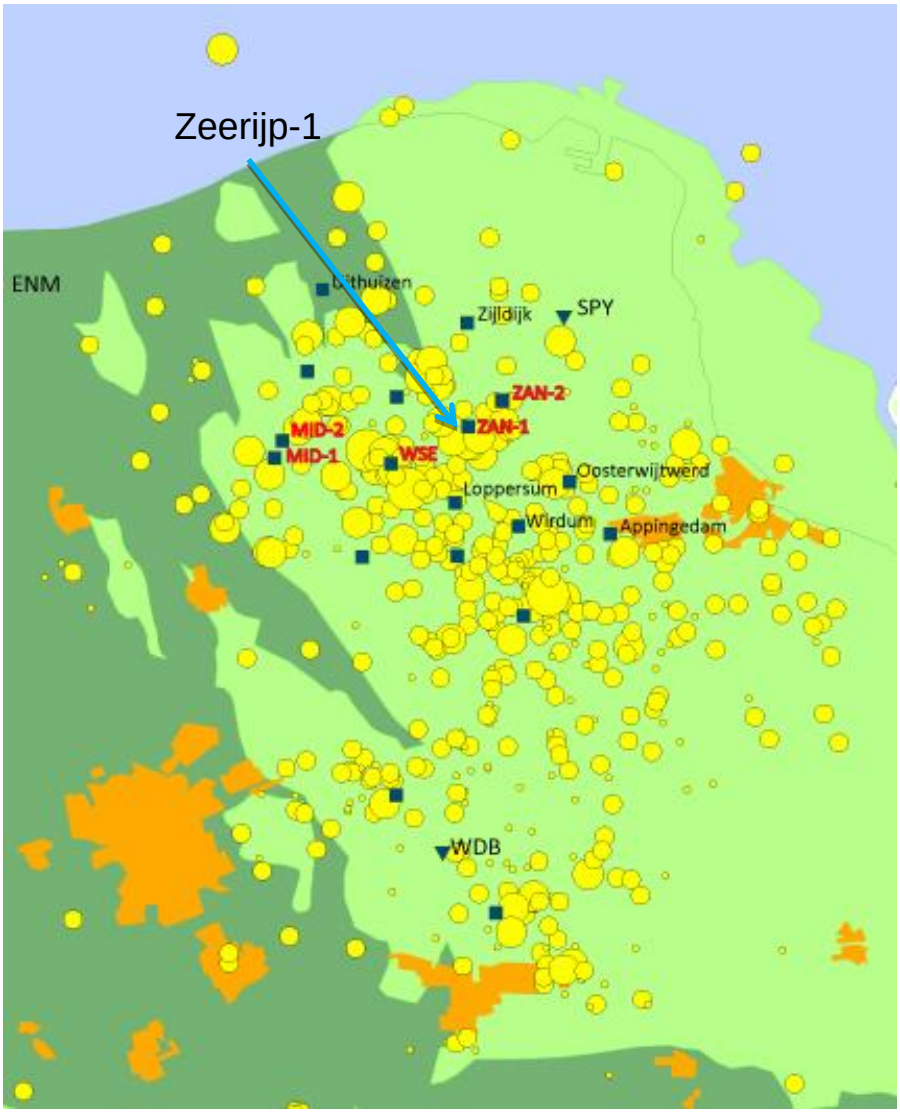
The Objectives of Data Acquisition are:

- Improved determination of the locations of the hypocenters of the tremors will allow better tie-in with the structural model of the Groningen Field. This is important especially for geomechanical understanding of the tremor. Placement of additional seismometers aims to improve the resolution over the whole field. Placement of a vertical array in the Zeerijp-1 well will improve this locally in the Loppersum area.
- Improved understanding of the acoustic velocity field of the overburden. This is important in understanding the transmission of energy from the subsurface tremor to the surface. Especially understanding of the propagation of shear waves is important. Acquisition of acoustic logs in the Borgsweer-5 well and a VSP in the Zeerijp-1 well aim to achieve more insight.
- Improved understanding of the existing stresses and their direction in the field. Acquisition of borehole image logs and fall-off tests in the Borgsweer-5 well will locally improve our understanding.

#### Description of Activities

#### Replace old and place additional new accelerometers.

The area around the Groningen Field is covered by a seismometer network consisting of 14 borehole stations (8 installed in 1995 extended in 2010 with an additional 6 stations). Additionally, 12 accelerometers are in place. This network will be upgraded with replacement of 5 older accelerometers and the installation of additional 6 accelerometers to improve measurement of lateral movement at surface and the location of hypocenter of seismic events.




*Figuur 3. Overzicht van de seismiciteit (gele cirkels) in het Groningen veld (licht groen) met daarbij de accelerometers (blauwe vierkanten) en de boorgat sensors (blauwe driehoeken). In rood zijn de oudste accelerometer stations aangegeven. Nieuwe accelerometer stations zijn aangegeven met de volledige naam van de locatie*

This project is in progress. Presently KNMI is testing the first accelerometer at its facility. Upon completion of the test the remaining accelerometers will be ordered and placed in the field. This is expected late Q1 2013.

| | |
|---|---|
| External Partner<br>(for execution of project and monitoring) | KNMI |

### Run acoustic and borehole image logs in Borgsweer-5 well

The drilling of Borgsweer-5 well offers an opportunity to acquire sonic logs for both P- and S-wave determination. Additionally, data to determine the local stress field can be obtained.

The current plan is to run over the full well length from the reservoir to surface the following logs:

- GR-Sonic Scanner-UBI borehole image and GR-Density in two runs over the 24", 16" and 12 ¼" sections
- GR-Sonic Scanner-UBI borehole image in 8 ½" reservoir section
- Density log over the reservoir section will be MWD.
- In-situ formation stress test at Slochteren reservoir level.

In view of well safety these log will be acquired from the Slochteren reservoir to surface, but not over the lower section of the Slochteren reservoir and top of the Carboniferous. Schlumberger will prepare an analysis report on the stress field, integrating all acquired data. The well is planned to be spudded in April 2013.

Additionally, formation stress has recently also been evaluated in-situ in the vicinity of the Groningen Field; at Kielwindeweer, Blija, Lauwerszee, Kollumerpomp. These will also be relevant for the stress field in Groningen and incorporated in studies.

| | |
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| External Partner (service provider) | Schlumberger |

### VSP and place a vertical sensor array in existing observation well (Zeerijp-1)

Observation well Zeerijp-1 is located near the Loppersum area, where most seismic activity in registered. This well is currently used for pressure monitoring (by Static Pressure and Temperature Surveys; SPTG) and observation of gas-water contact movement (by Pulsed Neutron Logs; PNL). Two activities are planned in this well:

- a VSP to calibrate the local acoustic velocity field and
- installation of a vertical array of geophones for permanent seismic monitoring.

The objective of the VSP is to improve calibration of the acoustic velocities in the Loppersum area. Especially, the Huizinge tremor in August 2012 showed this information is required to better explain the observed surface movement.

With a vertical array of geophones in the well, the determination of tremor hypocenters will be improved in the Loppersum Area.

Discussions with ESG Solutions Inc. from Canada are in progress, with focus on the maximum depth the sensors can be installed at, given the higher temperatures at depth. Temperature robustness of the electronic components to achieve a longer lifetime of the deepest sensors is investigated. The current schedule is based on implementation with ESG Solutions Inc. However, alternative use of equipment supplied by Avalon Sciences Ltd from the UK is investigated as their equipment can potentially withstand higher temperatures and therefore allow deeper installation. Design of the array, focusing on the number of sensors and depths, is in progress. An initial design is expected to be ready for review before the end of the year. Lead time of sensors installation is about 40 days.

The VSP can potentially be combined with the calibration of the vertical array. Activities to make the well available for the installation of the array (SPTG and PNL) are planned for January 2013. This will make the well available for installation of the array in February 2013.

| | |
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| External Partner (Provider of the Array equipment) | ESG Solutions Inc. (Contractor Array) |
| External Partner (Service provider) | Schlumberger (VSP) |
| External Partner (Data integration and advice on functionality and monitoring) | KNMI (Functionality) |

### Feasibility study into extension of the passive seismic monitoring network to enhance resolution

Seismicity induced by production of the Groningen field is monitored with an array of seismic stations. The current network is able to record a complete dataset for events with local magnitude > 1.5 resulting in an average of 10 to 20 locatable events being recorded per year. Improved statistics are required in order to be able to investigate possible correlations between monthly variations in production and the rate of occurrence of induced earthquakes. For this purpose it will be necessary to increase the number of recorded events by approximately a factor of ten. This implies (assuming a Gutenberg-Richter b-value of 1) that we will need a location threshold of magnitude=0.5 (or better) and an improved velocity model of the subsurface. Possible passive seismic network configurations that would be able to meet these goals are currently investigated by Shell (P&T). Subsequently the preferred option is planned to be tendered.

External Partner (definition of functionality) Shell P&T

## 4.4.2 Sub-surface Studies

### Objectives of Studies

- Insight into the future development of the seismicity in the Groningen Field
- Understand relationship of the induction of seismic events with static and dynamic parameters.

### Description of Studies

### Statistical analysis of magnitude and frequency of earthquakes

In their reports on monitoring of induced seismicity in the North of the Netherlands, KNMI has estimated the maximum probable magnitude of the induced events. This is based on a statistical analysis of all available seismic events data in the North-Netherlands. The last report issued by KNMI covers the period up to 2010. An update which includes the Huizinge tremor of August 2012 is in preparation and expected to be available by end-2012.

Currently, a similar analysis is performed independently within Shell (P&T), using seismicity data from the Groningen area only. Results of this work will be reviewed by XoM and externally. Initial results have become available early December 2012. External review was done by Julian Bommer, Professor in Earthquake Risk Assessment at Imperial College and by Ian Main, Professor Seismology and Rock Physics at the University of Edinburgh.

External Partner Shell P&T

### Pre-processing and re-imaging of the Groningen seismic data

As part of the Groningen Field Review (2012) a consistent velocity model was prepared over the full Groningen Field. The ability for this velocity field to impact on the seismic monitoring needs to be discussed with KNMI.

A project to pre-process and re-image the Groningen seismic data was started July 2012 with the objective to improve imaging of the fault system and identification of areas where acquisition of new seismic data could be beneficial. The pre-processing study is planned to be finalized June 2013 and

will deliver a state-of-the-art pre-processed seismic dataset to fuel future pre-stack depth migration (imaging) projects.

Based on the preprocessed data, it will be possible to do a pre-stack depth migration over the Loppersum Area commencing in June 2013. This could potentially deliver an improved acoustic velocity field in the overburden of the Groningen field and therefore enhance the ability to locate hypocenters from the seismometer data. This pre-stack depth migration would take some 4 – 5 months.

### Study relation between field-scale neotectonic-stress and geometry of fault system

The technical objective of this study is to assess the relative impact of depletion on the shear stress level on the interpreted faults in the Groningen field. To this end, both the absolute shear stress and the Shear Capacity Utilisation will be evaluated along (a selection of) fault planes under virgin and depletion conditions. Furthermore, the impact of uncertainty of various model parameters will be assessed.

The project is split in two phases with a go/no-go decision point at the beginning of the second phase. In the first phase of the project, the change of stress on the fault planes due to depletion is simulated by so-called stress path coefficients. That is, the change of total stress is assumed to be proportional with the depletion pressure $\Delta P$, which is taken from MoRes simulation results, and is the same across the field. The study will be performed with SVS and include all 1800 interpreted faults in the field.

In the second phase of the project, the existing linear-elastic Geomec model of the subsurface or an alternative analytical model will be used to calculate the change of stress in and around the Groningen reservoir. Also, other or more faults could be included in the evaluation. Finally, the location and magnitude of the recorded seismic events in the field will be included in Phase 2 of the project.

The Study will consist of the following activities:
Phase 1

- Establish virgin in-situ stress condition
- Definition of shear failure
- Fault modeling
- Fault evaluation (Base case)
- Uncertainty evaluation & Risk assessment
- Correlation of model with Seismic events
- Reporting

Phase 2

- Check and update existing Geomec model
- Fault evaluation (Base case)
- Uncertainty evaluation & Risk assessment
- Correlation of model with Seismic events
- Reporting

With input from XoM, a follow-up study plan will be formulated based on the results.

| | |
|---|---|
| External Partner | Shell (P&T), Peter van den Bogert |
| External Partner (Review) | XoM |

### Geomechanical Finite Element Analysis of Groningen Seismicity

This study will explore the effect of ongoing pressure depletion on the stress state and deformations in the Groningen field. The study largely aims at demonstrating the effect of gas production on the stability of existing faults and the related possibility of seismic hazards. A three-dimensional geomechanical model of (a selected area in) the Groningen field will be used to calculate changes in stress, deformation and fault stability. The geomechanical models depend on a large number of input parameters about the geologic structure, stress state, initial conditions and material properties, not all of which can be specified accurately. Results of geomechanical modeling alone, by themselves, cannot quantify the seismic hazard. They can, however, provide a useful picture of the processes in the reservoir and can contribute to the understanding of induced earthquakes.

| | |
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| External Partner (Providers of expertise) | GMI, XoM |

### Correlation study: relation between earthquakes, structural model and depletion through time

To gain more insight in the parameters that trigger or induce tremors, a correlation study is in progress. The study will try to identify possible relationships between the occurrence of earthquakes and static and dynamic reservoir parameters like the local reservoir pressure.

Areal correlations with reservoir properties like porosity, compaction and fault density are investigated in the sub-surface and geomechanics teams, while the search for correlations with dynamic parameters like production and reservoir pressure has been carried out within the production analytics team using the Wikker tool.

### Geo-mechanical aspect of subsidence; in particular delayed subsidence response.

An important parameter in the induction/triggering of seismicity is the change of stresses in the subsurface as a result of reservoir compaction. Therefore a correct understanding of reservoir compaction and resulting surface subsidence is very relevant.

The issue of subsidence is an important part of 'License To Operate' issue in the Netherlands. Essentially these require that, within certain limits, the subsidence process is well characterised, predictable, and most importantly controllable. This fundamentally relies on the validity and fidelity of the underlying physical models used. It is relatively simple to achieve acceptable matches where the constraining data have limited coverage and low resolution. However, as constraining data have accumulated and accuracy has improved, mismatches between predictions and measurements have become more apparent, revealing the limitations of the basic subsidence models.

The purpose of the study is to:

- improve subsidence prediction procedures,
- identify if there are previously unidentified physical processes that can become dominant or major contributors to subsidence in the future,
- identify mechanisms that are responsible for discrepancies between subsidence predictions and observations.

The research program has been broken up into categories of: data quality, uncertainty and statistics; physical models (continuum mechanics); subsidence data; constitutive laws; and validation and testing.

To improve our understanding of the geomechanical rock properties, a core was acquired in Moddergat (North Friesland). Deformation testing on this core is vital to understand possible non-linear behavior in reservoir compaction. Presently, the core is being studied and measurements are taken. Upon arrival in Rijswijk, the cores were CT scanned to look for any damage incurred to the internal (micro-) structure.

Results of these compaction measurements will also be relevant for differential compaction in the Groningen Field and therefore induction of earthquakes.

### 4.4.3 Damage and Risk

#### Objectives of studies into Damage and Risk

- Assess potential damage of future earthquakes,
- Identify classes of building and structures most at risk of damage.

#### Description of Studies

#### Placement of tiltmeters on reference buildings.

"Reference" buildings in the Loppersum/ Middelstum area will be identified and equipped with tiltmeters. Advice on the scope and extent of this type of monitoring to better assess the impact/damage after an earthquake is sought from the same "technische commissie" that monitored progress on the "Gebouwschade" study. Once the scope of this project is agreed, installation of the monitoring equipment could start. Monitoring data from the extended accelerometer network and the "reference" buildings will then become available after any earthquake perceptible at surface in the "reference" area.

#### Analysis of dependency of damage caused by earthquake on age or type of building.

This study will be based on historical damage reports. For different age and type of buildings, the damage resulting from ground movement will be studied.

#### Update of 2009 TNO "Kalibratiestudie schade door aardbevingen" part 1: Check if reported damage from Huizinge 16/8/12 earthquake is in line with published damage probability curves .

Using information from the damage claims after the recent Huizinge earthquake, NAM also plans to update the existing "Kalibratiestudie schade door aardbevingen" by TNO. This should improve our understanding of the type and extent of damage that could result from gas production induced seismicity in Groningen and what class of buildings will be most affected. Timing of this update will be in 2013, after the claims of the recent earthquake have been processed.

- The radius of the area where damage from the Huizinge earthquake has been reported will be compared with the expectations according to the damage curves in the "kalibratiestudie"report.
- Based on the damage reports it will be verified whether the damage expected according to the EMS scale (intensity class VI-VII) is overestimating the actual damage.

#### Update of 2009 TNO "Kalibratiestudie schade door aardbevingen" part 2: Extrapolation to "worst case magnitude" scenario.

Scope of this study phase will depend on the outcome of:

- Statistical analysis of magnitude and frequency of earthquakes
- Update of 2009 TNO "Kalibratiestudie schade door aardbevingen" part 1

#### Update of 2009 TNO "Kalibratiestudie schade door aardbevingen" part 3: Include results of longer term geomechanics/seismology studies .

Scope of this study phase will depend on the outcome of:

- Statistical analysis of magnitude and frequency of earthquakes
- Update of 2009 TNO "Kalibratiestudie schade door aardbevingen" part 1

### 4.4.4 KNMI Studies

The KNMI will also perform a number of studies relevant to the understanding of induced tremors in the Groningen Field. These have been listed in Appendix B (table 3).

## 4.5 Milestones and Schedule

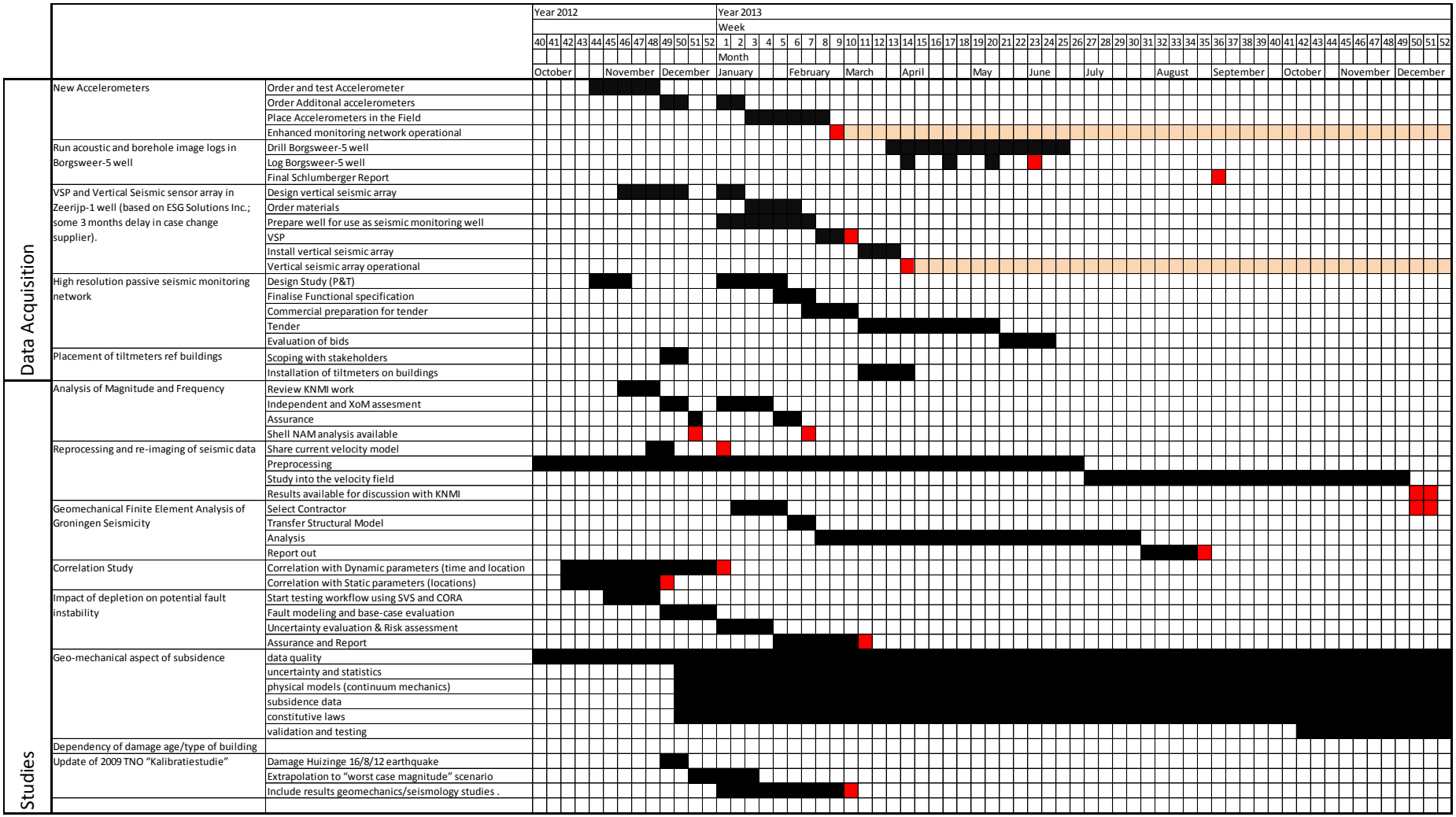
The activities will be coordinated by the technical team and opportunity lead in NAM. A preliminary schedule is presented below. Tracking of the activities against the schedule will initially be done on a weekly basis.

### 4.5.1 Timeline of the Study and Data Acquisition Activities

Preliminary timelines have been prepared for all study and data acquisition activities. These are shown in the schedule below.

### 4.5.2 Deferment Winningsplan Groningen Field

The timeline of the study and data acquisition activities in Groningen needs to be aligned with the preparation of a revised Winningsplan for Groningen. This revised plan needs to be submitted to EZ if and when the analyses and measures are ready to be implemented. Current thinking is that this will be by end 2013. Any results that are available before this date will be communicated with the relevant stakeholders.


Year 2012
Year 2013
Week
40 41 42 43 44 45 46 47 48 49 50 51 52 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52
Month
October November December January February March April May June July August September October November December
Data Acquisition
New Accelerometers
Order and test Accelerometer
Order Additonal accelerometers
Place Accelerometers in the Field
Enhanced monitoring network operational
Run acoustic and borehole image logs in Borgsweer-5 well
Drill Borgsweer-5 well
Log Borgsweer-5 well
Final Schlumberger Report
VSP and Vertical Seismic sensor array in Zeerijp-1 well (based on ESG Solutions Inc.; some 3 months delay in case change supplier).
Design vertical seismic array
Order materials
Prepare well for use as seismic monitoring well
VSP
Install vertical seismic array
Vertical seismic array operational
High resolution passive seismic monitoring network
Design Study (P&T)
Finalise Functional specification
Commercial preparation for tender
Tender
Evaluation of bids
Placement of tiltmeters ref buildings
Scoping with stakeholders
Installation of tiltmeters on buildings
Studies
Analysis of Magnitude and Frequency
Review KNMI work
Independent and XoM assesment
Assurance
Shell NAM analysis available
Reprocessing and re-imaging of seismic data
Share current velocity model
Preprocessing
Study into the velocity field
Results available for discussion with KNMI
Geomechanical Finite Element Analysis of Groningen Seismicity
Select Contractor
Transfer Structural Model
Analysis
Report out
Correlation Study
Correlation with Dynamic parameters (time and location
Correlation with Static parameters (locations)
Impact of depletion on potential fault instability
Start testing workflow using SVS and CORA
Fault modeling and base-case evaluation
Uncertainty evaluation & Risk assessment
Assurance and Report
Geo-mechanical aspect of subsidence
data quality
uncertainty and statistics
physical models (continuum mechanics)
subsidence data
constitutive laws
validation and testing
Dependency of damage age/type of building
Update of 2009 TNO “Kalibratiestudie”
Damage Huizinge 16/8/12 earthquake
Extrapolation to “worst case magnitude” scenario
Include results geomechanics/seismology studies .

# Appendix A. Completed Studies

Geomechanical mechanisms:


1. Begeleidingscommissie Onderzoek Aardbevingen (BOA), 1993: Eindrapport multidisciplinair onderzoek naar de relatie tussen gaswinning en aardbevingen in Noord-Nederland, pp.1-76.
2. Eleveld - Roest, J.P.A. & W. Kuilman Geomechanische analyse van de lichte aardschokken in het Eleveld reservoir. Report by Delft University of Technology, Dept. of Applied Earth Sciences, Delft, Netherlands.
3. Eleveld - Roest, J.P.A. & W. Kuilman Geomechanical analysis of small earthquakes at the Eleveld gas reservoir. Proc. Int. Conf. Eurock '94, Delft Netherlands 1994, pp. 573-580. Publ.: Balkema, Rotterdam Netherlands.
4. Roswinkel – Geomechanische analyse bevingen TU-Delft – Roest e.a. in opdracht van NAM
5. Roswinkel – Geomechanische analyse bevingen TNO - van Eijs e.a. in opdracht van Ministerie EZ
6. Roswinkel - Van Wees, J.D., B. Orlic, R. van Eiis, W. Zijl, P. Jongerius, G.J. Schreppers, M.Hendriks & T. Cornu (2001). Integrated 3D geomechanical modelling for deep subsurface damage: A case study of tectonic and man induced damages in the eastern Netherlands. Geol. Soc. of London Spec. Publ.
7. Norg - Nagelhout, A.C.G. & J.P.A. Roest (1997). Investigating fault slip in a model of an underground gas storage facility. Int. J. Rock Mech. & Min. Sci., Vol. 34, No. 3-4, Paper No. 212.
8. TU-Delft, Mulders, F. Gasvelden in Nederland - Modelling of stress development and fault slip in and around a producing gas reservoir -2003, Ph.D. Thesis.


Measurement analysis and interpretation, magnitude, acceleration and 'hazard':


1. KNMI De Crook, Th., H.W. Haak & B. Dost (1995) Analyse van het seismische risico in Noord-Nederland
2. KNMI De Crook, Th., H.W. Haak & B. Dost (1998). Seismich risico in Noord-Nederland.KNMI (Koninklijk Nederlands Meteorologisch Instituut), Techn. Rep., De Bilt, Netherlands.
3. TNO Seismisch hazard van geinduceerde aardbevingen - Rapportage fase 1 (TNO-rapport, NITG 03-185-C, november 2003)
4. TNO Seismisch hazard van geinduceerde aardbevingen - Rapportage fase 2 (TNO-rapport, NITG 03-186-C, januari 2004)
5. KNMI Dost Seismic hazard due to small induced earthquakes 2004
6. TNO van Eijs hazard analyse voor geïnduceerde seismiciteit in Nederland 2004 NITG 04-171-C
7. TNO KNMISeismisch hazard van geinduceerde aardbevingen - Integratie van deelstudies (TNO-rapport, NITG 04-244-B, KNMI publicatie 208, 20 december 2004)
8. Van Eck, T., F. Goutbeek, H. Haak, B. Dost [2006] Seismic hazard due to small-magnitude, shallow-source, induced earthquakes in The Netherlands, Engineering Geology 87 (2006); p. 105–121.

9. Van Eijs, R.M.H.E, F.M.M. Mulders, M. Nepveu, C.J. Kenter, B.C. Scheffers [2006] Correlation between hydrocarbon reservoir properties and induced seismicity in the Netherlands, Engineering Geology 84 (2006), p. 99–111.
10. Groningen KNMI Van Eck, T., F. Goutbeek, B. Dost [2007] Site specific hazard estimates for the NUON energy plant in the Eemshaven, KNMI internal report; IR 2007-02.
11. Groningen KNMI Van Eck, T., F. Goutbeek, B. Dost [2008] Site specific hazard estimates for the LNG energy plant in the Europoort area, KNMI internal report; IR 2008-01.
12. KNMI Dost Monitoring induced seismicity in the North of the Netherlands: status report 2010 draft
13. TNO Van Thienen-Visser Deterministische hazard analyse voor geïnduceerde seismiciteit in Nederland-update 2012

Relation earthquakes - damage to structures

1. TNO Staalduinen, P.C. van, C.P.W. Geurts en H.S. Buitenkamp, 1998: De relatie tussen schade aan gebouwen en lichte, ondiepe aarbevingen in Nederland: inventarisatie, TNO-Bouw. 1998
2. TNO Waarts Kalibratiestudie schade door aardbevingen 2009
3. Deltares Hoelscher Schade aan buisleiding door aardbeving 2010
4. TNO KNMI Maximale schade door geinduceerde aardbevingen: inventarisatie van studies met toepassingen op Bergermeer (TNO-KNMI rapport, 3 mei 2011)

# Appendix B. Studies and research plan

These specific questions are:

1 What is the future trend of the seismic events:

- a. In terms of intensity;
  - i. Will the magnitude of stronger earthquakes (M > 3) increase with time?
  - ii. Will the number of stronger earthquakes (M > 3) increase?
  - iii. Will the total energy of the earthquakes in a given time period increase?
  - iv. What is realistically the largest magnitude of earthquake we could expect?
- b. In terms of area;
  - i. Is the area subject to earthquakes changing through time?
  - ii. Is the area where the high magnitude earthquakes occur changing through time?

2 Is there a relationship between the occurrence of seismic events and:

- a. geological structure (fault geometry and density),
- b. subsurface (paleo-)stress conditions
- c. reservoir parameters like porosity and compaction,
- d. gas production and production fluctuations and
- e. pressure differences over faults?

3 How does an earthquake at reservoir level translate into surface movement?

4 What is the relationship between surface movement and

- a. Damage to buildings “gebouwschade” and
- b. Safety of the general public?

5 Can a strategy be developed, based on a relationship possibly identified under item 2 , to reduce the occurrence of (high magnitude) earthquakes or their impact on the surface?

The following research studies and projects are planned by NAM in order to demonstrate its prudent operatorship, answer to queries from SodM and to inform the general public:

Table 1 Data Acquisition Activities by NAM (in cooperation with KNMI)

| Research Initiatives | Partner | Benefit and Data | Research Question | Status (1/12/2012) |
|---|---|---|---|---|
| Replace old and place additional new accelerometers. | KNMI | Measurement of lateral movement at surface. Improved location of hypocenter of seismic events | 1, 4 | Agreed and in progress for 2012. PO sent to KNMI. |
| Run acoustic logs in future wells (starting with MWD sonic in the Borgsweer-5 well) | In-house Schlum-berger | Velocity of sound waves through overburden rock (full field coverage), allowing improved location of the seismic events hypocenter. | 2, 3 | Included in Well Functional Specification BRW-5 (change proposal). Spud Expected 1/4/2012. |
| Acquisition of image logs and formation stress test data in BRW-5. | In-house Schlum-berger | Possible derivation of stress magnitude and orientations in the Groningen field | 2 | Included in Well Functional Specification for BRW-5. Spud Expected 1/4/2012. Results due for Q3 2013. |
| Place a vertical sensor array in existing observation well (Zeerijp-1). Calibration can be combined with VSP. | ESG | Improved location of hypocenter and magnitude (locally) threshold and seismic velocity through overburden rock. | 1, 3 | Discussions with ESG (PO before year-end). Activities to make well available planned for Feb. 2012. Aim for installation Mar - April 13. |
| Feasibility study into extension of the passive seismic monitoring network to enhance resolution. | P & T, GFZ - Potsdam, t.b.c. | Improved detection limit of seismic events to magnitudes below M=1, to expand the data set for statistical analysis (also relates to #6); improved location of hypocenters; improved understanding of relation between fault geometries and fault movement. Initial focus on areas such as Loppersum and Ten Boer. | 1, 2 | PO for investigation possible network configurations and their capability (resolution and location). |

Table 2 Study Activities by NAM

| Research Initiatives | Partner | Benefit and Data | Research Question | Status (1/12/2012) |
|---|---|---|---|---|
| Study relation between field-scale neotectonic-stress and geometry of fault system | P&T | Theoretical evaluation of fault movement in response to pressure depletion. To be calibrated with the observed earthquakes | 1, 2 | In progress |
| Statistical analysis of magnitude and frequency of earthquakes. | NAM P&T | Evaluation of acquired data | 1 | In progress |
| Reprocessing and re-imaging of the Groningen seismic data. | NAM | Improved imaging of fault system, identification of areas where acquisition of new seismic data could be beneficial. | 2, 3 | Ongoing, first results in Q2 2013. |
| Correlation study: relation between earthquakes, structural model and depletion through time (ongoing, results in Q4 2012) | NAM | Improved understanding of seismic activity developing through time possibly correlate to subsurface parameters | 1, 2 | Ongoing, results in Q4 2012 |
| Geo-mechanical aspect of subsidence; in particular delayed subsidence response. | NAM | This will impact earthquakes and potentially timing wrt depletion. | 2 | In progress |

Table 3 Study Activities by KNMI (independent from NAM)

| Research Initiatives | Benefit and Data | Research Question |
|---|---|---|
| Statistical analysis of magnitude and frequency of earthquakes. | Evaluation of acquired data | 1 |
| Research into the relationship between duration of tremors at surface and subsurface geological parameters. | Tentative identification of areas with higher risk of damage at surface. | 4 |
| Update of the seismic hazard analysis with latest seismic data | Update of the hazard maps for Groningen | 4 |
| Investigation of recent Huizinge tremor | Study of small scale stress changes along faults as a result of earthquakes (also relates to #5) | 2, 4 |

Table 4 Surface studies to assess building damage as a result of expected intensity (impact on surface)

**Subsurface studies coordinator Jan Willem Resink (Dirk Doornhof supporting); Jan van Elk also overall studies coordinator**

| Research Initiatives | Partner | Benefit and Data | Research Question | Status (1/12/2012) |
|---|---|---|---|---|
| Placement of tiltmeters on reference buildings. | Stabi-Alert | Will be placed on specific buildings to obtain indication of potential for damage on specific buildings as a result of actual earth quakes. Data will be used as basis for assessment of damage potential to similar buildings. | 5 | |
| Analysis of dependency of damage caused by earthquake on age or type of building. This study will be done based on damage reports. | In-house initially; later part of 17 | Better understanding historic building damage; also input for 17. | 5 | |
| Update of 2009 TNO "Kalibratiestudie schade door aardbevingen" part 1: Check if reported damage from Huizinge 16/8/12 earthquake is in line with published damage probability curves . | Deltares/ TNO | Use damage reports from Huizinge earthquake to assess whether damage from actual earth quakes is confirming the predictions in the report of the 2011 "gebouwenschade studie"; the calibration results may also be used to validate or update the report – input for 18 - Medium term (2013) | 5 | |
| Update of 2009 TNO "Kalibratiestudie schade door aardbevingen" part 2: Extrapolation to "worst case magnitude" scenario. | Deltares? | Use worst case scenario for an expected earth quake magnitude and intensity as input for a validation or update of the "gebouwschade studie" – Medium term (2013) | 5 | |
| Update of 2009 TNO "Kalibratiestudie schade door aardbevingen" part 3: Include results of longer term geomechanics/seismology studies . | Deltares? | Use results of sub-surface study on intensity expectations of future earth quakes for a validation or update of the "gebouwschade studie" – Long term | 5 | |

## Appendix C: External Parties

| Contractor | strength | weakness | contact person | website link |
|---|---|---|---|---|
| Microseismic Inc | 1. Largely responsible for recent development of (near-)surface stimulation monitoring applications<br>2. Very good staff including inspirational & accessible CEO, Peter Duncan<br>3. Can also offer other monitoring options (downhole) | 1. Shell experience with surface stimulation monitoring method is very inconclusive & poorly understood | Peter Duncan (pduncan@microseismic.com)<br>Mike Thornton (mthornton@microseismic.com)<br>Chris Neale (cneale@microseismic.com) | www.microseismic.com |
| Kinemetrics | 1. Major supplier of earthquake monitoring systems<br>2. Wide experience across a range of applications<br>3. Highly regarded<br>4. Kinemetrics Etnas successfully used by Shell in El Salvador | None known | Ogie Kuraica (ogie@kmi.com)<br>Mauricio Ciudad-Real (MCR@kmi.com) | www.kinemetrics.com |
| Nanometrics | 1. Well respected supplier of earthquake monitoring systems<br>2. Understand importance of strong motion sensors for oil&gas induced seismicity applications | None known | Jeff Potter (jeffpotter@nanometrics.ca) | www.nanometrics.ca |
| Guralp | 1. Well resepected supplier of earthquake monitoring solutions<br>2. Supplying hardware for Kashagan network | None known | Nathan Pearce (npearce@guralp.com) | www.guralp.com |
| ESG | 1. good track record in Shell<br>2. effective communications<br>3. demonstrated hybrid networks<br>4. (arguably) market leader for permanent reservoir monitoring | Based in Canada (but demonstrated global reach) | Ted Urbancic (urbancic@esg.ca)<br>Andreas Wuestefeld [Andreas.Wuestefeld@esgsolutions.com] | ESG |
| Weir-Jones | 1. Well respected supplier of permanent monitoring systems - may be global market leader | 1. Little known in Shell<br>2. Maybe a bit "niche"? | Iain Weir-Jones (iain.weir-jones@weir-jones.com) | www.weir-jones.com |
| Geosig | 1. Established earthquake monitoring company<br>2. Experience in engineering projects (eg. induced seismicity associated with dams)<br>3. Set up successful system for Shell at Sakhalin | 1. Relatively minor player? | | www.geosig.com |

| | | | | |
|---|---|---|---|---|
| Pinnacle Halliburton | 1. Market leader in stimulation monitoring<br>2. Strong track record<br>3. Halliburton has office in Rijswijk | No NAM experience.<br>Not a recognised provider for monitoring of larger induced events | Stephen Wilson (stephen.wilson@pinntech.com)<br>Norm Warpinski (norm.warpinski@pinntech.com) | Pinnacle-Halliburton |
| Schlumberger | 1. Increasing market share<br>2. Understand near-surface monitoring<br>3. Very strong technically | Not a recognised provider for monitoring of larger induced events | Shawn Maxwell (SMaxwell@slb.com)<br>Olivier Peyret (peyret@slb.com) | www.slb.com |
| Magnitude | 1. CGG-Baker Atlas Company<br>2. TAQA experience<br>3. Strong track record - one of the grandaddies of microseismic | Complex business structure - Magnitude is now seen as VSFusion's microseismic R&D arm | Christophe Maisons (info@magnitude-geo.com)<br>Mark Houston (Mark.Houston@bakeratlas.com) | www.magnitude-geo.com |
| Institute of Mine Seismology (formerly ISS International) | 1. Highly regarded mine monitoring company<br>2. Did good job for Shell in El Slavador | 1. Seem to have focused themselves on Southern hemisphere mine monitoring market<br>2. Less experience in monitoring larger induced events? | Richard Lynch seismology@imseismology.org | www.imseismology.org |
| ApexHiPoint | 1. Offer a somewhat novel migration based approach<br>2. Experience with Shell Canada & Shell China<br>3. Professional operational performance & surprisingly good quality results end 2012 in Fushun concession<br>4. Some good people known in Shell (Ken Mahrer & Larry Walter) | 1. One of the less well established microseismic service companies?<br>2. Less experience in monitoring larger induced events? | Larry Walter (lwalter@apexhp.com)<br>Kenneth Mahrer (k.mahrer@sigmacubed.com) | www.apexhp.com |
| DMT | 1. Experience Europe<br>2. Recognised contractor in Germany (BEB) | Familiar for geodesy but less known track record in microseismic | | www.dmt.de |
| NORSAR | | Not a widely recognised provider of monitoring systems | Volker Oye (volker@norsar.no) | www.norsar.no |
| READ | 1. Respected seismic/reservoir monitoring supplier developing credible capability in microseismic<br>2. Attractive looking hardware system for on-tubing | 1. Limited or no experience monitoring larger induced events | Tor Hilton (Tor.Hilton@readgroup.com) | www.readgroup.com |

| | | | | |
|---|---|---|---|---|
| | deployments<br>3. Highly regarded in Shell for VSP | 2. Microseismic capabilities not tested in Shell | | |
| Sercel | 1. Respected supplier of seismic hardware to service companies<br>2. On-tubing and wireline systems for deep well microseismic monitoring<br>3. On-tubing system supplied to PDO for Al-Noor stimulation monitoring 1999-2000 | 1. Limited or no experience monitoring larger induced events<br>2. Suppliers to service companies (ie. not direct to asset holder) | Thierry Bovier-Lapierre (Thierry.BOVIER-LAPIERRE@sercel.com) | www.sercel.com |
| Avalon | 1. Respected supplier of VSP/microseismic tool strings to service companies | 1. Limited or no experience monitoring larger induced events<br>2. Suppliers to service companies (ie. not direct to asset holder) | sales@avalonsciences.com | www.avalonsciences.com |
| Imperial College | Shell P&T experience/reference | | Julian Bommer (j.bommer@imperial.ac.uk) | |
| GFZ Potsdam | Experience in Europe, reference by KNMI | | Torsten Dahm (torsten.dahm@gfz-potsdam.de) | |
| Freie Universität Berlin | Experience in Europe, reference by KNMI | | Serge Shapiro (shapiro@geophysik.fu-berlin.de) | |
| Edinburgh | Shell P&T reference | | Ian Main (ian.main@ed.ac.uk) | |
| MIT | Shell/NAM Experience: Groningen, Oman.<br>Taqa experience: Bergermeer | | Nafi Toksoz (toksoz@mit.edu) | |