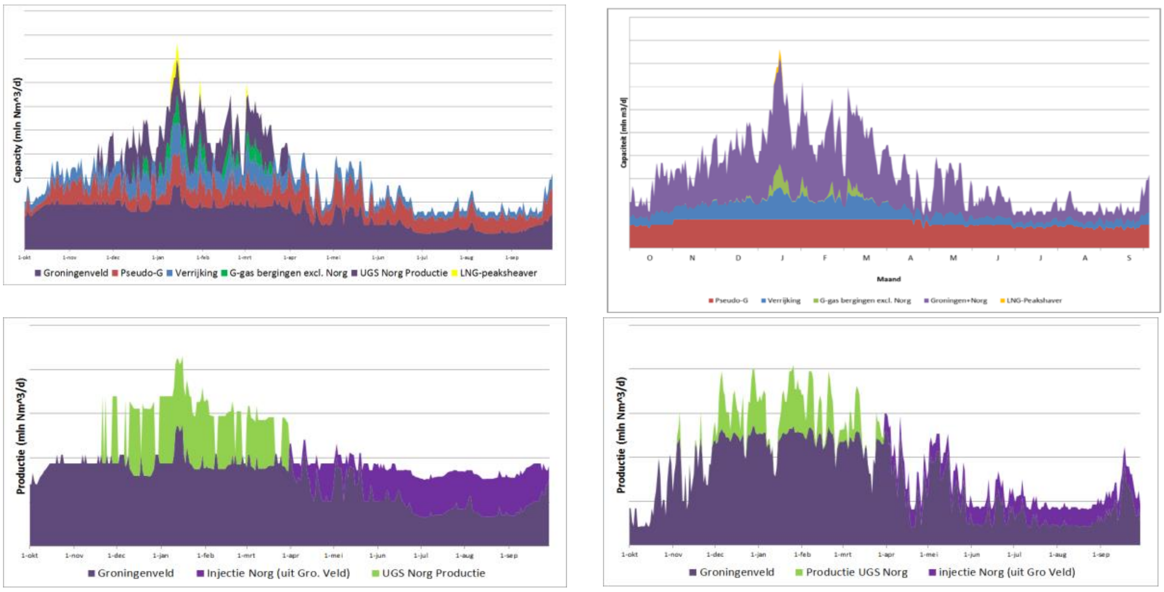
<u>Summary of studies related to the relationship between production fluctuations and seismicity</u>

Introduction

The Ministry of Economic Affairs (MEA), supported by GTS, GasTerra and NAM, is conducting a study "Onderzoek andere benadering van gaswinning" [1] to investigate the feasibility of a reversal of the gas system to minimize gas production from the Groningen field. Their final report is expected to be ready by the end of November.

In parallel, a research program is being executed by NAM, under supervision of a Scientific Advisory Council established by MEA, to establish an acceptable level of gas production from the Groningen field that satisfies the relevant safety norms. The recent interim update of the Hazard and Risk Assessment as submitted to SodM [2] demonstrates that the risks associated with Groningen gas production can meet the norms as proposed by the Meijdam Committee when combined with a doable strengthening program, without further production curtailment or moving to a reversal of the gas system.

A reversal of the gas system will result in increasing production fluctuations, because the Groningen field would need to accommodate peaks in gas demand that are currently covered by the conversion facilities of GTS. Increased variability in gas production is expected on short timescales (hours, days, weeks, and months) as can be seen in the figure below, but also across years, as years of high and low production may alternate depending on temperature conditions (cold/warm winters).



The top graphs show a typical gas demand market profile in a cold year with (left) the current system using Groningen as base provider, and (right) the reversed model with base-load conversion. The bottom graphs show the corresponding Groningen production profile including Norg injection and Norg production for the current system (left) and the reversed model (right).

NAM prefers a long term stable production profile and believes that it is undesirable to experiment with a reversed gas model that drives increasing production fluctuations of which the potential consequences on seismicity are currently not well understood. In mechanics in general, large variations or gradients of local stress conditions in materials can cause failure. However, without good understanding of the underlying triggering mechanisms at geological faults, it is not possible to model or validate the impact (or lack thereof) of production fluctuations on seismicity scientifically.

The Ministry of Economic Affairs has asked NAM to investigate the potential seismic risks of production fluctuations and has asked SodM to review these studies before December 1st. This note summarizes the research initiated by NAM and the preliminary findings to date. The note ends with conclusions and recommendations for further study work.

Research initiated by NAM and preliminary findings to date

The relation between production fluctuations and seismicity is a new research topic in the context of induced earthquakes in the Groningen field. Over the summer, NAM – supported by Shell Research and ExxonMobil's Upstream Research Company (URC) – initiated several new studies to investigate the potential relation between production fluctuations and seismicity: (1) statistical trend analyses, (2) learning from analogues such as induced seismicity as a result of water level changes in hydro dams, (3) pressure modelling of high frequency production swings, (4) potential triggering mechanisms for fault slip, and (5) investigating the applicability of the theory of Self-Organized Criticality to the Groningen field.

The preliminary findings of these studies are summarized below and the individual papers are attached separately. To date, it is not yet possible to make quantitative assessments and hence the findings are of a qualitative nature. It is noted in this context that the probabilistic Hazard and Risk model developed over the last few years as part of NAM's Data Acquisition and Study Program is not suitable to study the impact of production fluctuations. Finally, we highlight that this work is still immature and serves as a starting point for more in-depth analyses and research.

1. Statistical trend analyses

The report "Statistical methodology for investigating seasonal variation in rates of earthquake occurrence in the Groningen field" [3] is an update of the initial report published in May 2015. It confirms earlier observations of historical seasonal trends in seismicity. Strong evidence was found of within-year seasonal variations of earthquake rates with magnitude $M \leq 1$, which can be correlated with within-year variations in gas production with a delay of approximately 3 to 4 months: 3-4 months after a significant decrease in production, the number of $M \leq 1$ tremors decreased as well. For earthquakes with magnitude $1 < M \leq 1.5$ some evidence was found for a similar correlation, but for earthquakes with $M > 1.5$ (those that may be felt at the surface) there was no statistical evidence for seasonal variations. The latter may be due to a lack of data. It is noted that this study does not provide any evidence for a causal relationship between production rate and seismicity and that potential underlying causes of the observed seasonal trends in seismicity are unclear.

In the draft paper "Statistical note: regional seasonal pattern in earthquake rates" [4], this work is supplemented by an assessment of seasonality in seismicity by region. It is observed that the seasonal patterns are not constant across the field and that the Eastern region appears to have a more pronounced seasonal pattern than other regions of the field. It is expected that more insight will be gained when in the future a denser network of geophones is in operation.

2. Learning from analogues – induced seismicity in artificial lakes

In the paper "Artificial lake induced seismicity – a summary" [5] a summary of findings is presented of the literature on induced seismicity observed in artificial lakes or hydro dams around the world.

Reservoir Induced Seismicity (RIS) is understood as the failure of existing geologic faults below an artificial lake due to reservoir impoundment after initial infill of water or as a result of cyclic water level fluctuations. The column of water in an artificial lake alters the stress along faults, either increasing the stress as a result of direct loading, or decreasing the stress as a result of increased pore water pressure (acting as a lubricant). Faults at RIS sites typically are in unstable or critical conditions, meaning that even small changes in stress at fault zones (possibly less than 0.05 MPa) can trigger earthquakes.

Two types of seismicity can be distinguished, initial seismicity and protracted seismicity. Initial seismicity is associated with water level increases (above a previous attained maximum) and results from the almost instantaneous effect of loading (as well as the delayed effect of pressure diffusion). Protracted seismicity is often observed associated with the frequency and amplitude of water level changes, after the effects of the initial filling of the reservoir have diminished. This type of seismicity can persist for many years.

In highly porous and highly permeable rocks, no protracted seismicity or fault reactivation will occur, as the pore pressure can diffuse easily and pressure differences rapidly reach equilibrium. In contrast, in low permeability rocks, pore pressure diffusion will be hindered, making the system more sensitive to fault reactivation and the development of a series of seismic events.

Laboratory experiments on cores show that cyclically varying pore pressures, compared to a single step increase in pore pressure, can compact the rock and reduce permeability, slowing down pore pressure diffusion and extending the period of seismicity. At fault planes, progressive shearing due to cyclically varying pore pressures, has been shown to gradually smoothen irregularities and reduce the friction on the surface, lowering the shear strength of the fault and causing protracted failures.

To investigate if these or similar types of mechanisms are applicable to the induced seismicity in the Groningen field, it is proposed to expand the geo-mechanical modeling effort to combine fault-structures and reservoir details with dynamic well data.

3. Pressure modelling of high frequency production swings

In the “Note on simulation model pressure response for high frequency response“ [6] the pressure response in the Groningen reservoir to high frequency production swings is investigated . A reservoir simulation was run with hourly time-steps to test the impact of intra-day swings as a pressure response at fault planes.

The simulation results show that at a distance of 1 km from the production cluster the intra-day pressure response dampens quickly. Wells that are in close proximity to a fault plain (<500m) will exert a measurable pressure on the fault plain (>0.2 bar). The potential impact on seismicity of such pressure-build ups as a result of high frequency swings at fault planes is unclear and has not yet been investigated as part of this work.

Calculations by URC [7] also show that pressure disturbances as a result of variable production are only observed in close proximity to the wellbore, however these calculations do not address the impact at fault planes.

4. Potential triggering mechanisms for fault slip

This paper [8] describes a fault rupture mechanism based on geomechanical principles that could explain the occurrence of earthquakes in depleting reservoirs.

Faults are considered planes of weakness relative to neighboring formations. The geological model of the Groningen field includes 1037 mapped faults that intersect the depleting Slochteren reservoir formation. The relative weakness of faults and the fact that earthquakes in the Groningen field have occurred along fault planes has led geomechanical work to focus on the behavior of faults.

In all engineering disciplines, failure of materials and structures is described by a stress-based criterion, whereby failure is predicted if the loading (stress) exceeds the strength. Local disturbances are often providing a very strong stress signature and thereby dominate the failure behaviour. For example: (i) the presence of a borehole disturbs the local stress condition and may lead to bore-hole instability when using an inappropriate mud weight, or (ii) rapid changes in operating conditions affect the local stress condition, such that rapid changes in production rate may lead to (transient) sand production. Both examples are explained by local and steep stress gradients, and hence the principle of (geo)-mechanics could read “steep gradients (in space or time) lead to failure”.

For an assessment of fault stability it is important to incorporate reservoir depletion and reservoir offset to better assess the impact of the local stress condition along fault planes. The relevance of reservoir formation offset has been demonstrated in previous work, and recently this framework has been extended to also simulate the dynamic rupture behaviour of faults. New hypotheses have been formulated based on the insight that the brittleness of the fault determines the critical slip length at which a fault becomes instable.

These geomechanical fault stability studies do not provide direct answers to questions related to which production scenario is better to reduce the frequency or magnitude of seismicity in the Groningen field. However, the new insights help to refine questions and focus further research:

- Are faults in an area with a higher seismic event rate closer to a critical state than faults in an area with a lower event rate? If so, this would imply that minimal disturbance locally could cause an earthquake.
- Are earthquakes larger in magnitude in areas with larger reservoir thickness? Or larger along faults with more along dip exposure to depleting reservoir?

In order to develop predictive capability an improved understanding is needed of the variability of the stress and strength condition locally, but also essential is the availability of more and more accurate seismic event data in terms of location and magnitude. The best opportunity is provided by the seismic event data captured by the two Groningen wells that are equipped with down-hole geophones. Using Full-Wave Inversion techniques, a more accurate fault location and magnitude determination of seismic events is expected. Furthermore, statistical tools are being developed to verify hypotheses and find possible aerial differences.

5. Self-Organized Criticality

The applicability of the theory of Self-Organized Critically (SOC) to induced earthquakes in the Groningen field was investigated, as suggested by SodM. SOC is a thermodynamic approach to earthquakes whereby a geological seismic system can be classified in three states of criticality (subcritical, critical and super-critical) and depending on a “tectonic temperature parameter” may exceed critical points where the earthquake magnitude- and frequency distributions change. The implementation challenge of this approach to the Groningen field is calibrating this parameter to achieve a predictive model given the relatively small number of seismic events and the lack of a clear connection to depletion and production scenarios. URC has not been able to establish this parameter empirically based on the Groningen event catalogue, and concludes that SOC has its limitations as a predictive tool when constrained by limited data [9]. It is noted that this evaluation has been made at the field level, and not by region. This may be a topic for further investigation.

Conclusions and way forward

The recent interim update of the Hazard and Risk Assessment as submitted to SodM [2] demonstrates that the risks associated with Groningen gas production can meet the norms as proposed by the Meijdam Committee when combined with a doable strengthening program of houses, without further curtailment or moving to a reversal of the gas system.

NAM prefers long-term stable production and believes it is not desirable to experiment with a production philosophy that drives increasing production fluctuations, of which the potential seismic consequences are currently not well understood. In addition, moving to a reversal of the gas system is also undesirable from an operational efficiency perspective.

Given the immaturity of the research into production fluctuations, it is to date not yet possible to draw firm, quantitative, scientifically sound conclusions on the impact (or lack thereof) of these production fluctuations on seismicity. Qualitatively, some indications of a relation between production fluctuations and seismicity are observed and based on analogues first hypotheses are formulated with regard to potential triggering mechanisms at fault zones. Clearly more research is needed to investigate these mechanisms.

To this end, NAM, with support from Shell Research and ExxonMobil’s Upstream Research Company will continue the following work towards the submission of the new Winningsplan in July 2016:

- Progress the development of a geo-mechanical model that combines fault-structures and reservoir details with dynamic well data.
- Continue the geo-mechanical research into earthquake triggering mechanisms.
- Continue data evaluation from the new observation arrays to improve our capability to measure and locate future events and to produce a richer dataset for modeling and analysis.
- Continue the work on SOC or alternative agent-based modeling. NAM would welcome to work together with TNO and/or other research institutes on this topic.

References:

[1] *Onderzoek andere benadering van de gaswinning*, conceptrapportage ten behoeve van openbare consultatie, oktober 2015. www.internetconsultatie.nl
[2] *Hazard and Risk Assessment for induced seismicity in Groningen*, interim update, NAM, November 2015.
[3] *Statistical methodology for investigation seasonal variation in rates of earthquake occurrence in the Groningen field*, Shell Global Solutions International B.V., Amsterdam, October 2015

[4] *Draft Statistical Note: Regional Seasonal Patterns in Earthquake Rates*, Shell Global Solutions, October 2015

[5] *Artificial lake induced seismicity – a summary*, Shell Global Solutions, October 2015

[6] *Note on simulation model pressure response for high frequency production swings*, NAM, October 2015

[7] *Pressure disturbance estimation for variable production at Groningen, illustrative calculations*, ExxonMobil Upstream Research Company, October 2015

[8] *Faults and Earthquakes*, Shell, November 2015

[9] *Self-Organized Criticality*, ExxonMobil Upstream Research Company, October 2015