NAM

External Panel Report: Induced Seismicity resulting from Injection (Workshop Amsterdam, 9-10 June 2016)

External Panel (EP) members:

Georg Dresen (GeoForschungsZentrum Potsdam), Quentin Fisher (University, of Leeds), Florian Lehner (University of Salzburg), Ian Main (University of Edinburgh), Serge Shapiro (Free University of Berlin), Robert Zimmerman (Imperial College London)

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General Introduction

As part of the studies to identify possible mitigations against production induced seismicity NAM has studied the feasibility and effectiveness in reducing seismicity of pressure maintenance by balancing production volumes with nitrogen injection. An initial screening study was carried out in 2013 and reported with Winningsplan 2013 (Ref.1).

Studies continued after Winningsplan 2013 (Ref. 2 and 3) confirming the large scope of the project. Although the project is very large with a considerable impact on the surroundings, it would be feasible to implement and execute. However, the main drawback of the project is that its effectiveness in reducing seismicity is very uncertain. In other places in the world, injection is recognized as the cause of seismicity (for instance in Oklahoma). Injection of nitrogen into the Groningen reservoir with an already (critically) stressed fault system, could potentially cause seismicity through an alternative mechanism and result in seismicity.

As there was no unambiguous opinion in this area, NAM organized a workshop to ask an expert panel to provide their expert judgment on this matter. This report contains their findings.

Reference

1. 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.
2. Groningen Pressure Maintenance (GPM) Study, Progress Report February 2016, Richard Hofmann and team, February 2016.
3. 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.

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Title	**An activity rate model of induced seismicity within the Groningen Field**	**Date**	February 2016
		Initiator	NAM
Autor(s)	Stephen Bourne and Steve Oates	**Editors**	Jan van Elk Dirk Doornhof
Organisation	Shell P&T	**Organisation**	NAM
Place in the Study and Data Acquisition Plan	Study Theme: Seismological Model Comment: A number of alternative seismological models have been prepared. In 2013, a strain-partitioning seismological model was presented in the technical addendum to the winningsplan 2013. This model is further described in a scientific peer-reviewed paper titled “A seismological model for earthquakes induced by fluid extraction from a subsurface reservoir”, published in the Journal of Geophysical Research. In the current report an alternative seismological model, an activity rate model, is described. Like the strain-partitioning seismological model, the new activity rate model is based on a statistical analysis of the historical earthquake record data of Groningen, in combination with the measured subsidence.		
Directliy linked research	(1) Reservoir engineering studies in the pressure depletion for different production scenarios. (2) Seismic monitoring activities; both the extension of the geophone network and the installation on geophones in deep wells. (3) Geomechanical studies. (4) Subsidence and compaction studies.		
Used data			
Associated organisation	Shell P&T		
Assurance	Review Ian Main, Professor Seismology & Rock Physics at the University of Edinburgh. This report will also be published in a peer-reviewed journal. The independent and anonymous experts of the Journal of Geophysical Research will provide further assurance.		

External Panel Report

Date of Report: 24/06/2016

Shell Workshop on Induced Seismicity, Amsterdam, 9-10 June 2016

External Panel (EP) members

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Introductory remarks

The external panel was asked to comment on technical work done by Shell on the Groningen Pressure Maintenance Project (GPM). To this end, the EP members participated in a two-day workshop in which a comprehensive series of technical presentations on the key results of the studies carried out in preparation of the GPM project were given and discussed. In addition, the EP was provided with excellent and comprehensive background reading material prior to the workshop. This short report states the joint views of the EP on the presented material, and on the results achieved in the presented studies, and includes suggestions for further research. Individual opinions not shared by all EP members are stated at the end of the report. EP members contributing to this report: Georg Dresen, Quentin Fisher, Florian Lehner, Ian Main, Serge Shapiro, Robert Zimmerman.

Summary statements

- The work of Shell has been rigorous and thorough. The studies represent state-of-the-art research and are of a high technical standard.

- Before embarking on a large-scale injection test we suggest to put more resources into downhole seismic monitoring, perform additional data-driven modeling, to assess the stress paths in different parts of the reservoir, to quantify the susceptibility of different reservoir facies to faulting, and to test the scaling of laboratory-derived rock mechanical parameters.

- We propose to conduct additional research to improve our understanding of the mechanisms of depletion-induced and injection-induced earthquakes, including their sensitivity to pressure maintenance scenarios.

Suggestions for further research

Stress state

Currently, knowledge about the reservoir stress state and the stress state of faults activated during depletion seems rather limited. We propose to collect more data on the stress state in the reservoir and the surroundings. Planning of new wells should include additional stress measurements, including minifracs, leak-off tests, etc. Potential vertical changes in stress field orientation and stress ratios above the Zechstein salt, and below in the reservoir, will allow to better constrain potential local stress changes due to the salt body. In particular, significant local stress variations are expected near the top end of faults if they are in contact with shale and/or Zechstein salt.

Laboratory testing

From the provided material and the presentations we feel that the existing laboratory data should be more extensive as this is needed to constrain further poro-thermoelastic/plastic numerical models. In particular, failure tests on intact reservoir rock should be performed under reservoir conditions to yield data on strength and its variability between different parts of the reservoir.

Additional measurements of the Biot coefficient α and Poisson ratio ν on core material under *in situ* conditions seem appropriate as input parameter for poroelastic models and in estimating local variability across the reservoir. These measurements of static parameters should be combined with ultrasonic V_p/V_s measurements in the laboratory to estimate dynamic parameters that could be compared to field estimates of α and ν from seismic data and sonic logs.

Dedicated rock mechanics tests simulating fluid injection and depletion should be performed on reservoir material. The tests should include volumetric strain measurements and advanced non-destructive measurements of acoustic emission activity to characterize potential plastic damage (for example compaction, shear-enhanced compaction) that may occur in high-porosity specimens during pore pressure reduction. Measurements of dynamic elastic parameters during injection/depletion should be included, as they could provide a proxy for damage-related changes of static poroelastic parameters. These measurements may allow assessment of hysteresis in the stress path and non-linear feedback effects that are quite likely to occur in a near-critical, complex system that is already operating beyond the yield point.

Microseismic monitoring and data analysis

We understand that with the planned extension of the monitoring network, the detection threshold and magnitude of completeness will be lowered significantly, allowing for more detailed and advanced seismological analysis. In addition, we suggest putting far more resources into monitoring seismicity, particularly via down-hole, broadband three-component instrument arrays, providing more and well-constrained event locations, depths, and focal mechanisms.

Relocation of hypocenters using standard techniques will provide more precise relative locations (locations of event cluster with reference to absolute master event location). This technique will allow more accurate correlation of seismic events and event clusters with structural elements such as faults and fault segments.

Shale will show significant elastic anisotropy. The earthquake mechanisms (e.g., fault plane solutions) obtained from the reconstructed moment tensors will be strongly biased by shale anisotropy. Results of the seismicity-based stress tensor inversion (including the stress ratio) will be also subject to this bias. The effect will be especially strong for events located in shale layers. Other rocks, such as the overlying salt layer, are likely less problematic in this respect unless affected by large shear strains and resulting textural changes.

Provided that sufficient and well-constrained focal mechanisms will be available from the expanded seismic network in the future, it will be possible to perform stress tensor inversion using available software such as SATSI (Hardebeck and Michael, 2006). Stress tensor inversion of a representative population of focal mechanisms will allow constraining stress tensor orientation and stress ratio, $R = (\sigma_1-\sigma_2)/(\sigma_2-\sigma_3)$. With sufficient data available, the approach could provide important additional constraints complementing direct stress measurements. For example, potential changes in stress field orientation related to fluid pressure changes and/or thermal loads may be captured with this approach (Martinez-Garzon *et al.*, 2013), and in any case will provide an indirect means of interpolating between measurement points.

Modeling approaches

It is conceived that compared to simulation modeling, full-field FE-based geomechanical modeling is in its infancy and it is unlikely that any results produced would allow Shell to definitively show that pressure maintenance would not increase seismicity. In addition, there is some concern that the reservoir fault map is based on rather old seismic data and may not be entirely correct. (For hydraulically reactivated faults, a principal component analysis of interwell flow rate correlations may assist to check the existing fault map; Main *et al.*, 2006).

As an alternative, the Imperial College geomechanics simulator could be used to perform poro-thermo-elastic FE modelling for a sector/restricted area of the reservoir, to investigate the potential for production- and injection-induced faulting.

We also suggest running forecasting models, for example, to explore modeling based on the seismogenic index (SI) approach to investigate a 'depletion/injection' equilibrium scheme. Seismicity and subsidence are considered two indications of an underlying master process: the (non-linear, inelastic) stress-pressure relaxation. The SI (see Shapiro, 2015 and Shapiro *et al.*, 2010), is a quantitative measure of the seismicity reaction on 1 m^3 of an injected/extracted fluid in terms of the induced event rate. This index is a key parameter for a forecasting modelling of the depletion/injection-induced seismicity. It allows one to understand, for example, the established depletion–injection equilibrium. Serge Shapiro presented observations of the depletion-related seismicity showing that the SI in Groningen seems to be quite low but it increases slightly with production. To test if a depletion-derived SI is valid for injection scenarios would require small-scale injection tests that would allow estimating SI and it evolution in different boreholes.

Finally, we suggest undertaking an analysis of fault stability, using slip weakening constitutive laws, constrained by laboratory-derived parameters.

General comments on the GPM project

Pressure maintenance as a strategy is intuitively appealing but there are no precedents for reservoir stress state management by pressure maintenance after depletion on such a large field anywhere in the world. Hence, the uncertainties involved in any risk analysis, however carefully done, could not be informed by a suitable prior, and may never be sufficient to allow high confidence that a field–wide program would achieve the desired aim. The large uncertainties are reflected to some extent in differences of opinion of the effect of pressure maintenance both within (see below) and outside the panel.

Consequently, it would be irresponsible to proceed with a field-wide pressure maintenance program without smaller-scale tests in key parts of the reservoir brought to different levels of criticality, as implied by the spatial pattern of seismicity. Importantly, small-scale injection tests in suitable locations in the reservoir would be key to link laboratory tests results to field scale and provide benchmarks for the modeling suggested above. (In addition, there are some indications from seismic monitoring of hydraulic fracturing jobs that an early indication can be obtained as to when injection is leading to larger events; see work by Verdon and Kendall, University of Bristol).

There may be a creative tension between the desire to do such a test safely (*i.e.*, in a less critically stressed part of the reservoir), and the need to have a representative sample of the most reactive part of the reservoir in order to establish the extremes of reservoir response that are likely to result. One such test is unlikely to be definitive, given the likely variability. Further data collection and modeling as suggested above will allow identify the extent of this variability, but also to assess the spread of associated risk.

Appendix: Additional views and further technical suggestions

Quentin J. Fisher expressed the opinion that further work on pressure maintenance is not likely to provide a definitive answer as to whether re-injection is likely to cause an increase in seismicity. Hence there is a strong case to stop further work on pressure maintenance, particularly given the huge cost of the exercise. It may also be argued that the results from an injection test could not be easily extrapolated to the entire field, and therefore the test may not provide a definitive answer. On reflection, the long-term test could be used as a last resort solution to locally reduce seismicity should it start to dramatically increase in the future, as the plan appears to be easy to implement.

Serge A. Shapiro suggested that the critical stress state should be considered in its dynamic development. It is probable that, before the depletion, no significant seismicity was present at the field. At a given moment after the depletion started, the seismicity started. At this moment, the friction forces arrived at the critical vicinity of the Mohr-Coulomb circle. It is very likely that the depletion-induced seismicity is still located in this domain of the stress space. On the other hand, the recently obtained fault plane solutions (S. Oates contribution) and reflection-seismic indicated that fault planes seem to be inclined with 70° to the horizontal direction. Precisely these planes are in the centrum of the stability analysis of the GPM project. This angle corresponds to the 20° angle to the vertical direction, assumed to be parallel to the largest compressive principal stress (normal faulting regime). There is a contradiction here: such a critical angle corresponds to a friction coefficient higher than 1. Correspondingly, these fault planes are outside of the critical vicinity of assumed Mohr-Coulomb circles. A possible resolution of this contradiction is in the influence of the salt body on the stress state. One of the principal stress components must be normal to the surface of the salt body. Thus, it is probable, that the main principal stress may deviate from the vertical direction.

GPM project: Due to the production reduction in the NW (where the reservoir has a thickness of around 200 m) and its concentration in SE (where the reservoir has a smaller thickness, around 100 m) a rather comfortable situation in respect to the induced seismicity has been achieved. The reservoir thickness is one of key parameters controlling large magnitude statistics (Shapiro 2015, Shapiro *et al.*, 2011, 2013). Due to the pressure equilibration in the reservoir, this comfortable situation will not be permanent. With time, significant events may start to reoccur. In view of such a scenario, the GPM project is an important and useful study. It will provide a basis for possible GPM operations, which could be the only alternative for the case, if the production has to be further continued. A possible scenario of the induced-seismicity reaction on such operations is: firstly a reduction and then an increase of the activity to a level being lower than the initial one. Such scenarios should be the subject of the forecasting modelling addressed above in our recommendations. Shapiro expects that the maximum magnitude of the injection-induced seismicity will be of the same order as the one for the depletion. Observations of other case studies show that maximum magnitudes are controlled by the minimum principal axes of the seismically activated volume, approximated by an ellipsoid. Estimate of the most probable M_{max} of the depletion-induced seismicity in Groningen made by Shapiro's group is around 4.6-4.7 (local Magnitude); it is approx. 4.2 M_w.

References

Hardebeck, J.L., and Michael, A.J. (2006). Damped regional-scale stress inversions: Methodology and examples for Southern California and the Coalinga aftershock sequence. *J. Geophys. Res.*, 111, B11310, doi:10.1029/2005JB004144.

Main, I.G., Li, L., Heffer, K.J., et al. (2006). Long-range, critical-point dynamics in oil field flow rate data. *Geophys. Res. Lett.*, 33, L18308, doi:10.1029/2006GL027357.

Martínez-Garzón, P., Bohnhoff, M., Kwiatek, G. and Dresen, G. (2013). Stress tensor changes related to fluid injection at The Geysers geothermal field, California. *Geophys. Res. Lett.*, 40, 1–6, doi:10.1002/grl.50438.

Shapiro, S.A. (2015). Fluid-Induced Seismicity, *Cambridge University Press*, 289 pages, ISBN: 9780521884570.

Shapiro, S.A., Dinske, C., Langenbruch, C., and Wenzel, F. (2010). Seismogenic index and magnitude probability of earthquakes induced during reservoir fluid stimulations. *The Leading Edge*, pp. 936-939, 2010.

Shapiro, S.A., Krüger, O.S., Dinske, C., and Langenbruch, C. (2011). Magnitudes of induced earthquakes and geometric scales of fluid-stimulated rock volumes. *Geophysics*, 76(6), WC55-WC63, doi:10.1190/GEO2010-0349.1.

Shapiro, S.A., Krüger, O., and Dinske, C. (2013). Probability of inducing given-magnitude earthquakes by perturbing finite volumes of rocks. *J. Geophys. Res.*, 118, doi: 10.1002/jgrb.50264.