To: NL Ministry of Economic Affairs
Drs Pieter Jongerius

From: Groningen Scientific Advisory Committee:

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Dr Stefan Baisch	QCON; Induced Seismicity
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Date: 23 May 2016

Final Note on NAM's Winningsplan Groningen 2016; Groningen Scientific Advisory Committee

The Groningen Scientific Advisory Committee (SAC) has monitored and reviewed, based on the material provided, the investigations executed by NAM or its contractors as part of the development of the Groningen Winningsplan (WP) 2016. The role of the SAC is to ensure the *quality*, *completeness* and *impartialness* of these investigations.

This note summarizes the SAC observations. It has checked the findings against the following documents:

1. The Groningen Winningsplan 2016 (*Dutch-speaking members of SAC*)
2. The Technical Addendum providing background to the technical assessments
3. Supplement to the Technical Addendum for Winningsplan Groningen 2016
4. The meet - and regel (measurement and control) protocol
5. The Study & Acquisition plan accompanying Winningsplan2016

Various meetings have been held between NAM and SAC in the process leading towards the WP2016, which have been reported to the Ministry of Economic Affairs in three separate progress notes (30 May 2015; 1 December 2015 and 4 March 2016; see attachments).

A milestone workshop on Hazard and Risk Assessment (HRA) held in Assen on 3 and 4 November 2015 discussed the Interim Update November 2015 (V2 update). Early 2016, the deadline for WP2016 was re-set by the Ministry of Economic Affairs to 1 April 2016 rather than 1 June 2016, as in the original planning. As a consequence, the WP2016 is based on the V2 Hazard and Risk Assessment (Interim Update 2015), with optimisation of production distribution. On 12 May 2016, a final meeting between NAM and SAC was held discussing the WP 2016 documents. All meetings with NAM and contractors, as

well as the study of the documentation provided during the process, have been helpful to grasp the work in progress.

The SAC views, presented below, are based on data, reports and presentations provided by NAM, up to 12 May 2016, which are made publicly available via www.namplatform.nl

Summary

Quality
The WP2016 hazard and risk assessment is, as far as the SAC members are aware of, a unique undertaking with no analogues on a worldwide scale. It appears the most comprehensive risk assessment study in the field of induced seismicity. It has a strong multi-disciplinary character and in most disciplines well-known (international) experts have contributed to the study. Given the sheer size of the study, it is clear and understandable that the quality standard varies over work packages.

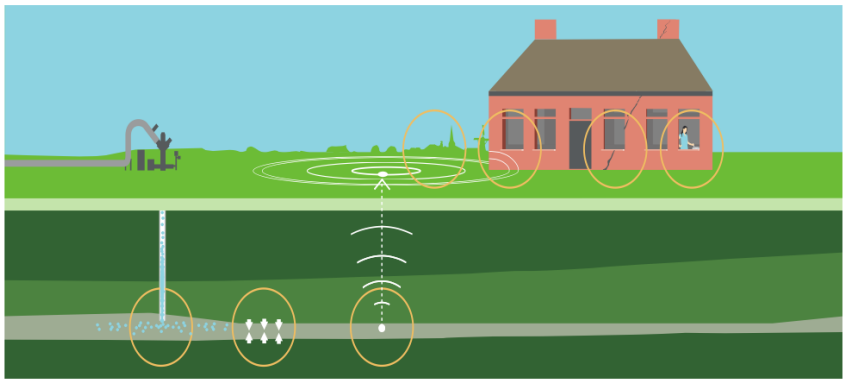
The scientific level of the study is *state-of-the-art*. The overall approach based on a chain of models is correct. We would like to emphasize that high quality does not necessarily means that it cannot be improved. Several of the models employed are susceptible towards refinements in credibility and accuracy.

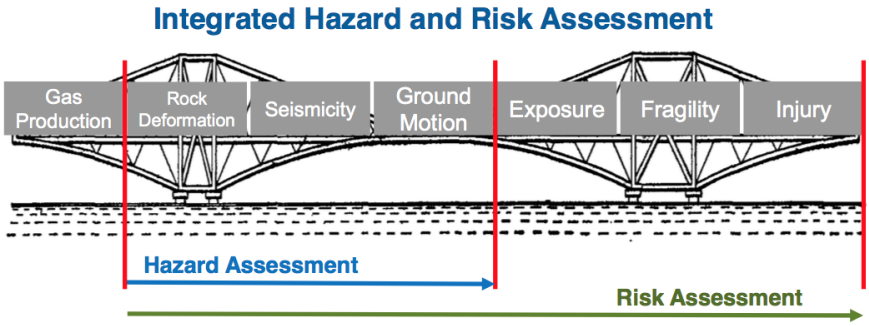
Impartialness
There is no reason to doubt the scientific integrity of the researchers involved. We have seen no indications for a hidden agenda.

Completeness
The aspect of completeness can only be judged in view of limited time available to perform the investigations, which forced NAM to make choices. Clearly, various alternative options could have been chosen. Risk assessment is complete from the components point of view although it is limited to direct consequences of building damage, while infrastructure and the broader societal/community impact is left out of the study.

NAM stated in their Study & Acquisition plan accompanying WP2016: "*All is work in progress and highlights the operational fact that risk management will be a learning process, informed by feedback in the light of new data and the actual outcomes".* Strictly spoken we think that this type of study is inherently incomplete and of a continuously evolving nature.

From a more pragmatic perspective, we feel that the study reached a 'sufficient level of completeness given the limited time available' We recommend that in a decision on future production levels the following aspects are taken into account: 1. the lower the production level the more time there is available to reinforce houses and thus reduce risk, and 2. the lower the production level the more time there is available to reduce epistemic uncertainties in the hazard and risk assessment.





Technical observations

General

1. Assumptions and choices in the applied models and parameters have been made from the start. These have not always been made explicit nor are their potential consequences discussed in detail. This applies in particular to the choice for an empirical seismological model that uses cumulative total compaction as a proxy for the amount of seismicity to be expected. The predictive power of such a model is unclear for situations that differ considerably from those prevailing during the historical production period on which the model has been calibrated. An example is the seismic response after the January 2014 production measures when production from the centre of the field was suddenly almost completely halted.

2. An independent check on the NAM results is not possible at this stage and it cannot be excluded that NAM will identify errors in one or more components of the risk analysis. The earlier error in the hazard code had significant impact on the results obtained and was not identified for quite some time by NAM nor by any of the reviewers. It is to the credit of NAM that they provided the error and that they communicated this in a very open and transparent manner. In general, the information passed to SAC is/was insufficient to clearly spot any kind of error in the calculations.

3. The documentation provided by NAM is of limited depth, in particular those parts related to the calculation of the seismic hazard and the seismic risk. It will be difficult for others to set up control calculations based on this information. NAM has, however,

indicated regularly that they are prepared to provide further details, including the sharing of software codes.

4. The WP2016 and the technical addendum show signs of a rush job. There are apparent errors in the reported numbers of observed tremors. The internal consistency between the various chapters is limited both with respect to style and with respect to content. The documents are difficult to read, even for informed readers. Nevertheless the total volume of information provided appears generally consistent.

Measurement and control (M&C) protocol

5. The development of the M&C protocol started late and involved numerous interactions between NAM and SodM. The protocol has been improved relative to earlier versions. This has, however, resulted in a document that does not display the same level of scientific rigour as the HRA.

6. The M&C protocol does provide a set of publicly verifiable monitoring parameters and a set of rules for acting on their measured values. However, the scientific basis for the choice of the monitoring parameters and the specifics of the control actions and their relationship with the HRA are unclear. In particular, the scientific basis for control actions corresponding to status 1 is not defined, the range of control actions for both status 1 and 2 is incomplete (no reference is made to structural strengthening as a risk control action), and the scientific basis for invoking the level of control (i.e. the threshold parameters leading to status 1 or 2) is unclear.

7. A clearer distinction should be made between the WP2016 and the flexibility and adaptability thereof, and the background material. The status of the M&C protocol deserves more attention in this respect. As the science and technology continues to develop, together with the societal response, the agreed consequences in terms of flexibility and adaptability should be made more transparent.

Groningen pressure maintenance

8. The discussion in WP2016 of the possibility to perform pressure maintenance through large-scale nitrogen re-injection is very brief. The decision to not pursue re-injection, or not even perform tests, is considered over-cautious (although given the current epistemic uncertainties this decision is necessarily a matter of judgement), and lacks symmetry with respect to the decision to continue production from the Groningen field, especially because re-injection will reduce pressure depletion which forms the root cause of Groningen earthquakes. It is recommended to further investigate the options to perform pressure maintenance.

Integrated hazard and risk assessment

9. The approach of the risk assessment is state-of-the-art and founds its roots in the paradigm of performance-based earthquake engineering (PBEE), about which there is large scientific consensus worldwide. The mentioned paradigm has been developed for specific structures and, as far as we know, this is the first PBEE study taken at regional

level and not developed within a research program. In this sense, we believe it is a fit-for-purpose decision support tool for risk management at Groningen.

10. During the process leading to the risk assessment study that accompanies the WP2016, several assumptions and working approximations were taken so as not to impair the risk of failing in delivery. Nevertheless, the tolerability of these approximations seems not quantified, or at least this information has not been made available to SAC, and this prevents acknowledge them fully.

11. In WP2016,at least two choices have been made that set a priori epistemic uncertainty: 1) the 'evidenced-based approach' and 2) ignoring tectonic stresses. The SAC is not criticizing these choices but it is important to keep in mind their a priori nature. In fact, the study contains several of these expert judgement-based settings, the implication of which appears limitedly discussed.

12. The seismological model builds on linear elasticity with time-variance incorporated in the subsidence calculation, which is a proxy for seismicity. Since earthquakes occur, plastic and brittle non-elastic deformations need to be part of a physically-based model. This includes in particular the response of faults to stress changes emerging from pore pressure changes during production. As long as the pore pressure is monotonously decreased, the current approach may be acceptable, but refinements are required to account for changes in production strategy, such as changing rates and locally or globally increasing pore pressure.

13. The subsidence calculations are based on time-variant compaction models. The hazard and risk calculations are based on a linear compaction model. This is inconsistent and not mentioned while the potential implications for the predicted future seismicity are not discussed.

14. No attention is given to the observed changes in the seismic behaviour of the field in response to the significant production measures that have been taken in the recent past. An analysis of the predicted versus the observed response on a regional basis (e.g., for the centre of the field) is missing. No analysis is made of the impact of the large annual summer-winter production swings on the seismic behaviour of the field. The feedback provided on why earlier analysis results are not valid has not been used.

15. The submitted WP2016 gives little attention to the amount of damage still to be expected. Although loss exceedance curves are given, expected values are not explicitly provided. The risk reduction after retrofit is based on simplistic assumptions on the class-scale fragility reduction that require testing and validation. .

16. The different kinds of seismic risk to which an individual is exposed are not added together in the WP2016 documentation (e.g. the local personal seismic risk due to collapsing buildings, the seismic risk due to falling objects and the chain reaction seismic risks e.g. due to fires, flooding, industrial accidents and infrastructure failures following an earthquake).

Study and data acquisition programme

17. The proposed study and data acquisition programme addresses a number of the questions raised above with respect to WP2016.

18. Little attention is given to further analyzing and interpreting the existing seismological data associated with observed earthquakes, e.g. improving the hypocenter location and magnitude estimates. This observation data plays a key role in NAM's evidence based approach, which is currently not reflected in the study plan.

19. A number of components of the risk assessment may still need significant maturation/improvements (e.g., the fragility assessment for the building classes, the consequence modelling, and/or the effect of the building strengthening program). We are under the impression that NAM and its contractors are working to improve along these lines.

Closing Remarks

20. The present study is far from ready; WP2016 is a snapshot. An example is the shortly planned use of V3 fragility curves and a V3 consequence model which will have an impact on the calculated risks. NAM is aware of this issue as confirmed during the 12th of May meeting. As a result, NAM do not recommend to update the present building strengthening program on the basis of the current results.

21. The SAC recommends all data and tools required to make the Groningen hazard and risk assessment study reproducible are made publicly available.

22. We have only started to learn lessons from the recent history in East Groningen, and certainly the lesson is not only technical, but also societal, where NAM and the public governance share responsibilities. We recommend further communication from the national government that completes the current picture, and could also contain a societal cost benefit analysis *(MKBA - maatschappelijke kosten-batenanalyse).*

23. We recommend the development of a "readable" technical summary of the Groningen Winningplan accessible for laymen, explaining the key physical mechanisms of production-induced seismicity, the resulting building response, the train of thought behind the HRA, and an overview of the main assumptions and outstanding technical questions.

Lucia van Geuns
Chair Groningen Advisory Committee
The Hague, 20 May 2016

Attachment to the Final Note on NAM's Winningsplan Groningen 2016 - Groningen Scientific Advisory Committee

Progress note Groningen Scientific Advisory Committee
4 March 2016

The Groningen Scientific Advisory Committee (SAC) monitors and reviews the investigations performed by NAM or its contractors as part of the development of the Groningen Winningsplan (WP) 2016. The role of the SAC is to ensure the quality, completeness and impartialness of these investigations.

This note summarizes the SAC observations on the focus of NAM's ongoing research program. It has checked the findings against the most recent versions of the Study & Acquisition plan and the progress/plans presented by NAM during the V2 workshop on Hazard and Risk Assessment on 3 & 4 November 2015 in Assen. After this workshop representatives of the SAC participated in two Expert meetings (Pressure Management 1 March 2016; Ground Motion Prediction (GMPE)/Building Fragility and Risk Metrics 3 March 2016).

The deadline for WP 2016 is set by the Ministry of Economic Affairs for 1st April 2016 rather than 1st June 2016, as in the original planning. The March expertise meetings served as scientific discussions prior to the newly set final Milestone meeting on 22/23 March 2016.

New Developments

During the quality assurance process, NAM found an error in the hazard calculation after submission of the November 2015 Hazards and Risk Assessment. The error came to light by systematically comparing results of two programming codes (C and Python) (regular assurance process, standard procedure in the scientific world). NAM has a pre- and post-submission quality assurance process. The mistake is a unit conversion mistake. Implementation of the correct parameter shows a decrease of the "hazard" by 35%. The corresponding PGA value decreases from 0.27 to 0.17 g.

NAM proposed a way forward as follows:

- Perform a review, quality assurance and validation of the GMPE model and other elements of the Hazard and Risk Assessment model.
- Perform a review by Jonathan Stewart (Stanford University)
- Issue the Winningsplan 2016 based on the V2 Hazard and Risk Assessment – Interim Update 2015 with optimisation of production distribution. The Winningsplan will include comments on and acknowledgement of the "error".
- Issue a new (V3) Hazard and Risk Assessment before 1st June 2016.

Observations

1. The open and transparent way NAM communicated the error in the engine was appreciated by the members of the SAC.

2. NAMs reluctance to correct the error and then publish corrected risk estimates in WP16 strongly indicates that NAM themselves consider the possibility of similar, yet undetected errors existing in the engine.

3. NAM already focusses on quality control/assurance but this should not be done in a hurry.

Advice

1. The error duly reported in the implementation of the V2 GMPE by NAM is such that the results towards the Winningsplan 2016 should definitely reflect the error fixed. Our committee cannot endorse any document based on knowingly erroneous calculations.

2. NAM quality control/assurance should have been more transparent and should be part of the documentation made available by NAM and/or illustrated to SAC.

3. Before proceeding with any further developments, the same results presented in the November 2015 update should be re-calculated with the errors fixed. This only would make an assessment of the impact of the error in the GMPE possible.

4. The presented hazard and risk assessments are both based on a logic-tree approach. It seems that weights are based on expert judgment without following any formal procedure to assign them to the various models involved. It is recommended to explicitly report on assignment of probabilities in the logic tree.

5. On the risk metrics, NAM is required by the reporting of the Commissie Meijdam to compute a societal risk metric corrected for individual risk, which seems a contradictory definition. Based on the little information provided in the meeting, concerns raised about whether the metric has a proper probabilistic definition and interpretation. To evaluate whether results produced in terms of this metric are sound, more clarification is needed.

6. The SAC committee has to grasp the evolution of the hazard and risk assessment study with short presentations only and pre-read material, if at all, often sent shortly before the discussion events. It is very difficult to assess whether this large work is scientifically sound based on this short and fragmented information alone.

7. The revised static and dynamic models have been produced with a primary focus on "classic" field development planning and with only limited emphasis on aspects relevant to the Hazards and Risk Assessment, such as pressure (re-)distribution with time. However, this is not deemed to be a serious shortcoming by the SAC. The computer-assisted history matching exercise has been performed with a focus on physical and geological interpretation of the results, and, based on the limited information available to the SAC, has probably been performed with due care and skills. The uncertainty quantification is not state of the art and the results are of qualitative (indicative) rather than quantitative value. However, given the relatively small role of uncertainty in the reservoir model compared to uncertainty in other elements of the Hazards and Risk

Assessment (in particular the epistemic uncertainty in the GMPE), this level of uncertainty quantification is fully acceptable.

8. An optimization exercise was performed by NAM for the 33, 27 and 21Bcm scenarios to redistribute production in space (over clusters) and time to eliminate fluctuations in production until 2020 as much as possible while honouring the complex constraints of the surface pipeline and facility network. Basing its judgement on just a presentation, and without having access to documented results, the SAC is of the opinion that this exercise has probably been carried out with due care and skills. It was noted that the (government-prescribed) elimination of production fluctuations may be well be an overconservative requirement limiting the scope for optimization. However, pending further scientific results supporting or falsifying the need for this requirement, the current optimization exercise is judged to be the correct approach.

9. A second optimization exercise was also presented, based on more advanced optimization techniques but with limited capacity to take into account complex surface constraints. This second exercise will not form part of the Winningsplan but the SAC appreciates that some first steps have been made to approach the problem from a more systematic optimization and control perspective.

10. A revised "Meet- en regel protocol" (Measurement and control protocol) was presented following a format as mandated by SodM earlier this year. It consists of a "traffic light system" where exceedance of (combinations of) one or more thresholds for three indicators results in different levels of alerts requiring measures ranging from production adjustments to a complete re-evaluation of the Hazard and Risk Assessment. The choice of the thresholds as presented by NAM appeared to be based on engineering judgment rather than on quantified criteria related to the Hazard and Risk Assessment. In particular it was unclear of exceedance of one, two or three thresholds resulting in the same alert level were related to the same probability. The SAC considers the scientific foundation for the choice of these thresholds insufficient. Moreover, the SAC recommends to take into account a fourth indicator allowing for the spatial distribution of seismic events.

11. On request of the SAC some comments were given on the completion of the Groningen pressure maintenance study. Apparently a decision by NAM has now been taken that pressure maintenance, in the form of injection of N_2 to (partly) replenish the produced reservoir contents, will not be pursued. Without having access to the report and the underlying studies the SAC cannot comment on the scientific validity to no longer pursue this option. In particular the potential to use partial re-injection (with limited near-well pressure increase) in combination with the optimization approach currently pursued by NAM (see above) may offer opportunities to reduce the pressure decrease during the end-life of the reservoir and thus reduce compaction and the associated number of seismic events.

The expert meeting of 3 March 2016 discussed mostly scientific progress for the V3 Hazard and Risk Assessment. The current SAC commitment is for the Winningsplan 2016 based on V2 material, hence, it is not clear to the SAC members what their role will be after the WP2016 process.

The Hague, 4 March 2016

Attachment to the Final Note on NAM's Winningsplan Groningen 2016 - Groningen Scientific Advisory Committee

Progress note Groningen Scientific Advisory Committee

1 December 2015

The Groningen Scientific Advisory Committee (SAC) monitors and reviews the investigations performed by NAM or its contractors as part of the development of the Groningen Winningsplan (WP) 2016. The role of the SAC is to ensure the quality, completeness and impartialness of these investigations.

This note summarizes the SAC observations on the focus of NAM's research program. It has checked the findings against the most recent versions of the Study & Acquisition plan and the progress/plans presented by NAM during the V2 workshop on Hazard and Risk Assessment on 3 & 4 November 2015 in Assen. Prior to this workshop representatives of the SAC participated in four Expertise Workgroup meetings (Seismological Model 2 June 2015; Ground Motion Prediction (GMPE) 17 September 2015; Groningen Pressure Maintenance 24 September 2015; Fragility & Risk Metrics 9 October 2015).

The SAC views, presented below, are based on data, reports and presentations provided by NAM, up to 4 November 2015. All available documents can be found in the SAC-shared folder within Dropbox. A 2-page summary of NAM's Probabilistic Hazard and Risk Assessment for Induced Seismicity Groningen – Interim Update 7th November 2015 – is given as a addendum to this note.

General

The November 2015 workshop was most effective and started with the outcome/status overview and subsequently the details on how these were arrived at. That enabled the SAC to focus more on matters that have higher impact on the outcomes.

In general, the SAC members are impressed by the quality of the work performed within the project, which is of high scientific level. NAM/Shell/contractor staff involved are genuinely aiming for a best possible hazard and risk quantification within the constraints of time and data available. The researchers involved are open-minded and willing to communicate and discuss the results of their work.

From V1 to V2 Hazard and Risk Assessment: Observations

1. Uncertainty in GMPE has by far the largest impact on the results, also in V2. The impact on PGA (Peak Ground Acceleration) maps and hazard is limited going from V1 to V2. Impact on risk is much larger, about a factor of 10 reduction in risk numbers. If this outcome is correct the safety problem is becoming manageable. NAM is of the opinion that they can demonstrate that they meet the proposed norm at a 33 BCM production scenario. External risks (industrial, infrastructure, flooding etc.) are not in the presented risk numbers. At the moment these numbers only include risk from building collapse.

2. It makes sense to prioritize on a clearly-defined track towards assessment of risk for residents, while it is also in line with the norms of the Commissie Meijdam. However, major public concern is related to the risk to assets, i.e. the damage to houses. Therefore we would expect that the risk assessment also addresses a more complete quantification of risk to assets, or at least gives a road map how this will be done in the future.

3. Production scenarios have not been optimised on risk and are mainly dictated by the present operational constraints. In particular the two lower production scenarios have not been optimised on risk. Production is reduced in areas with relatively low seismicity. Production is not reduced in the south and not in the southwest where seismicity is higher and increasing. As a result, the calculated impact of production changes on risk is limited. In contrast, the housing strengthening is prioritised in areas with high seismicity. The resulting comparison of its impact with that of production measures is therefore arguable.

Seismological Model

4. The seismological model, which is a base for the further hazard and risk assessment, has reached a level of sophistication that makes it suitable for the purpose of developing the Winningsplan 2016. Being built on experience from the Groningen field, in particular the subsidence history, it is likely to predict the near future behaviour in an adequate manner.

4. In a longer time perspective, it is important to incorporate a better link between processes driving seismicity (stresses and stress changes on faults). In its current form, we do not see how pore pressure increase (for instance as a result of a longer production stop, or as a result of injection for pressure maintenance) could be handled. In the long term we believe the predictability of any model relies heavily on having the physics incorporated in as correct manner as possible, and at the same time being able to calibrate with relevant field data.

5. The inherent complexity and the potentially large impact of "the engine" on the outcome of the Winningsplan call for detailed sensitivity analysis. The difference between the three different compaction models is of little relevance for the outcome of the risk analysis. This could mean that the compaction models are very similar in terms of what they predict for the near future, or that the cumulative strain is more important than the incremental strain for the outcome.

6. It is important to see how Mmax but also related parameters like b-values influence the final risk. Plans for future data collection, and how these are going to affect updates on predictions, are of great importance for the long-term production and associated safety.

Pressure Management

7. One way to reduce remaining uncertainties might be the “Meet-en-Regel-Protocol” (Measurement and Control Protocol). The “Meet-en-Regel-Protocol” plays a key role for the public, therefore it should be simple and transparent also for non-scientists. The version of the “Meet-en-Regel-Protocol” as presented during the workshop was

immature. No specifics were presented on how to decide on which action to take in response to which measurements. Mention was made of a more specific document, but no details were presented.[1]

8. No link was made between the "Meet-en-regel-protocol" and potential control actions related to: 1) reducing gas production rates to allow relaxation of compaction-induced stresses, and 2) pressure maintenance through nitrogen injection to reduce compaction. The general public often suggests these as solutions, and therefore we believe it needs to be clarified by NAM to what extent the underlying assumed relationships can be confirmed/dismissed/quantified and why these potential solutions are not used in a control strategy.

Risk Metrics

9. NAM believes the present risk calculation is probably still conservative. Not clear if this is indeed the case. A list of conservative assumptions taken in the risk assessment was compiled by NAM and presented. Conservative assumptions are to be avoided as much as un-conservative assumptions in risk assessment. This is because conservative assumptions also bias the risk, impairing cost-benefit-based decision making; i.e. the ultimate goal of risk assessment. In any case, it is worthwhile to keep track, explicitly, of the conservative assumptions still remaining while progressing toward their removal.

10. It was claimed the 'engine' simulates a non-stationary process of earthquakes and then of consequences. This is only partially true. In fact, damage accumulation in successive events is neglected in the vulnerability (fragility) modelling. Moreover, using, in each simulation's run, the same fragility functions, implicitly means to assuming that each damaged (collapsed) building is instantaneously rebuilt and that residents can die more than once. In summary, non-stationarity, if any, is only in the hazard and not in the other components of the risk assessment.

11. The risk coming from the falling objects (e.g., chimneys) is still modelled separately from the risk following structural damage and it is also outside the 'engine' so far. In the case there will be an integration of this potential cause of fatality, if deemed relevant to the risk, it seems not an easy issue to address given that the considered objects are part of the building, and their collapse is not independent from the behaviour (and virtual collapse) of the structures they belong to.

12. Some so-called epistemic uncertainty is still assigned based on expert judgment in V2 fragilities. Similarly, the effect of strengthening of buildings on fragilities is arbitrarily assigned. These points seem to reflect a level of detail in modelling different from the rest at this stage. These issues should be more formally addressed toward the Winningsplan 2016.

13. Stochastic spatial dependence of ground motion intensity is not yet fully modelled. In particular, the intra-event residuals are uncorrelated, while it is inherent to the model the (likely strong) correlation carried by the mean of the GMPE and by the inter-event

[1] Post-workshop note: The Readers' Guide in the Interim Update report of 7 November 2015 states that the Meet-en-Regel Protocol "ensures the continuous data acquisition and monitoring needed for the Hazard and Risk management". This seems indeed a key aspect of "measurement protocol", however, the "control" part is missing.

residuals. It was not entirely clear whether (or when) full stochastic dependence will be accounted for the Winningsplan 2016.

14. It seems that cluster-triggering events follow an independent and stationary increments process (i.e. homogeneous Poisson), while the aftershock are sampled according to ETAS (Epidemic Type Aftershock Sequence) models. This seems not the standard way ETAS model is used, as it does not require distinction between triggering events and aftershocks, while all events come from the same model. We wonder whether and how declustering of the catalog to generate the triggering events is carried out to make sure to not over-produce seismic events with this simulation approach.

15. It could turn out difficult to find the houses that need strengthening. At the moment the category of a house is assigned probabilistically. That is not a problem when calculating average risk levels. A large number of houses will need to be inspected to find the category of each individual house. Secondly there is a large variation of the fragility curves within each category. Effect could be that the majority of houses in the weakest categories will need to be strengthened to make certain that all the truly weak building are incorporated. NAM's estimate of a factor of 2.5 for these two effects combined might be a considerable underestimate.

16. The group risk numbers shown seem to be P50. This is not a useful number. For earthquake group risk the fulllogic tree needs to be incorporated to calculate the mean risk.

17. NAM proposes to use activity level as "gebruiksruimte" and not risk. This is not a good approach as the effects of the e.g. b-value cannot be taken into account this way. A field wide PGA "gebruiksruimte" seems a better approach.

Recommendations

18. It is clear that the big picture is coming together in the V2 hazard and risk assessment. Now that different pieces of work are linked in the so called 'engine', the need for a back-analysis of the results produced seems necessary. Moreover, a number of issues, which may be relevant are still left to future work, or rely on expert judgment, waiting for modelling with a level of detail comparable to the rest.

19. To gain further confidence, it would be beneficial if a third (independent) party could test the 'engine' as a whole. By reproducing NAMs forecasts this third party could get an understanding of the little screws that might be adjustable in the process and assess their combined impact on risk. This is of particular importance since NAMs results draw a clear picture regarding the efficiency of mitigation measures (i.e. impact of reducing production is relatively minor).

20. We would like to see a more detailed presentation of the current risk assessment in the framework of NAM's/Shell's internal HSE Management System. We advise to seek contact with professionals with a systems and control background in the process industry to assist in developing the Meet-en-Regel Protocol. Suggestions for names: Dr. K.C. Goh (Shell), Prof. Bjarne A. Foss (Norwegian University of Science and Technology

(NTNU)), Prof. B. Erik Ydstie (Carnegie Mellon University, USA), Prof. Wolfgang Marquardt (RWTH Aachen University, Germany).

What's next?

Follow-up expertise workgroup meetings have been planned in the first quarter of 2016.

Early March 2016, a Mmax workshop is organised by NAM. Several experts have proposed values or distributions for Mmax. As the Mmax potentially has a large impact on the hazard assessment, NAM would like to use a formal and recognized process for expert opinion elicitation and aggregation, resulting in a well-documented Mmax (distribution) estimate. They will follow a SSHAC (Senior Seismic Hazard Analysis Committee) process of the US Department of Energy and Nuclear Regulatory Commission (NRC). SAC members are approached to be observer in this technical peer review.

May/June 2016 - Milestone workshop for Winningsplan 2016 (NAM, Assen)

The Hague, 30 November 2015

Addendum to SAC progress note December 2015

NAM's Hazard and **Risk** Assessment for Induced Seismicity Groningen – Interim Update 7th November 2015

Summary

Conclusions

- This update to the May 2015 Probabilistic Hazard and Risk Assessment (PHRA) evaluates the risk to residents from failure of buildings as a result of induced earthquakes due to gas production from the Groningen field. This information may be used to assess the acceptability of the risk compared to the risk norm, and to determine the appropriate mitigation measures to ensure continued safety of residents.
- Key conclusions of the November 2015 updated PHRA include:
- The November 2015 PHRA update shows that no houses exceed a risk of 10^{-4} (i.e. consistent with the criteria proposed by the Meijdam Committee) for a 33 bcm scenario, for 2016–2021.
- In the longer term (2017-2021), the scope of the structural upgrading programme, will depend on further reduction of the uncertainties in the PHRA (risk assessment). In the current PHRA update, the programme until 2021 encompasses some 5,000 buildings for a 33 bcm/annum scenario.
- Based on a production scenario of 33 bcm/annum, no more than a few hundred additional buildings are likely to require upgrading each year after 2021. The total size of the structural upgrading programme also depends on the effectiveness with which these buildings can be identified through inspection. As a consequence, buildings that do not require upgrading might actually be upgraded. The actual scope of the upgrading programme will therefore be wider.
- Seismic hazard maps indicate a smaller geographical area is exposed to significant (> 0.25 g PGA) ground accelerations for 2016–2021 than was projected for the same period in the May 2015 PHRA report. The reduced hazard area is consistent with KNMI's PGA map update published in October 2015 and now reflects the improved ground motion prediction method, based on the detailed description of the soil layers in the Groningen field area.
- For the first time it is possible to match a fully probabilistic risk assessment to an established risk norm. This outcome was achieved by comprehensive studies of building materials and construction in the area, advanced fragility modelling and the results of a shake table test of a Groningen-type terraced house.
- The building fragility studies reveal that in general buildings built in the 1960s and 70s are much stronger than originally thought. Particularly SiCa bricks that are often used for load bearing interior walls have a greater resilience to earthquakes than previously estimated.
- All studies supporting this PHRA assessment have been reviewed through an independent peer review process conducted to international scientific standards.

Background to this Study

- A Study and Data Acquisition Plan describes the objectives and interdependencies of all the studies and research efforts into induced seismicity being undertaken by and on behalf of NAM. The plan was first shared with SodM and the Ministry of Economic Affairs (Ref. 2) in November 2012 and was made public in early 2013.
- As part of the original Study and Data Acquisition plan, a probabilistic hazard and risk assessment (PHRA) for the Groningen gas field region was proposed. The original probabilistic hazard assessment (PHA) and scenario based risk assessment for the Groningen field were published in December 2013 as part of the 2013 Production Plan (*Winningsplan*) update. The next update to the PHRA will underpin the 2016 Winningsplan for the Groningen field to be submitted to SodM in mid-2016.
- The six-monthly updates provide insight into the progress of the assessment of the hazard and risk of earthquakes versus the assessment that underpinned the 2013 Winningsplan update.
- NAM continues its Study and Data Acquisition Plan which:
- is based on specific evidence and targeted data
- involves many Dutch and international experts, including those from academia, university

laboratories, independent experts, commercial parties and consultants
- is subject to an extensive voluntary assurance and verification programme, through an independent peer review process conducted to international scientific standards.

New in this November 2015 update:

A deeper level of analysis and more data specific to Groningen

- Revised static and dynamic reservoir modelling (with improved history match to production, pressure and subsidence data).
- Improved seismic model.
- A major update of the model used to predict ground motion. The updated equation now also incorporates such factors as area-specific details of shallow sub-surface and soils. Data from the newly available geophone network have contributed to this.
- New data on strength of buildings and building materials from lab tests, tests in pilot houses and shake table testing conducted in Italy. This was used to update building fragility relationships.
- Updated exposure to risk for people, reflecting more comprehensive work on collapse hazard. Furthermore, the risk of falling objects outside of buildings has also been studied.
- This work has resulted in the first quantified probabilistic risk assessment by location. In the previous May 2015 update the risk data were qualitative, as the results had not been fully calibrated to sufficient actual data.

Study Scope

- In this update, NAM has evaluated both the risk in the near term (2016-2017) and the measures necessary to maintain risk within acceptable levels during that period. The risks were assessed on the basis of the criteria laid down by the Meijdam Committee.
- This evaluation was conducted for three production scenarios: 33, 27 and 21 bcm/annum.

Further work

- Study and data acquisition work will continue to improve understanding of the specific hazard and risk situation in the Groningen field area.
- The main work planned between now and the PHRA updated for the mid-2016 Winningsplan update is as follows:
- Continue the experiments and studies to understand the fragility of buildings. Incorporate additional data from field and building tests.
- Set up an expert panel to establish the maximum magnitude for earthquakes in the Groningen field.
- Further refine the GMPE and seismological model.
- Independent external oversight for the studies supporting the Hazard and Risk Assessment in the Winningsplan 2016 is provided by the Scientific Advisory Committee (SAC), chaired by L. van Geuns, which was installed by the Minister of Economic Affairs.

Many activities are aimed primarily at preparing the Hazard and Risk Assessment for the Winningsplan 2016, but many other activities are geared to developing a broader understanding of the physics of induced earthquakes. These activities will not be completed by mid-2016, but may provide further insights and a broader foundation for the Hazard and Risk Assessment of the Winningsplan 2016.

Attachment to the Final Note on NAM's Winningsplan Groningen 2016 - Groningen Scientific Advisory Committee

Progress note Groningen Scientific Advisory Committee

30 May 2015

The Groningen Scientific Advisory Committee (SAC) monitors and reviews the investigations performed by NAM or its contractors as part of the development of the Groningen Winningsplan (WP) 2016. The role of the SAC is to ensure the quality, completeness and impartialness of these investigations.

This note summarizes the SAC observations on the focus of NAM's research program. It has checked the findings against the most recent versions of the Study & Acquisition plan and the progress/plans presented by NAM during the V1 workshop on Hazard and Risk Assessment on 22 & 23 April 2015 in Assen (for programme: see below). Prior to this workshop representatives of the SAC participated in three Expertise Workgroup meetings (Subsurface/Geomechanics 19 March 2015; Seismological Model/ Ground Motion Prediction/Seismic Hazard 24 March 2015; Fragility & Risk 26 March 2015). SAC meeting reports of these Expertise Group gatherings are attached to this progress note. During the April workshop all points have been discussed with NAM.

The SAC views, presented below, are based on data, reports and presentations provided by NAM, up to 23 April 2015. All available documents can be found in the SAC-shared folder within Dropbox.

General

The members of the SAC were impressed by the quality of the NAM work presented as well as the pace at which progress is made. The workshop in Assen was held in good spirit.

The interim results of the Risk Assessment were revealed at the end of the V1 workshop which left little time for in-depth questions and reflection on the numbers. The final presentation on 23 April 2105 was not shared by NAM in electronic format. NAM concluded that the level of maturity of the V1 Risk Assessment means absolute risk values are not reliable given the current large epistemic uncertainty. Relative risk values are therefore considered more useful for upgrading prioritization. Tornado charts presented, based on one seismic modelling approach, showed that the Ground Motion Prediction Equation (GMPE) and Fragility are most uncertain and, hence, drive the risk.

At the workshop in November 2015, a change in meeting format will be suggested to NAM, starting with the outcomes/status overview and subsequently the details on how these were arrived at. That will enable the SAC to focus more on matters that have higher impact on the outcomes.

Gap analyses

1. Seismological Model

- Much progress was made in the short time frame after the Expertise Workgroup meetings in March 2015, especially the new "strain thickness" seismological model, which strongly reduces the inconsistency between the spatial distribution of seismicity and compaction. There is still an on-going discussion whether or not the existing seismological models sufficiently covers the range of epistemic uncertainty. The seismological model is key and a broader perspective needs to be investigated. Therefore another Expertise Workgroup meeting on this topic is planned for 2 June 2015.

- Tectonic stresses are not considered in the current hazard analysis. We suggested investigating the natural (tectonic) stress criticality of existing faults. Depending on how far away mapped faults are from stress criticality, it might be possible to justify why tectonic stresses could be ignored in the hazard analysis. We expect that this will be further discussed during the June 2nd meeting.

- In the seismological model, seismicity is directly coupled to cumulative compaction. This is a rather unique model for seismicity, and it would be interesting to benchmark it against other seismological models as well as to field cases other than Groningen

- In the present risk calculations, predictions are based on a linear model, a time-decay model, or a modified rate-type isotach model. At the moment it is not clear to us which of these models best captures the observed field behavior. We would like to see more clearly the influence of the geomechanical model used on the risk outcomes. The June 2nd meeting will provide a forum to discuss this further.

2. Fragility & Risk

- The following are gaps, which need to be addressed for V2 Risk Assessment, and that will improve the results from the V1 for more reliable decision making:

  a. Building-typology-based risk assessment
  it is important that the effect of the variability of risk within a typology is embedded in the main risk assessment and propagated towards the results. Further work is required on fragility, e.g. the Monte Carlo simulation for fragility assessment is presently carried out while sampling without accounting for the (possible) stochastic dependence between the inter- and intra-building random variables defining a structure within a typology. The fact that these dependences can be neglected has to be confirmed, and e.g. some building typologies feature buildings that are close or attached to other structures, while they are analysed as isolated so far, this is another assumption, on the structural side, that requires more support to justify it.

  b. Risk metrics

It is believed that the more appropriate risk metrics among those shown is the one accounting for the variation of probability of presence within the day.

As the risk changes with time given the time-variant seismological model, the annual risk needs to be expressed explicitly as a function of time.

We believe that the (regional) group risk may for decision making, be more important than the local personal risk. In particular the annual probability that at least one fatality occurs, in the area affected by the possible earthquakes, is a key risk metric to be computed. The simulation engine seems ready to account for that.

c. Structural-damage-to-fatality relationship
The computation of fatality probability, given the occurrence of structural damage, is a key point of the risk assessment. It was found that the numerical analyses of buildings at the basis of fragility models are not able to provide the required input to the fatality models employed, which make use of the volume loss. Also, the fatality risk occurring when the volume loss is zero was acknowledged to be a gap in the computations and is being worked on by NAM.

d. *Industrial risk*
An important issue that keeps coming back is that the different risks (buildings, infrastructure, industry, dykes etc.) need to be brought together.
NAM stated that industrial risk (e.g., risk of an industrial accident related to gas production, storage, and distribution) is outside of their risk assessment. This is being carried out separately. But the industrial risk may, at some locations, be a non-negligible portion of the local personal risk (i.e. comparable or larger than that of collapsing buildings). It may be hard to combine risk from buildings and from industrial facilities, if the latter is not quantitative and probabilistic as the former. The risk of critical infrastructures also seems to be outside the scope of the NAM study.

3. Discussion

The SAC members discussed at length how to present the results of the risk study for the new Groningen Winningsplan. The results can be presented as the outcome of a bi-objective optimization problem. The spirit of the study should than be: how to find a balance between economics and safety, not how to maximize economics while getting away with a certain risk. Rather than looking at the seismic risk under a number of different scenario's, the approach should be from a measurement and control perspective: how do we keep the risk below an acceptable level. In addition, we recommend to look into the feasibility of developing an operational “measurement and control” strategy to enable quick operational response (production reduction or shut-in) based on (near-) real-time measurements of seismic activity.

Pending full optimization, the SAC recommends to approach the Groningen Pressure Maintenance (GPM) study to include spatial and temporal optimization of both production and injection as an engineering tool to optimize one or more objectives and develop an (adaptive) dynamic strategy. This could be done, e.g., by maximizing annual

production given constraints on the compaction differentials (positive or negative) around injection and production wells. A next step could be to specify the constraints in terms of geo-mechanical parameters. We propose to discuss these options during the planned Groningen Pressure Maintenance (GPM) workshop in September.

4. What's next?

Follow-up expertise workgroup meetings have been planned:

2 June 2015 - expertise workgroup Seismological Model
September 2015 (date tbd) - expertise workgroup Groningen Pressure Maintenance
17 September 2015- expertise workgroup Ground Motion Prediction
5 or 9 October - expertise workgroup Fragility/Risk Metric

3/4 November 2015 - V2 Workshop on Hazard and Risk Assessment (NAM, Assen)

The Hague, 30 May 2015

Agenda for the Workshop on the Hazard and Risk Assessment for induced seismicity Groningen
Day 1
Date: Wednesday 22nd April
Location: NAM Offices, Schepersmaat 2, Assen

Start Time	Activity	Presenter	
12:00	Welcome and Lunch	Martijn Verwoerd & Martijn Kleverlaan	
12:30	Introduction	Jan van Elk & Dirk Doornhof	
13:00	Summary of work group meetings in March	Lucia van Geuns	
13:15	Production Scenarios	Jan van Elk	Bird's eye overview of the main parts contributing to the Hazard Assessment
13:30	Compaction	Dirk Doornhof	
14:00	Seismological Model	Steve Oates	
14:30	Ground Motion Prediction	Julian Bommer	
15:00	Tea and Coffee		
15:15	Hazard Assessment	Steve Oates & Stephen Bourne	
16:00	Discussion		
16:30	Close Day 1		

Day 2
Date: Thursday 23nd April
Location: NAM Offices, Schepersmaat 2, Assen

Start Time	Activity	Presenter
09:00	Welcome and Recap day 1	Martijn Kleverlaan & Lucia van Geuns
09:15	Hazard Assessment	Steve Oates & Stephen Bourne
09:30	Exposure Database	Janwillem Beckers
10:15	Building Fragility	Rui Pinho & Helen Crowley
11:00	Tea and Coffee	
11:15	Consequence Modelling	Helen Crowley & Rui Pinho
11:45	Risk Metrics	Stuart Hardie
12:15	Lunch	
13:00	Structural Upgrading Program	Stuart Hardie & Janwillem Beckers
14:00	Tea and Coffee	
14:15	Risk Assessment	Stephen Bourne & Steve Oates
15:00	Discussion	
16:00	Close-out Day 2	

Attachment

Meeting notes Expertise Group Meetings held 19, 24 and 26 March 2015

Members of the Groningen Scientific Advisory Committee (SAC) participated in three one-day Expertise Group Meetings on 19, 24 and 26 March 2015 to better review the quality of the investigations by NAM and its contractors as part of the development of the Groningen Winningsplan 2016.

The meetings were open with ample time for high-quality discussions on scientific issues. The focus was on the Hazard and Risk Assessment for the Winningsplan 2016 (WP16). A list of participants to the meetings is given below.

Detailed minutes of the meetings have been made by NAM. The observations below are a summary of the notes provided by the individual members of the SAC.

General

1. NAM presented the 'bridge' model to illustrate how the scope of the meeting fittted in the overall Hazard and Risk Assessment. The studies part of the evidence-based approach is most relevant for WP16. The model-based approach will have a longer-term timeline and will influence WP16 by demonstrating physical processes and providing support for causality.

Subsurface & Geomechanics

2. The new approach of direct inversion of levelling data to build the compaction model removes some of the inconsistencies with observation data. INSAR data currently analysed by NAM might further improve the model.

3. Geomechanical studies are far from providing quantitative results but can help to bring more insight and physics into the partially empirical seismological model that is now being used for the risk calculations.

4. The Groningen Pressure Maintenance (GPM) study is presented in a defensive rather than a pro-active fashion. Injection is presented as a "Measure of last resort/insurance project". We appreciate that there are major hurdles in terms of economic feasibility, logistic capacity, public acceptance and technical risks (e.g. re-activation of stressed faults), but the GPM study should be focussed on overcoming these rather than just inventorising them.

Seismological Model, Ground Motion Prediction and Hazard

5. CBS presented new work investigating correlations between production parameters and seismicity. Underlying is an analytical solution for pressure diffusion assuming a reservoir-wide constant hydraulic diffusivity. Preliminary results presented were not conclusive. CBS will publish their analysis in the near future after further work and discussions with statistical experts.

6. NAM briefly presented an extended activity rate model invoking faults and fault offsets. Details of the model are not clear yet and a documentation of the model will not be available before May 2016. The model will be considered for WP16 only if a mismatch between seismicity and compaction persists with the new compaction model.

7. TNO expressed concerns that the seismological models currently used by NAM are too similar (i.e. compaction driven) and might not cover the full range of epistemic uncertainty. TNO recognized the key importance of the seismological model(s) and are investigating alternative models within TNO. NAM has considered and discarded a variety of alternative models but have not communicated previously on this exercise. SAC proposed a separate meeting to further discuss this.

8. GMPE work showed major progress. Needs to address the changes to be expected when going from V0 to V1 and then V2 approach. Need to indicate the potential effects of moving to a next phase. Also later outcomes should fall within the uncertainty range of the previous versions.

9. The Deltares Shallow Geological Model study is well received. Effects of local soil improvement actions are not addressed in the present work.

Building Fragility and Risk

10. On building-typology-based risk assessment: grouping buildings based on typology, and using a single representative building, factually means that the risk computed for a specific typology is an approximation (average) of risk within the class. For some structures the risk is underestimated, while it is overestimated for others. Therefore, it is recommended that, whichever risk metric is used, a measure of the variability of risk within the class is provided.

11. A clear definition and/or interpretation of the risk metrics is important. Preferably all the fragility/risk deliverables should start with clearly defining the probabilistic meaning of the risk being computed. This would greatly help in assessing whether the work is fit for purpose. TNO will organise an additional meeting on risk metrics with NAM and NPR (Nederlandse Praktijk Richtlijn) experts to address a number of issues raised.

12. The computation of fatality probability, given the occurrence of structural damage, is a key point of this work. Some preliminary insights on the semi- empirical models to be used were presented. They are a function of volume loss given collapse; it is not clear at this stage how the numerical analyses of buildings at the basis of the fragility models will be able to provide the required input to these models. Moreover, if the fatalities occurring when the volume loss is zero are a non-negligible fraction of total casualties, these need to be considered, while they seem not so far.

13. Industrial risks are not accounted for in the NAM studies. The risk assessment from industrial accidents induced by earthquakes is generally more complex of that of buildings and may have a large impact at some scale, significantly contributing to the

total personal (seismic) risk.

More in general

14. We would like to see a detailed flow chart specifying all steps in the risk assessment (and preferably also in other uncertain elements of the Winningsplan, in particular expected pressure depletion figures), including an explicit indication of all the input parameters and how the uncertainties in these input parameters are quantified.

15. Many elements of the studies presented would benefit from (an attempt to) a more explicit quantification of the uncertainties in the inputs and the results (both in intermediate steps and final outcomes). This would help to build a better picture of the key uncertainties in the many steps of the process, to allow focussing limited resources on the reduction of those uncertainties.

The Hague, 10 April 2015

ATTENDANCE

Groningen Scientific Expertise Working Groups – Subsurface & Geomechanics
Schiphol, 19 March 2015

Lucia van Geuns, Chair SAC
Jan Dirk Jansen, SAC member (TUD)
Rune Holt, SAC member (NTNU)
Stefan Baisch, SAC member (Qcon)
Jaap Breunese, SAC member (TNO)
Hans de Waal, SAC member (SodM)

Hans Roest, SodM
Bastiaan Jaarsma, EBN
Marc Hettema, EBN

Jan van Elk, NAM
Dirk Doornhof, NAM
Rob van Eijs, NAM
Clemens Visser, NAM
Eddy Kuperus, NAM

Richard Hofmann, Shell (GMP)
Sander Hol, Shell (Core Experiments)
Joop van der Steen, (GMP)
Kirsteen van Weelie-Campbell, (GMP)
Sadok Lamine, (GMP)
Casper Buitendijk, (GMP)
Stephen Bourne, Shell
Stijn Bierman, Shell (Statistician)
Peter van den Bogert, Shell
Peter Schutjens, Shell (GMP)
Famke Kraaijeveld, Shell (Statistician)

Groningen Scientific Expertise Working Groups – Seismological Model, Ground Motion Prediction and Hazard
Rijswijk 24 March 2015

Lucia van Geuns, Chair SAC
Stefan Baisch, SAC member (QCon)
Bernard Dost, SAC member (KNMI)
Hans de Waal, SAC member (SodM)

Hans Roest, SodM
Brecht Wassing, TNO
Karin Thienen-Visser, TNO
Frank Pijpers, CBS
Marc Hettema, EBN
Bastiaan Jaarsma, EBN
Barthold Schroot, EBN
Pauline Kruiver, Deltares

Jan van Elk, NAM
Remco Romijn, NAM
Karel Maron, NAM
Steve Oates, Shell
Ewoud van Dedem, Shell
Stephen Bourne, Shell
Stijn Bierman, Shell
Julian Bommer, Consultant for NAM

Groningen Scientific Expertise Working Groups – Building Fragility and Risk
Schiphol, 26 March 2015

Lucia van Geuns, Chair SAC
Iunio Iervolino, SAC member (U.Napels)
Hans de Waal, SAC member (SodM)

Annemarie Muntendam-Bos, SodM
Ilse de Vent, SodM
Raphael van Steenbergen , TNO
Jan Gijsberts, TNO
Marc Hettema, EBN

Jan van Elk, NAM
Karel Maron, NAM
Julian Bommer, Consultant for NAM
Helen Crowley, Consultant for NAM
Rui Pinho, Consultant for NAM
Tony Taig, Consultant for NAM
Damian Grant, Consultant for NAM