KEM Research review, evaluation and interpretation (max. 4 pages + annex)
TITLE *Seismogenic Source Models for the Groningen Gas Reservoir*

KEM Quality review

The seismogenic source model as part of the Groningen induced seismicity risk train has been developed largely in-house by NAM over the past 8+ years. It is a critical element of the entire risk-train and closely related also to important decisions on production scenarios as well as mitigation actions. However, this part of the model train is currently also possibly the least transparent component, and the one least exposed to external reviews and critical feedback. KEM-08 addresses this gap, and it does so following the three-step approach adopted by KEM to many model components: In step 1, the existing seismogenic source models are critically reviewed; in step two, alternative approaches are evaluated for their applicability to the Groningen case, and in step three, specific recommendation for next steps formulated.

The three reports supplied by NORSAR and GFZ closely follow this partitioning and, overall, the quality and depth of the reports is excellent, representing good value for KEM money invested. NORSAR and GFZ are two of the world-leading institutions in the domain of seismology, with relevant specialisations in seismic hazard assessment and statistical seismology. They have less expertise in reservoir modelling, a limitation that is apparent in some of the chapters. The reports were clearly written as a team effort and the complementary competencies of the team members – researchers with an outstanding scientific track record but also practical experience – lead to a document that is well written, clearly structured, well-referenced, well-illustrated and pleasantly typeset. It addresses most of the research question posed by KEM-08 in sufficient depth and thoroughness, representing a highly valuable in-depth and independently conducted review of the seismogenic source models for Groningen (and for other such hydrocarbon reservoirs). The group has interacted with the NAM team to clarify open issues; it also takes into account existing reviews. It does not, however, evaluate the code basis itself, and more integration with the TNO team reproducing the NAM implementation would have been desirable even if it was not explicitly called for in the contract. Especially WP1 and WP2 are highly useful and well-balanced summaries and recommendations helpful for many future research and implementation efforts, including efforts of TNO. There are a few areas, for example, physics-based reservoir modelling and models used in industry where more details would have been useful. In some areas, the specific mindset of the authors is overly visible, and a somewhat broader view of the community could have been adopted. WP3 also contains highly useful recommendations but is written in parts with a somewhat narrow perspective of a continuation of the research by the same team. However, in summary, the quality of the reports is excellent, the methods applied adequate and the results presented will have a significant impact.

KEM Evaluation of the results

The task 1 of KEM-08, to review the existing NAM seismogenic source model, is fully addressed in the report WP1. In 68 pages, NORSAR and GFZ critically review all aspects of the existing model. Their findings confirm and quantify some previously existing concerns on the source model: 1) The model is not well enough documented to be fully reproducible, especially with respect to the dynamic reservoir model; 2) While the NAM seismogenic source model is a reasonable and sophisticated approach, it does make a number of assumptions and choices that are not well enough justified, sometimes arbitrary and non-unique; 3) The model does not fully represent the existing aleatory variability and epistemic uncertainties, nor does it capture fully the range of available models and expert opinions in the community. A full sensitivity analysis of all model parameters has not yet been conducted, due to computational constraints. The review discusses not only the model, but also in some depth the available data to calibrate the model, and the sensitivity of the model to data uncertainties. For example, the effect of uncertainties in earthquake source parameters (location, magnitudes) are discussed at length, and rightly so, since for example the b-values describing the earthquake size distribution can critically influence the hazard and risk results and there are good reasons that the approach chosen by NAM has limitations.
The NAM seismogenic source model has substantially evolved with time, a challenge that WP1 addresses well but that increases the complexity of the review in KEM-08. The review, however, contains a number of specific suggestions and highlights existing inconsistencies in the model or its documentation that should be taken into account in the continued development of the NAM model and its implementation by TNO. The review also highlights the fact that so far, the seismogenic source model does not take advantage of the recently collected and greatly enhance earthquake data (i.e. since the installation of the KNMI borehole network), which is unfortunate given the investments taken and the fact that these data offer the potential to substantially enhance the robustness and statistical significance of some of the calibrations. The WP1 report, in summary, is a highly useful document for many stakeholders: For a regulatory body that needs to assess the risk and production planning, for NAM and/or TNO in the continued model development, for a scientist interested to develop forecasting models and the general public interested to understand the work and assess its validity and value.

Task 2 extends the review of WP1 by considering alternative approaches to building a seismogenic source model. This document is also quite comprehensive, reviewing 21 alternative approaches from four model classes, models of variable degree of sophistication. This comprehensive overview, and a certain assessment of the pros- and cons of each model, is useful as a reference document and can help guide the discussion on future model developments to SoDM, NAM, TNO and the broader research community, including DEEPNL. The review conducted is fully based on a literature review by the study authors; the report in this respect falls somewhat short of the expectation in the proposal to also involve expert elicitation and possible implement/test selected models or model components. The review is also limited in the sense that some of the models reviewed are only partial models that in themselves may not be suitable as branches in an alternative logic tree to capture epistemic uncertainties. Missing is a better description of the general requirements that a model needs to fulfil in the first place (in terms of input/output/uncertainty quantification etc.; for example, a model must allow analysing production scenarios? Or represent aftershocks?), the data available to calibrate the model and the inherent limitations in the data), the combination of models or model components into a more comprehensive holistic model, and the needs and opportunities to build future, 'next generation' models.

Task 3 addressed in WP3 lays primarily outlines briefly the foundation for a model testing framework of models, and it does this in a clearly structured way. However, while testing the model performance in a community-supported framework is an important component of model validation and enhancements, lacking is a stronger focus on the models and model building itself, including the ability to assess production/mitigation scenarios, as well as building a Groningen seismogenic source model logic tree that fully samples the uncertainty. The proposes approach outlined in WP3 assumes that modellers will simply produce models and that the main task is testing these (which is the CSEP approach often taken). However, this is not the case for most models for Groningen, and building/calibrating/maintaining/improving a hydro-geomechanically coupled, 3D and time-evolving model, plus automate calibration approaches as new data emerge, is a massive task in itself, vastly exceeding the efforts needed for testing (the efforts to construct the NAM model over the years are for example massive). WP3 should have put more emphasis on the future needs and future directions of seismogenic source modelling in the Groningen areas itself, rather than focussing almost exclusively on a testing framework. WP3 also is narrow in the sense that the proposed future work is written centred on the expertise and interest of the research team involved in KEM-08 but does not consider the broader community (of modellers, for example). However, even if WP3 only partially fulfils the research questions raised, it is a useful reference document to define some of the future directions; the report should also be made openly available but excluding sections after chapter 5.2.

KEM interpretation of the outcome

The outcomes of KEM-8 are important for the community and the reports WP1 and WP2 should be made openly available to the community. These results are not per se publishable in the peer-reviewed literature (unless for a review paper) but they are highly valuable to regulators, NAM, TNO, scientists working on Groningen or induced seismicity in general. They can be used as an important document when building a roadmap for future model development needs as well as model performance evaluation.

Closure text for the website

The seismogenic source model as part of the Groningen induced seismicity risk train is an important component model. This KEM research question, KEM-08, focusses on a critical review of this model, in three steps: In step 1, the existing seismogenic source model is critically reviewed; in step two, alternative approaches are evaluated for their applicability to the Groningen case, and in step three, specific recommendations for next steps formulated. The review has been reported in 3 well-written reports. The reports are technically at a high competence and well-executed.

In the first report, NORSAR and GFZ critically review all aspects of the existing seismogenic model of the NAM seismic HRA model. Their findings confirm and quantify some previously existing concerns on the source model concerning (1) documentation and reproducibility: (2) a number of assumptions and choices that are not well enough justified; 3) not fully representing the existing aleatory variability and epistemic uncertainties based on a full sensitivity analysis due to computational constraints. The review discusses not only the model, but also in some depth the available data to calibrate the model, and the sensitivity of the model to data uncertainties. For example, the effect of uncertainties in earthquake source parameters (location, magnitudes) are discussed at length, and rightly so, since for example the b-values describing the earthquake size distribution can critically influence the hazard and risk results and there are good reasons that the approach chosen by NAM has limitations. The review also highlights the fact that so far, the seismogenic source model does not take advantage of the recently collected and greatly enhance earthquake data (i.e., since the installation of the KNMI borehole network), which is unfortunate given the investments taken and the fact that these data offer the potential to substantially enhance the robustness and statistical significance of some of the calibrations. The WP1 report, in summary, is a highly useful document for many stakeholders: For regulatory bodies that need to assess the risk and production planning, for NAM and/or TNO in the continued model development, for scientists interested to develop forecasting models and the general public interested to understand the work and assess its validity and value.

The second report extends on the review by considering alternative approaches in the literature to building a seismogenic source model. This document is also quite comprehensive, reviewing 21 alternative approaches from four model classes, models of variable degree of sophistication. This comprehensive overview, and a certain assessment of the pros- and cons of each model, is useful as a reference document and can help guide the discussion on future model developments. The overview is also limited in the sense that some of the models reviewed are only partial models that in themselves may not be suitable as such. A broader community feedback or a structured expert elicitation session/workshop with the community could have provided more feedback on pro and cons of different modelling approaches to already start defining a roadmap towards the next-generation model.

The third report primarily outlines briefly the foundation for a model testing framework of models, and it does this in a clearly structured way. However, while testing the model performance in a community-supported framework is an important component of model validation and enhancements, lacking is a stronger focus on the models and model building itself, including the ability to assess production/mitigation scenarios, as well as building a Groningen seismogenic source model approach that fully samples the uncertainty. Although the proposed testing framework is useful, the report could have put more emphasis on the future needs and future directions of seismogenic source modelling in the Groningen areas itself.

The outcomes of KEM-8 are important for the community working on seismic risks to be shared and used by the community and highly valuable to regulators, NAM, TNO, scientists working on Groningen or induced seismicity in general. They can be used as an important document when building a roadmap for future model development needs as well as model performance evaluation.