KEM Research review, evaluation and interpretation (max. 4 pages + annex)

Improving the earthquake event catalogue in the Groningen region

KEM Quality review

The induced seismicity catalogue of the Groningen region, compiled by KNMI, is an extremely critical input to understanding the induced seismicity in relationship to reservoir- and geo-mechanical models; it also is critical for the subsequent analysis of seismic hazard and risk. Compared to the other elements of the seismic risk model of Groningen, the seismicity record has so far received comparatively little attention, despite its undeniable importance for the seismic risk assessment. KEM has commissioned a critical review of all model train components in order to ensure an independent assessment of the current status and to provide advice on future directions. The objective of research question KEM-11 was to critically re-evaluate and partially reprocess seismological data recorded in the area of the Groningen gas field, improving the existing induced earthquake catalogue of KNMI. Improvements should target the consistency, the completeness, the location accuracy and precision and the source parameter estimation. Finally, a priority ranking for future studies, based on simplified sensitivity studies, should be defined.

The contract was given to NORSAR, a well-established and internationally recognized, independent, not-for-profit, Norwegian research foundation within the field of geoscience with core competencies in seismology. The project lead was with Dr. Volker Oye, supported by a small team of established seismologist. The work was conducted with support and in parts in collaboration with KNMI. NORSAR has delivered in time, in June 2018 two in-depth reports to SODM, 150 and 50 pages respectively.

The two NORSAR reports are excellent examples of high-quality reviews and subsequent data analysis that deliver important insights at a technical highly competent level. The two reports are well written, detailed, well-illustrated and logically structured. They are extremely well referenced and in terms of scientific quality comparable with per reviewed papers in good journals. It is evident that the involved NORSAR scientist are experts in the relevant domain, with an in-depth understanding of the inherent problem in earthquake catalogues. Over the course of the past 30 years, the network over the Groningen gas field has developed in steps from virtually non-existent to a state-of-the-art network of dozens of borehole sensors, today resulting in a detection threshold of ML~0.5 and a 500m location accuracy. In addition, processing techniques and computer power have developed tremendously. NORSAR has dissected in their review this heterogeneous dataset and provided important assessments of the status quo; they also made a number of significant observations in selected areas that will be highly useful to KNMI and to other researchers. The review addresses essentially all points request in the research question, including sensors calibration, earthquake location, magnitude determination, completeness, focal mechanisms etc. Finally, as requested in the research question, NORSAR made a number of important suggestions for further post-processing and for improvements in future real-time catalogue. These future directions now open up important opportunities for enhancing process understanding and reducing uncertainties in seismic hazard and risk assessment and should be implemented in a second phase.

KEM Evaluation of the results

KEM 11, Phase I, was intended to archive three objectives:

Objectives 1

"Evaluate the existing earthquake catalogue in the Groningen area of the last 30 years, as well as the existing procedures to detect and located earthquakes. This evaluation should be based on the existing reports, existing data and procedures and establish a quantitative assessment of data completeness, data homogeneity and uncertainties in locations, use of velocity models, pick consistency and detection approaches, magnitude assessment, focal mechanisms and stress drop estimations. The magnitude of completeness, station residuals and relationship between different magnitude scales for the Groningen area and the comparison to existing techniques should be considered. Existing re-analyses of the data or parts of it (e.g., re-located events, cross-correlation etc.) should also be considered and compared to the existing state of the art in seismic monitoring at local to regional scale around the globe."

The first report delivered by NORSAR, WP1, fully addresses this objective. The report critically reviews the past current network practises applied by KNMI. The reports overall establishing that KNMI has followed good practises and state-of-the-art methodologies in the domain and no major problems were identified. This independently evaluation is in itself an important milestone, enhancing the credibility and usefulness of the existing database. The analysis of the event locations suggest room for improvement in pick consistency, in uncertainty quantification and in access to some of the metadata (uncertainties, temporary stations). These should be implemented by KNMI. The report also suggests that enhances in event re-location (using for example the EDT method) and in-depth location would be highly useful and are possible. These recommendations should

be picked up with high priority in phase 2, since it offers great potential for improved process understanding and modelling capability.

Magnitudes are especially relevant for the seismic hazard and risk assessment and again it is important that the NORSAR analysis confirms that the overall magnitude determination strategy as sound, state-of-the-art and consistent through time. The recommendations for improving the database of Mw determination also should be implement in Phase II. Likewise, suggested improvements in establishing the magnitude of completeness as a function of space and time should be considered by KNMI. The evaluation of stress drop determinations, focal mechanism determination and the use of full waveform-based methods likewise add important constraints for understanding an improving the current data and steers future research

The overall conclusion of the report states that *'... we consider the catalogue as extensive and of high quality. Over the years, huge progress has been made; certainly in instrumentation of the field, which is by now probably the best monitored gas field globally, but not least in data accessibility via KNMI's online data portal, the standardisation of their processing methodology and their continuous effort in research for further improvements*." This summary is well supported by the analysis in the reports and forms now a solid baseline for KNMI and other researchers to use the data with increased trust and understanding.

Objective 2
"Perform, at least in a qualitative sense, a sensitivity analysis, analysing the relative importance and impact of the seismic data for understanding the causes of induced seismicity and the impact on the ongoing and future hazard and risk assessment. The outcome should be an assessment of the requirements and opportunities for seismic monitoring and analysis in the Groningen region, for the purpose of induced seismicity risk assessment and mitigation."

This objective has been fully addressee in the WP2 report. The report is somewhat less useful than report 1, which is in parts a consequence of the complexity of conducting a full sensitivity analysis, and In parts due to the lack of a clear objective function for sensitivity analysis (as pointed out by NORSAR). The reports nevertheless provide a well-referenced and useful summary of the seismicity parameters influencing the hazard and risk computations, and also a qualitative ranking of their importance and potential for future improvements. The report thus feeds well into the third objective, the definition of a roadmap for future improvements. This WP might have benefitted from a feedback session between NORSAR, KNMI and the KEM panel, to reflect on the objectives and targets to address.

Objective 3
"Based on 1 and 2, propose a strategy for improving the existing seismological database and its description using post-possessing, considering also the feasibility, timeline, costs and potential benefits. This strategy will form the baseline for the work in Phase 2. This work-plan should also consider how improved processing in the future could be implemented and largely automated in near-real time."

The objective was fully addressed in the proposal for Phase II related work, delivered by NORSAR and KNMI in a joint proposal. The proposal builds sensibly on objectives 1 and 2 and delivers a realistic work pan, structured in 5 sub-tasks. The proposal is sensible overall and well structured, the work proposed is plausible and it is also much needed. KNMI on its own does not have sufficient resources (in terms of personal ad finances) to implement the proposed improvements with sufficient speed and quality control, because they are very much involved in the day to day business of running the network. There is a clear benefit involving independent experts in Phase II, rather than relying on KNMI only; however, this collaboration should be executed with a clear list of deliverables and milestones for Phase II, rather than already foreseeing a long-term collaboration

Phase II is the next logical step for the efforts related to improving the seismological database, and these efforts remain highly justified. They are possibly the most important improvements needs right now to enhance the process understanding and modelling capability in Groningen, but they are also useful for other gas field and related GeoEneregy applications where induced seismicity may play a role, such as seasonal gas storage and CO_2 sequestration. Improvements will also directly feed into the next generation of the hazard and risk assessment for Groningen. Because induced seismicity will likely remain a topic at Groningen even many years after the closure of the gas production, continued investment in seismological monitoring and processing is well justified and will lead to measurable enhancements in the quality of the research and risk assessment. It also might positively impact public acceptance by allowing scientist to decipher and communicating the causes and effects of earthquakes more precisely.

The tasks proposed for Phase II are all sensible and likely achievable within the time frame and budget proposed. They should all be tackled after double checking against the most recent literature and internal efforts at KNMI; however, if budget constraints do not allow to address the all, the following priority list is proposed:

Priority 1 - WP1: It is most beneficial an immediately relevant important to provide access to all relevant metadata etc. to the community. This should include open access to the digital data obtained in Phase I of KEM11.

Priority 2a - WP3a: An openly available, tested and regularly updated high-precision relative earthquake catalogue will be a great asset for the wider community and for KNMI/TNO and NAM. These methods are today state of the art, and it is not acceptable that in one of the most important seismological datasets should remain sub-standard in this respect.

Priority 2b - WP2: This task is closely linked with Task WP3a and could well be tackled jointly. Again, improved absolute hypocentre location are much needed as a resource and the proposed approach is sensible.

Priority 3 - WP4 & 5: These efforts are closely linked, and they could be addressed together: the effort is limited, but they will be providing important resources to the community and a pathway to sustained improvements of future data also.

Priority 4 - WP3b: Additional research on moment tensors and (relative) stress drops would be prosing and may open up new insights on the underlaying mechanism. NORSAR with Dr. Goertz-Allmann has an expert in this domain who would be able to perform an important and high-quality study on these subjects, and again deliver a relevant set of parameters to the wider community.

Priority 5 - WP3c: A useful and potentially important task, but it is considerably more research heavy and a useful output less certain than for the other tasks.

KEM interpretation of the outcome

These two reports provided by NORSAR are possibly the most systematic and most comprehensive summary of the seismic record in the Groningen area, making them a highly useful resource for future studies that should be provided as open access to other researchers. In this case, publication in a scientific journal may not be a preferred route, since the results are not per se original research. The work should be citable thought, suggesting the KEM deliverables/reports should gain a DOI. The reports represent a prime example of high-quality efforts and excellent reporting enabled by KEM research questions, and they can be showcased as good practise to other research teams working on KEM questions.

The results have immediately relevance for KNMI, who likely have already implemented a number of the suggestions. They also have relevance for other researchers and finally they will find their way into the next hazard and risk assessment. The KEM objective of independently evaluating all model train component has been achieved for an important part of the model train. However, without following up with Phase II, as originally intended, the impact of the efforts of Phase 1 will be more limited and less forward looking.

Closure text for the website

The induced seismicity catalogue of the Groningen region, compiled by KNMI, is an extremely critical input to understanding the induced seismicity in relationship to reservoir- and geo-mechanical models; it also is critical for the subsequent analysis of seismic hazard and risk. Compared to the other elements of the seismic risk model of Groningen, the seismicity event record has so far received comparatively little attention, despite its undeniable importance for the seismic risk assessment. KEM has commissioned a critical review of all Groningen HRA-model train components in order to ensure an independent assessment of the current status and to provide advice on future directions. The objective of research question KEM-11 was to critically re-evaluate and partially reprocess seismological data recorded in the area of the Groningen gas field, improving the existing induced earthquake catalogue of KNMI. Improvements should target the consistency, the completeness, the location accuracy and precision and the source parameter estimation. Finally, a priority ranking for future studies, based on simplified sensitivity studies, should be defined.

The project had 3 objectives.
1. "Evaluate the existing earthquake catalogue in the Groningen area of the last 30 years, as well as the existing procedures to detect and located earthquakes. ."
2. "Perform, at least in a qualitative sense, a sensitivity analysis, analysing the relative importance and impact of the seismic event data for understanding the causes of induced seismicity and the impact on the ongoing and future hazard and risk assessment."
3. "Based on 1 and 2, propose a strategy for improving the existing seismological database for Groningen (and elsewhere) and its description using post-possessing, considering also the feasibility, timeline, costs and potential benefits. This strategy will form the baseline for the work in the future. This work-plan should also consider how improved processing in the future could be implemented and largely automated in near-real time."

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