

#### KEM Quality review

The project part KEM-11b, Phase 2a, is part of a larger effort in parts financed by KEM to analyse the seismological network related components of the Groningen Risk Monitoring, Assessment and Management Model. While the first phase of the KEM 11 activities focussed on the earthquake catalogue, this phase 11b-2a focussed primarily on the acquisition and use of seismic recordings from the acceleration network and for the purpose of Ground Motion Modelling (GMM) as part of the Groningen Risk Assessment Model. This is not only an important topic for the risk models, because the GMM has a dominating influence on the hazard and risk, and they also carry a substantial uncertainty, the state of the seismic network and the resulting GMM are also a topic that has been controversially discussed in light of issues detected in some of the strong motion sensor network deployed by KNMI in the Groningen area. The sensibility of the topic is noticeable in the detailed comments on the report by KNMI.

The project was executed by NORSAR, Daniela Kühn served as the project lead. NORSAR and the team of scientists involved are globally recognised as one of the leading institutions in observational seismology and therefore the team was highly qualified to execute the work. The results of the evaluation are summarised in a report of about 150 pages, including 40 pages of appendix. The evaluation is reasonably structured, first focussing on the overall design and quality criteria of seismic networks (WP1) and the in a second part (WP2) focussing more on the specific data from the Groningen area. The final section (WP3) then concludes the work with recommendations for potential improvements to the current network and data collection. The first part in my opinion can be quite useful as a reference documents also for other and future seismic networks and should be made openly available. The second part is useful to an audience specifically interested in the Groningen data, and should also be openly available. The final part is useful mainly for KNMI and regulators that consider future directions. In summary, the report succeeds in showing that objectives of the related research question have been fulfilled. As a minor note: although the quality of the work is acknowledged a better link between the WPs could have improved the report.

As with past reports by NORSAR, the report is typeset in a very clear and visually attractive way, the graphics are excellent, and the overall presentation of the results is exemplary for KEM reports. The report benefitted from interactions with KNMI, parallel investigations into the sensor network (by John Clinton), feedback from SodM and a final feedback round by KNMI that resulted in changes to the report. This feedback process was extremely useful and ensured a high quality of the results.

The research methods is overall appropriate, although as also pointed out by the KNMI comments, the definition of a 'state of the art' seismic network is non-unique and not entirely quantifiable; this leaves a certain degree of – maybe unavoidable - fuzziness in the assessment and the interpretation. It is also true that not all relevant technical questions and interpretations are 100% resolved through the report, and that selected topics in the report will need to be rediscussed and further analysed. This is not a shortcoming per se but a result of a complex, highly technical context that is also changing with time and with new data being collected, and a topic where differences in opinion exist. The fact that the report triggers further discussion and additional analyses thus can also be seen as a sign of its quality. The report, however, does end up with very distinct and useful conclusions and suggestions. Overall, the report should help to settle some of the open issues and past/ongoing discussions on the seismic network and forms an important reference document on the seismic network and network data.

In summary, the quality of the investigation is judged to be excellent and the results, discussed in more detail below, are important for a number of stakeholders. The report and analysis thus are entirely consistent with the requirement for a KEM high-quality product.

#### KEM Evaluation of the results

Overall, the report delivers a wide range of important results that should not be undervalued because they are overall quite technical, and detail-oriented in nature. These results fall into different categories:

1. A key result is that the Groningen network is in almost all aspects state of the art, the applied data handling and quality assurance processes are adequate (although improvements are possible), the derived data can be almost entirely reproduced, and no major flaws or problems are detected. These findings are a highly important confirmation that seismological data acquisition and processing for the purpose of Ground Motion analysis is robust and reliable.
2. The report nicely established 'state of the art' in network seismology by bringing together a range of published quality criteria and procedures and best practises from different networks. These are generically useful and well-reasoned overall, and a widely useful read for network operators around the world. The report could have done a better job in sub-dividing the general parts from the Groningen applications. There is also the added complexity that networks grown with time under various constraints, they are hardly ever designed from scratch with best practise in mind. Therefore, some of the deviations from best practise in the Groningen network, as pointed out also by KNMI, were unavoidable and sometimes sensible. The report could have benefitted from a more in-depth discussion with KNMI during report writing to incorporate these considerations in the writing. This would, however, have impeded on the independence of the evaluation, an important goal, so on balance the way best practise is compared to Groningen is a useful result and reference document.

3. The report makes wide range of suggestions for changes to procedures, and these are highly valuable results that will influence in a multitude of ways operational and data analysis procedure and ultimately increase the quality of the Groningen seismic data. KNMI has already started to implement some of these procedures and hopefully more can be considered in the medium term.
4. The report also reviews the data to be used in GMM, confirming the quality of the record overall, reproducing the GMM V6 database, but also making some specific suggestions for post-processing and use. These seem overall sensible and should be made available to researchers that build future GMMs (e.g., GMM V7).
5. A specific suggestion regards excluding events with a presumed larger location uncertainty. This suggestion may have a significant effect on the GMMs, because it would exclude a substantial fraction of the events from the analysis. Depth uncertainty may be less relevant in this specific case, given that the depth range on known and well-located events is relatively narrow. It is also true that location uncertainty may not so relevant for GMM and is at least partially considered in the derivation of GMM. It would be useful to perform first of all sensitivity analysis on the relative importance of location uncertainty within the GMM derivation (which may have already been done?), and if this uncertainty turns out to be significant, then extra efforts are warranted to better constrain and homogenise the estimations of location uncertainty.
6. The final section of recommendation is useful and visionary in parts and can serve as input to KNMI for developing the network and analysis procedures in the next years.

In summary, the report documents a rich array of results at a high technical level and for different stakeholder.

#### **KEM interpretation of the outcome**

The outcomes of KEM11b, Phase 2a, are potentially valuable to different stakeholders:

- 1) **SoDM/EKZ and in general regulators:** The results are an independent check by a highly qualified team on the KNMI networks and GMM databases. The confirm evaluation by other groups that have investigated irregularities in network settings and overall confirm that the issues are understood and corrected, and likely based on honest mistakes that in one way or another can indeed happen in many seismic networks. The analysis also checked on numerous other potential problem areas and found none of any significance a very comforting finding. This does of course not absolute guarantees that not in the future new significant issues can be detected, but the chances are significantly reduced.
- 2) **The public, media or politics** may find the overall conclusions discussed in 1) also comforting and ideally this can be a small contribution to restoring trust in the seismic monitoring and risk assessment, and the involved institutions, in particular KNMI.
- 3) **KNMI** benefits in multiple ways, not only by a positive overall review but even more so by the numerous suggestions and recommendations. To take the maximum benefit from this review, it would be helpful if KNMI formulates a detailed response and roadmap that discusses the suggestions made. This should go beyond the short summery comments but clearly outline how the recommendation can be considered (and justify why they cannot in all respects). Moreover, this work may help KNMI as a basis in establishing a quality assurance and SoH (state of health) protocol for the data acquisition in Groningen.
- 4) **TNO**, as the newly responsible agency for the Groningen Seismic Risk Assessment Model, can benefit from the report in the sense that it provides detailed background on many of the relevant data for building GMMs, and suggestions for improvements and further studies in the domain of GMM.
- 5) **Scientists** overall would benefit from the detailed analysis as background for their own studies of ground motions etc, and many future studies can refer to this evaluation for clarifications and hence reduce the chance of errors.
- 6) **Other seismic networks** may benefit from the general recommendations and good practise examples.

In order for these results to have a positive impact, it is important that the report is made openly available.

#### **Closure text for the website**

The research question had, as a subject, the seismic data acquisition and processing in Groningen, which is the key input for seismic risk assessment and management in the region. The work has been undertaken by a leading European institution on the matter of seismic monitoring.

The quality of the investigation is judged to be excellent and the results, discussed in more detail below, are important for a number of stakeholders. The report and analysis thus are entirely consistent with the requirement for a KEM high-quality product. The final report delivers a wide range of important results that should not be undervalued because they are overall quite technical, and detail-oriented in nature. For instance, the report makes wide range of suggestions for changes to procedures, and these are highly valuable results that will influence in a multitude of ways operational and data analysis procedure and ultimately increase the quality of the Groningen seismic data. KNMI has already started to implement some of these procedures and hopefully more can be considered in the medium term. The report also provides interesting suggestions to better calibrate the GMM component model of the seismic and hazard risk model train.

The provided results are considered excellent and useful for regulators, KNMI and the public as an independent point of reference for quality assurance of current and future developments of the Groningen seismic monitoring system. In order for these results to have a positive impact, it is important that the report is made openly available.