

KEM Research review, evaluation and interpretation (max. 4 pages + annex)
KEM-36 Continuation of KEM-04 on data driven study on 3D seismic structural features

KEM Quality review

Description of the scientific quality of the results (team, research method, research results, quality of the products, ...), if needed external review result (project evaluation text website)

The activities of KEM36 were developed by the same competent team of KEM04, which includes Seister and Politecnico di Milano (Italy). The work was related to four main topics addressed in two phases:

1. Analysis of the improvements of the ground motion model (GMM) for Groningen, in its V7 version with respect to previous version.
2. The investigation of some issues persistent in the GMMs developed for Groningen so far, especially the underestimation of the models with respect to recorded data at short vibration periods.
3. Based on physics-based earthquake simulation, the evaluation of the feasibility that major earthquakes occurring in the area can be constrained in the reservoir.
4. Modelling of (vibration) period-to-period correlation in ground motion used in hazard analysis, and alternative modelling from earthquake physics-based simulations for the Groningen region.

Similar to the KEM-04 project, KEM36 was a successful project delivering results useful to gather a deeper understanding the current capabilities and limitations of the seismic hazard and risk assessment for Groningen, and to highlight issues that need further attention. The quality of the product is high such that at least topics 2 and possibly 3 or 4 might be susceptible of international scientific journal publication.

KEM Evaluation of the results

Evaluation whether the research questions are addressed adequately (questions answered, precision and uncertainties on outcomes, potential consequences on current practice addressed, ...) (project evaluation text website)

The main results of KEM 36 can be summarized as follows:

1. The GMM V7 represents an improvement of previous versions in several aspect although several issues remain, for example the underestimation of PGA and short period spectral accelerations with respect to data on which the GMM was calibrated. This has been a persistent problem with the GMMs developed for Groningen, but it could now be corrected relatively easily.
2. In depth investigation of the underestimation issue led to conclude that amongst several potential issues that could explain the underestimation, the most likely one is related to an inappropriate approach to compute response spectra in the very specific case of Groningen for which the input motion at NS-B level is very rich in high frequency, and the usual integration time step (0.005 s) proves to be unsuitably large.
3. Physics based simulations of occurred and hypothetical events led to conclude that confinement of sources in the reservoir is not the most likely option (at least on the basis of the current, limited knowledge of source parameters for such highly elongated sources) based on agreement with observed data, and that GMM V7 results grossly agree with the simulation results for larger (unobserved) earthquakes.
4. The correlation model used in GMM V7 could be not optimal with respect to its application at NS_B and considering the partially ergodic ground motion modeling approach adopted.

KEM interpretation of the outcome

The interpretation of the results (consequences on methods/data to be used in practice, on risk instrument modules, on inspection procedures and operator procedures, ...) (project evaluation text website)

The results of KEM 36 had the following consequences of direct or indirect relevance for the SHRA for Groningen:

1. GMM V7 is a model to adopt in SHRA for Groningen, as it generally represents an improvement of previous versions. It is also recommended that all the hazard and risk results (e.g., hazard maps and ShakeMap) of the Netherlands are all carried out with the same GMM implementation.
2. An interlocution between EZK and NAM has started in July 2024 to possibly finally identify the causes of the underestimation issues in GMM V7 (and previous).
3. The physics-based simulations provide insights especially in the nonlinear modelling of propagation in the Groningen region and may help to further elaborate on the location of source of future, relatively large, earthquakes in the region.
4. The results on period-to-period correlation modelling in GMM V7 are useful for further hazard modelling in Groningen; nevertheless, it is to note that the research question originally posed was intended also with respect to the consistent modelling of period-to-period correlation between hazard and vulnerability (structural) fragility modelling. Something that was not investigated in KEM 36.

Closure text for the website

A summary in simple terms of the goal, the outcome and impact on mining policies or toolboxes of the research project (project evaluation text website)

KEM 36 provided an independent assessment of various aspect related to ground motion modelling at the state-of-the-art for Groningen, related to GMM V7, which is one of the key components of the hazard and risk assessment of the region.

The work carried out and reported in **chapter 2** of the report finally provides a solid hypothesis to explain the underestimation of the amplitude of high-frequency (and short-distance) seismic motions in the GMMV7 model. Chapter 2 shows convincingly and didactically that the method used to compute the amplification factor (and more particularly the response spectra at base and surface levels) plays a role in the predicted level of amplification because of the unusually large high-frequency content at the reference NS_B level (very low κ_0 value). This is a major result, as the influence of the choice of the computation method (and also sampling frequency) had never been discussed or evoked previously by the NAM expert group or our sub-panel.

The 3D physics-based numerical simulations are improved and reported in **chapter 3**. It is first shown that a simulation with rupture on an elongated fault exclusively contained within the reservoir does not reproduce the observations for a past magnitude 3.4 earthquake. This conclusion however is conditioned on assumptions imposed by a) the limited knowledge on the source parameters of such peculiar geometries (constant slip, constant local rise time consistent with usual scaling relationships) and b) the 12 Hz high-frequency limit of limitations: a much smaller local rise time would probably lead to corner frequency and stress drop values more consistent with the observations. Nevertheless, for the case of a Mw4.5 event, simulations with such elongated ruptures are compatible with GMMV7 modelling. In the second part of chapter 3, the authors show the first results of models that take plastic non-linearity into account in 3D propagation models (SPEED-NLP). Such development is a major achievement in the engineering seismology field. The results show that such models have a significant impact on maximum high-frequency vibrations (20-30% reduction) for a magnitude 4.5 earthquake. Such a decrease is not observed when conventional models (Linear Equivalent) are used in 1D modeling, which is an important result.

The period-to-period (p2p) correlation model in GMM-V7 are discussed and reported in **chapter 4**. The authors analyze the data from 11 earthquakes and evaluate p2p correlation by separating the within-event residuals into site-to-site and single -site component. They show that present physics-based simulations overestimate (as expected) p2p correlations among sites. The authors conclude that the procedure adopted in V7 could be improved and suggest to replace the BJ08 model by the Kotha et al. (2017) model (to use correlations models specifically developed for between-event and single site residual) and test the impact of these models on risk. Such suggestion makes sense given the fact that the correlation of different residual components may be controlled by different physical mechanisms.

Chapter 5 Chapter 5 summarizes the main outcomes of the KEM36 investigations in relation to the main initial requests. The conclusions are sound with respect to all the KEM-36 findings and it is recommended they are considered for any further application and/or evolution of the GMMV7 model.

The reviewers do have the following recommendations or comments for future work:

- 2..1 The value of the sampling frequency used by NAM should be verified by contacting the authors of the GMMV7 model.
- 2.2 Some details or explanations are still missing or could be improved at some places in the report, but do not affect the main conclusions.
- 3.1 The use of this new non-linear plastic model has a strong impact on the amplitude of high-frequency movements for a moderate earthquake (Mw=4.5). To our knowledge, such non-linearities have not (yet) been observed/detected for such moderate earthquakes. This also means that even greater effects are expected for strong earthquakes (M=5.5). A test of the method on recent earthquakes would be very important to validate these calculations.
- 3.2 The fact that the method leads to larger decreases in 3D compared to 1D calculations (difference between Figure 3.18 and 3.17) is an intriguing, potentially very important result. This shows the limits of 1D calculations (whatever the method) and that the main choice is not only in the method (or the constitutive law) chosen for the non-linear calculation but rather in the possibility of performing NL 3D calculations. It would also be useful to understand the origin of such larger NL effects in 3D simulations.
- 4.1 This analysis should be presented/discussed with TNO, in order to consider the possibility of developing a "Groningen-specific" p2p correlation model based on the available recordings.
- 5.1 Would any source / hazard / consequence / risk model need to be developed for similar induced seismicity purposes, it is recommended to take advantage of the KEM-36 and NAM experience to carefully think about some important initial options for these models:
 - Hazard definition: response spectra or Fourier domain? The sensitivity (and in some cases inaccuracy) of the site amplification factor (AF) to be applied on response spectra, to the calculation method in case of high-frequency input motion, and their sensitivity to the earthquake scenario is a source of additional complexity in the hazard model. Deriving the hazard model in the Fourier domain could help to avoid some of these complexities (not all of course...)

- The issues related to the p2p correlation models are rather complex and uneasy to solve when local data are relatively rare. The consequences of p2p models are especially important when the final hazard is specified in a single scalar term (here SA_{avg}). Once again, some of the complexities might be avoided by keeping a vectorial description of the hazard and specifying vulnerability / fragility as a function of the spectral content at the vibration period of the considered structure. This would also offer the advantage of better accounting for the actual site amplification at the considered period, instead of averaging it over a wide period range.

In conclusion, the project successfully addressed all research questions, except the consistency of period-to-period correlation between hazard and vulnerability modelling. Its results are expected to have an appreciable impact on SHRA in terms of possible revision of GMM V7, period-to-period correlation, and source location. The quality of some of its results is such that international scientific journal publications are expected. The quality of some of its results is such that international scientific journal publications are expected.