Data driven study on seismic structural features of Groningen ground motions (KEM04/ IUC201804097)

Final Report |

1018-0338-000.R03/OD 01 | 14 July 2020

Ministry of Economic Affairs and Climate Policy

Document Control

Document Information

Project Title	Data driven study on seismic structural features of Groningen ground motions
Document Title	Data driven study on seismic structural features of Groningen ground motions (KEM04/ IUC201804097)
Fugro Project No.	1018-0338-000
Fugro Document No.	1018-0338-000.R03/OD
Issue Number	01
Issue Status	Final

Client Information

Client	Ministry of Economic Affairs and Climate Policy
Client Address	Procurement Office, P.O. Box 93144, 2509 AC THE HAGUE
Client Contact	Mr. P. Jongerius
Client Document No.	KEM04/ IUC201804097

Revision History

Issue	Date	Status	Comments on Content	Prepared By	Checked By	Approved By
01	14 July 2020	Final	After internal and external review	Team	Reviewers	OD

Project Team

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HG	Hanzehogeschool Groningen	Team member
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1. Introduction

Fugro has been commissioned by The Dutch Ministry of Economic Affairs and Climate Policy to perform a study for the Knowledge Program on Effects of Mining. This program, called KEM (www.kemprogramma.nl) addresses the recommendations of the Dutch Research Council for Safety (OVV) and aims at enhancing the understanding of hazard and risk of mining activities in The Netherlands. The KEM04 team was composed by specialists from multiple and international institutes from academic and private sector and covering various disciplines. The KEM04-team consisted of the following companies/institutions Fugro, Seister, Politecnico di Milano, CM Consult, GR8-Geo and Hanzehogeschool Groningen.

The objective of the KEM04 project is to better understand characteristics of induced earthquakes and especially the non-uniform propagation of seismic waves from the causative seismic sources to the surface in Groningen and to identify possible modelling improvement strategies of the vibratory ground motion. Available data from the seismic network is being used for 3D seismic simulations.

The study involves the following research questions, as specified by the client:

Research question 1: Analysis of the 3D features of the Groningen earthquakes wave fields with respect to engineering demand parameters relevant to seismic risk assessment in the area.
Evaluate quantitatively the Groningen risk assessment model in terms of 3D features of ground motions considered and their impact on the seismic structural response at multiple sites. The analysis should include structural models relevant for the area even at the Single Degree of Freedom (SDoF level) and benchmark analysis.

Research question 2: Wave propagation through heterogeneous media.
Develop a 3D heterogeneous wave propagation model for the Groningen area based on the rich existing geological, geophysical, geotechnical and seismological data and including the shallow subsurface. The model should use open-source software frameworks. The model should be able to reproduce the observed key features of the observed seismicity up to frequencies of 5 Hz. It should be used to address some of the key issues addressed before, and allow for scenario and sensitivity studies. Some of the specific questions can include, for example:

- What is the effect of Zechstein Salt Formations of variable depth and shape on the seismic wave propagation and observed ground motions?
- Can the model reproduce the observed relationship between signal frequency and duration of S waves, which influence the seismic demand?
- Discuss the relative importance of topography and near surface geology heterogeneity for variations in wave propagation and ground motions for seismic demand analysis at multiple sites.

Research question 3: Improving ground motion predictions.

- Based on result of questions 1 and 2, review the existing NAM models and comment on possible future improvements and data requirements.
- Discuss potential implications for seismic structural assessment.
- Discuss if simulation-based frameworks based on 3D wave propagation in heterogeneous media are a viable alternative to the existing ground motion prediction equation (GMPE) framework.

The study was performed independently, according to the instructions from the client. Only after presenting our findings to the client, meetings were organized to interact with external experts from KEM02 and NAM.

The data that was used as input for the study and the data-files that were made by the KEM04 team have been made accessible to the client digitally. Because of the amount and size of the data this has been organized separately.

During the study, a number of additional tasks was added to the original scope:

- After discovering irregularities in the original input data for the study, a corrected data-set was used
- For sensors, installed in buildings, the data was validated (see Report C)
- Study on the effect of nonlinear response was (see Report E)

Table 1.1 provides an overview of the technical reports that make up the deliverable.

Table 1.1: Overview of technical reports

Technical Report No.	Title	Report
Report n° STR_18P17_04	Project overview and recommendations (Research Question 3)	Report A
Report n° STR_18P17_02	Research Question 1: Specific ground motion features from data analyses and simulations using empirical Green's functions	Report B
Report n° STR_18P17_01	Analysis of consistency between B- and G-stations records for induced events in the Groningen gas field	Report C
Report n° STR_18P17_03	Research Question 2: 3D simulations of seismic wave propagation from induced events in Groningen.	Report D
Report n° STR_18P17_05	One dimensional nonlinear site response analyses	Report E

The KEM04 study resulted in the following additional work, which was done outside the KEM04 scope, but the KEM04 study did benefit from this work:

- 1018-0338-001 version 2, 2nd May 2019: Quality check of KNMI accelerometer network, for SSM
- 1018-0338-210 version 1, 20th May 2019: Geotechnical site investigation (SCPT’s), for SSM and MEA
- Validation and development of empirical CPT-Vs Correlations using a data analysis on a SCPT data set, 11th February 2019- 5th April 2019, Johan Schuringa, Fugro/TU Delft
- 1019-153172_21.KR01 revision 2, 26th November 2019: Geotechnical site investigation, Seismic CPT’s KNMI G-stations Groningen, for NAM

Report A

Report n° STR_18P17_04

Project overview and recommendations (Research Question 3)

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Glossary

Arias Intensity is a ground motion parameter calculated as

$$AI = \frac{\pi}{2g} \int a(t)^2 \, dt$$

where $a(t)^2$ is the acceleration time history.

CAV (Cumulative Absolute Velocity) is a ground motion parameter defined as the integral of the absolute value of the acceleration time series, is represented mathematically by the equation:

$$CAV = \frac{\pi}{2g} \int |a(t)| \, dt$$

where $|a(t)|$ is the absolute value of the acceleration time history.

CPT: Cone Penetration Test

EGF: Empirical Green's Function.

FAS: Fourier Amplitude Spectrum.

Flatfile: a flatfile is a file where a dataset is stored in the form of a parametric table. The table contains metadata and ground motion intensity measures of the dataset under consideration.

GIT: Generalized Inversion Technique**.**

GMIM: Ground Motion Intensity Measure.

GMM: Ground Motion Model.

GMMV5 is the Groningen Ground Motion Model Version 5 published by NAM in the report by Bommer et al. (2018) available from the NAM portal.

HRA: Hazard and Risk Assessment.

KEM: Knowledge Programme on Effects of Mining.

L1, L2, L3, L4 represent the 4 branches of the ground motion logic tree accounting for epistemic uncertainties in stress drop. This specifically refers to the GMMV5. L1 is the model assuming the lowest stress drop and L4 is the model with highest stress drop.

ML: local magnitude**.**

MaEA: Major effort action

MoEA: Moderate effort action

Mw: moment magnitude.

NS_B is the base of the North-Sea group formation in the Groningen geological model.

PGA (Peak Ground Acceleration) is the maximum of the absolute values of the acceleration time history.

PGD (Peak Ground Displacement) is the maximum of the absolute values of the displacement time history obtained from double integration of the acceleration time history.

PGV (Peak Ground Velocity) is the maximum of the absolute values of the velocity time history obtained from integration of the acceleration time history.

PSHA: Probabilistic seismic hazard assessment.

RQ1: Research Question 1 of the KEM04 project

RQ2: Research Question 2 of the KEM04 project

RQ3: Research Question 3 of the KEM04 project

SCPT: Seismic Cone Penetration Test

SGF: Synthetic Green’s Function.

SNR: signal-to-noise ratio

SodM stands for “Staatstoezicht op de Mijnen” which is The Dutch State Supervision of Mines (SSM)

SPEED (SPectral Elements in Elastodynamics with Discontinuous Galerkin) is an open-source code designed with the aim of simulating large-scale seismic events in three-dimensional complex media. It is used in the RQ2 of KEM04.

SPT: Standard Penetration Test

SRA: Soil Response Analysis

V/H: Vertical to Horizontal ratio

Vs: shear-wave velocity

Vs30 is the shear-wave velocity averaged over the top 30m of soil.

1. Introduction to KEM 04

1.1 Project's objectives

During the last decade, the gas production induced seismic activity in Groningen increased and became a real concern for the population, for the gas-field operator and for the local and national authorities and institutions.

After the occurrence of the ML 3.6 Huizinge earthquake of August 16 2012, an ambitious project was launched to conduct a full Probabilistic Seismic Hazard Assessment (PSHA) for Groningen, as required by the regulator (Dost et al., 2017). The event, largely felt by the population, triggered an immediate reaction to urge the gas field owner to carry out seismic hazard and risk analysis on the existing built environment. In parallel to the PSHA, extensive studies were conducted amongst others, to develop appropriate fragility curves for the different building typologies prevailing in the Groningen area. The outputs of the PSHA and vulnerability studies were then used as input data to develop the Groningen risk assessment model (Van Elk et al., 2017).

The risk assessment project was structured around sub-projects scanning the seismic risk analysis chain: the seismic hazard assessment focusing on components tailored to account for induced seismicity (seismic sources model, seismic activity parameters, ground motion prediction equation suitable for the Groningen area), the seismic behavior of structures and components of the build environment, the seismic risk and safety assessment.

A shallow subsurface modelling campaign (Kruiver et al., 2017) and dedicated studies to reduce the uncertainties in the ground motion estimates helped to refine a local ground-motion model for the Groningen area (Bommer et al., 2017b; Rodriguez-Marek et al. 2017) used to conduct risk-assessment analyses.

At the same time, due to the general concern generated by the induced seismicity, several questions were identified regarding the robustness of the predictive seismic hazard model like its ability to address specific structural features (such as the salt domes) and their effects on ground movements. The Ministry of Economic Affairs and Climate Policy decided to launch, among a series of technical studies within the KEM programme, a dedicated data driven study on seismic structural features of Groningen ground motions, hereafter referred as the KEM 04 project.

Any seismic risk model has three components: the seismic hazard model for induced seismicity needs as inputs a seismicity model described by the geometry of the seismic sources and their activity rates and a ground motion model (GMM) describing the propagation of the seismic energy between the sources to the surface; the third component is related to the vulnerability of the building of the area and to the fragility curves defined as function of parameters that characterize the noxiousness capacity of the ground motion at or near the surface.

The KEM04 project has focused on the research questions which are fundamentally related to the ground motion component mentioned above. The main objective was not to develop an alternative ground motion model nor to conduct a critical review of the current Groningen GMM, but rather to test alternative methodologies to predict ground motion features generated by the induced seismicity and to investigate the potential impact of 3D geological features not considered in the current GMM.

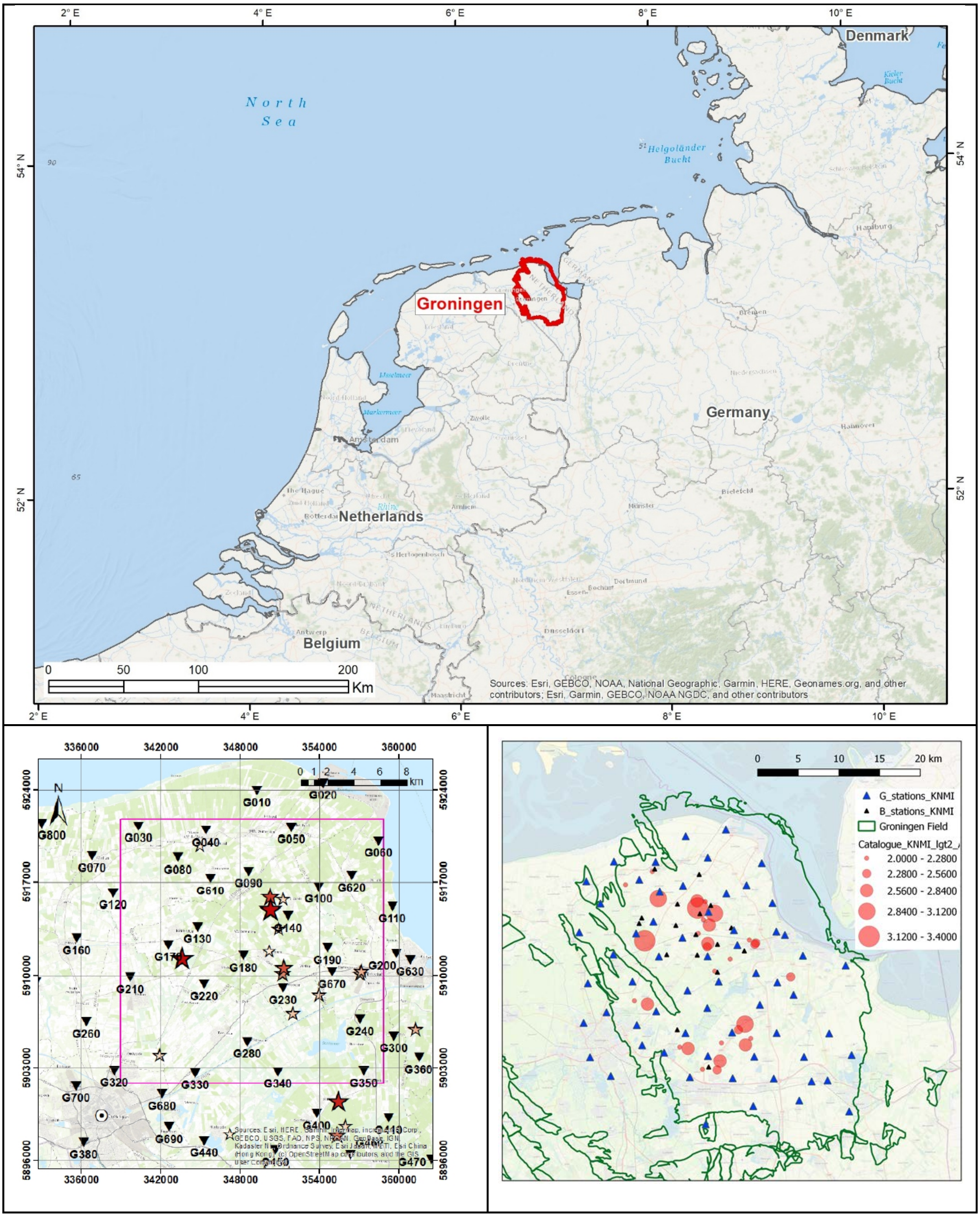

Figure 1-1 : Top: Groningen area relative to the Netherlands / NW-Europe. Bottom left: Location of the numerical model developed in RQ2. black triangles are recording stations of G network maintained by KNMI. Bottom right: area considered to generate the RQ1 flatfiles. Triangles are the B and G stations. Red dots are induced events with ML≥2 that occurred after 2013.

Overall these investigations were conducted to appreciate how the ground motion component could be improved based on potential findings when:

- Using data-driven approaches to investigate features of recorded ground motions
- Analyzing the comparison between the predicted ground motion using the GMM and the recorded ground motions;
- Exploring the ground motion characteristics conducting 3D simulations of the ground motions.

As such, the specific objectives of the KEM04 project were:

- To better understand the characteristics of induced-earthquakes ground motions due to area-specific 3D geological configurations in the Groningen area (Figure 1-1, right), through the analyses of recorded data (addressed in research question n° 1) and simulations (addressed in research questions n° 1 and n° 2)
- To appreciate the performance of 3D numerical simulations of wave propagation in a 20 km² of the area (Figure 1-1, left) through complex media to identify if and how certain distinctive features, not addressed by the GMM, could impact the predicted ground motion at surface and at depth.
- To address the effect on the 3D wave field of geological and site-specific features identified so far, such as:
    - The topography of the Zechstein Salt Formations;
    - The topography and near surface geology heterogeneity.
- To identify if alternative approaches bring additional information and constraints to the ground motion modelling strategy adopted in Groningen.

The work conducted within the RQ1 sub-project had the following main objectives:

- To evaluate the performance of the GMMV5 based on a residual analysis between observations and predictions using data that were not considered for the GMMV5 development ;
- To analyze source and path characteristics of the ground motion parameters of the induced earthquakes recorded so far using a generalized inversion approach which also provided useful parameters for the implementation of the simulation methods based on Empirical Green Functions (EGFs) and on the 3D physics-based modeling of the wave field;
- To implement EGFs-based simulations for moderate events at surface and at depth using the records at the G network, as empirical green functions.

The activities conducted under the RQ2 sub-project are complementary and were conducted:

- To develop a simulation model able to estimate ground motion characteristics up to 10 Hz

- To analyze the impact of 3D geological features and heterogeneities on ground motion estimates :
    - Peelo glacial valleys,
    - Topography of the Zechstein
    - Spatial variability of the velocity profile
- To develop induced-earthquake scenarios and corresponding 3D-specific ground motion wave fields for horizontal and vertical components, for various depths, at any X,Y,Z location and to compare these with the GMM V5 predictions
- To allow for an inter-comparison of the predicted ground motions between full 3D physically-based models, Empirical Green functions simulations (RQ1) and GMMV5, and to identify how the ground motion component of the Groningen HRA could be further improved or modified to account for the potential ground motions from specific features identified.

1.2 KEM 04 Project's strategy

The partners of the KEM 04 project suggested research and development activities based on the use of physics-based models to study the vibratory ground motion component of the Groningen hazard and risk assessment (HRA) model.

The exploratory work aimed in particular at assessing whether the models based on simulations and modeling of 3D seismic wave propagation from the causative induced-earthquakes to the soil surface (or near-surface at the depths of the vertical array stations) were able to address the impact of the geological features prevailing from the gas field at depth to surface, on the ground motion characteristics and how the corresponding predicted ground motions compare with the GMM currently used in the Groningen HRA.

Two categories of methods have been considered:

- Those based on the exploitation of earthquake records. The deployment of seismic networks over time has indeed made it possible to acquire a remarkable database of empirical data, providing direct information on the propagation of ground motion between the places of occurrence of induced earthquakes at depth and inhabited areas at surface.
- Those based on a complete simulation of the propagation of waves between these same places and the surface.

The flowchart of the approach is described in Figure 1-2.

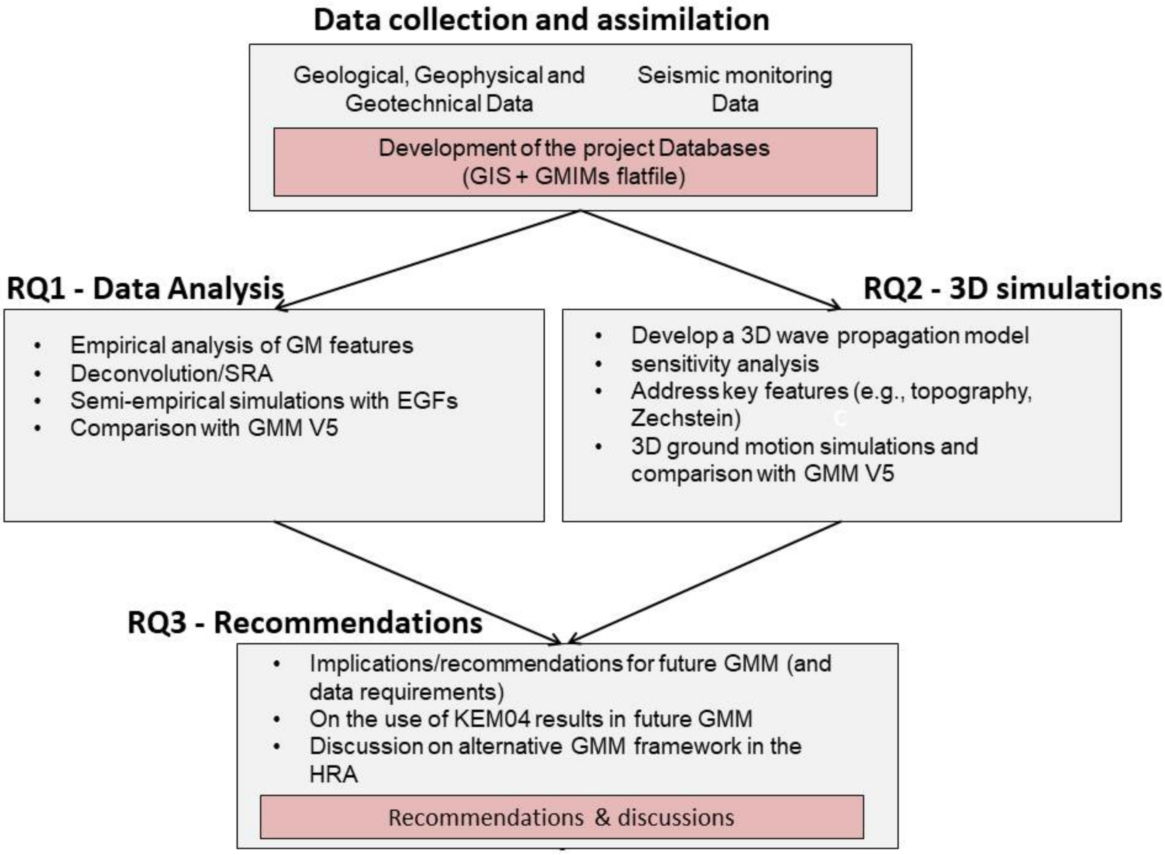

Figure 1-2 : Flow-chart of KEM 04.

Due to the respective schedules of the KEM 04 and NAM-GMM projects, the GMM version considered for conducting the comparisons is the GMM V5 (Bommer et al., 2017b), which was the version available at the time the project started. As the GMM development is a continuously evolving process, some of the findings specifically related to GMM V5 may be questioned if subsequent versions of the GMM would lead to significant changes in the ground motion predictions compared to those predicted by GMM V5.

All the comparisons which are presented in the KEM04 project documentation are thus relative to version 5. It will nevertheless be possible and relatively easy to reproduce these comparisons when any new version of the GMM model is published. It will also be easy to supplement the documentation in the future with new comparisons to these models, insofar as these bring notable modifications in the prediction of ground motion parameters, which could be the case with the GMM V6 published at the end of the KEM04 project (Bommer et al., 2019).

Although the research work was subdivided into two sub-projects (Research Question 1 and Research Question 2 later on called RQ1 and RQ2), the corresponding activities encompassed discipline interfaces so that they were conducted in parallel, with regular exchanges between the RQ leaders.

A preparatory work was necessary to develop the 3D geological model based on the abundant bibliography and reports made available and to prepare the flat-files (i.e., parametric Excel tables) into which the ground motion database was stored and all relevant parameters described. These preparatory works are respectively described in the RQ1 report for the project’s flat-file and in the RQ2 report for the 3D Geological model.

As part of the activities, regular technical meetings were organized between RQ1 and RQ2 teams to share the data and results and adjust the research activities. Meetings with the KEM02 research team and the NAM GMM team during the September 2019 NAM workshop on the ongoing development of the new GMM versions and during the NAM-KEM04-KEM02 December 2019 workshop, provided an invaluable opportunity to better understand the nature of the ongoing GMM improvements as well as to exchange on the technical issues raised during the respective projects and on progress achieved so far.

Regarding the 3D seismic wave propagation, the SPEED code (Mazzieri et al., 2013, http://speed.mox.polimi.it) was selected and used as the open-source numerical code to conduct the physics-based numerical simulations of seismic wave propagation.

The area of interest for the project was chosen to include a 3D geological model representative of the conditions prevailing in the agglomeration of Groningen, to contain the strongest earthquakes so as to benefit from calibration records, and to keep account for the SPEED calculation time constraints.

For SPEED simulations developed under RQ2, the 3D model covers a 20x20 km² area, including the geological subsurface layers down to a depth of 5 km (Figure 1 1, left) and involving a mesh size small enough to simulate the ground motion up to 10Hz. The requirement to benefit from high calculation capabilities was made possible thanks to CINECA, the largest supercomputing center in Italy. For RQ1 and the preparation of the ground motion database, the entire area was considered (Figure 1 1, right).

1.3 KEM04 project's team

The Research and Development (R&D) activities have been conducted by a multi-disciplinary team of academics (Politecnico di Milano - POLIMI, Hanze Research Group) and practitioners (FUGRO, SEISTER, GR8-GEO, Jongejan Risk Management Consulting, CMC International,) to address the complexity of the research questions. This team has experience in conducting seismic hazard and risk analyses in different regulatory contexts and seismotectonic environments and has industry-recognized expertise in the different disciplines involved in the research project: geology, seismotectonics, seismology, induced seismicity, geotechnics, ground motion database and records processing, analytical and numerical methods, dynamic soil response analyses, liquefaction, soil-structure interaction, engineering geo-solutions, software development and technical review.

The team organization chart is detailed Figure 1-3.

FUGRO has led the consortium and has been involved in the development of the 3D geological model that supported the idealized 3D model developed considered to conduct the 3D physics-based simulations (RQ2).

RQ1 activities have been conducted by SEISTER with the support of the Hanze Research Group that offered its experience of the recorded induced seismicity in the Groningen area.

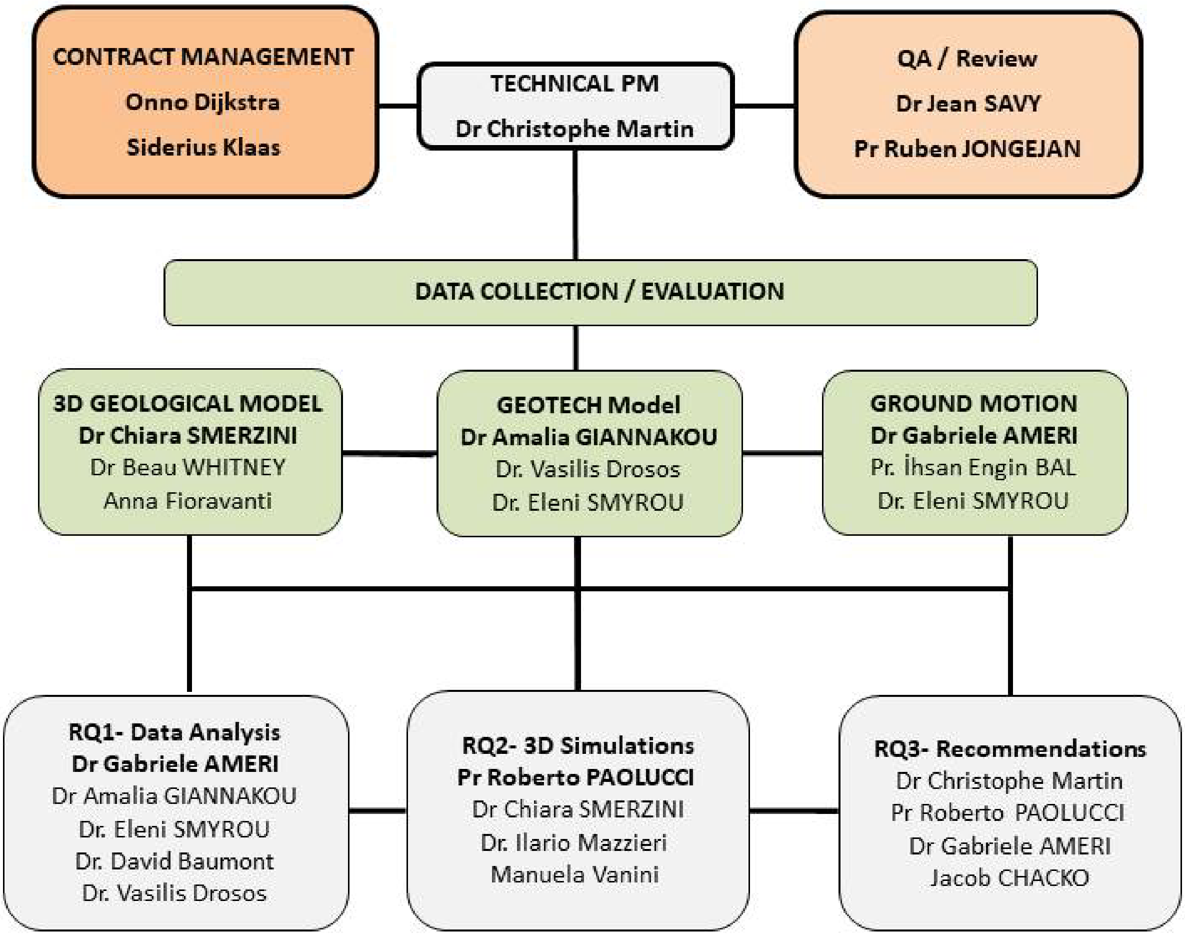

Figure 1-3 : KEM 04 Team organization chart

The activities developed under RQ2 have been conducted under the responsibility of the Department of Civil and Environmental Engineering at Politecnico di Milano. This academic group conducts research activities and industry-oriented projects and has developed the spectral-element based numerical code SPEED (http://speed.mox.polimi.it/), an open-source code that is used to conduct the numerical simulations of 3D seismic wave propagation within the Groningen area.

The technical project management was taken by Christophe Martin which assured the interfaces in between the RQ1 and RQ2 activities and arranged regular project meetings. Internal reviews of the research products and deliverables have been reviewed by Jean Savy having a strong experience in hazard and risk assessment and Ruben Jongejan having a strong background in the development of methods that are consistent with the requirements of Dutch codes and standards.

1.4 KEM 04 project's deliverables and reporting structure

The reporting framework adopted for the KEM04 deliverables is detailed in Figure 1-4.

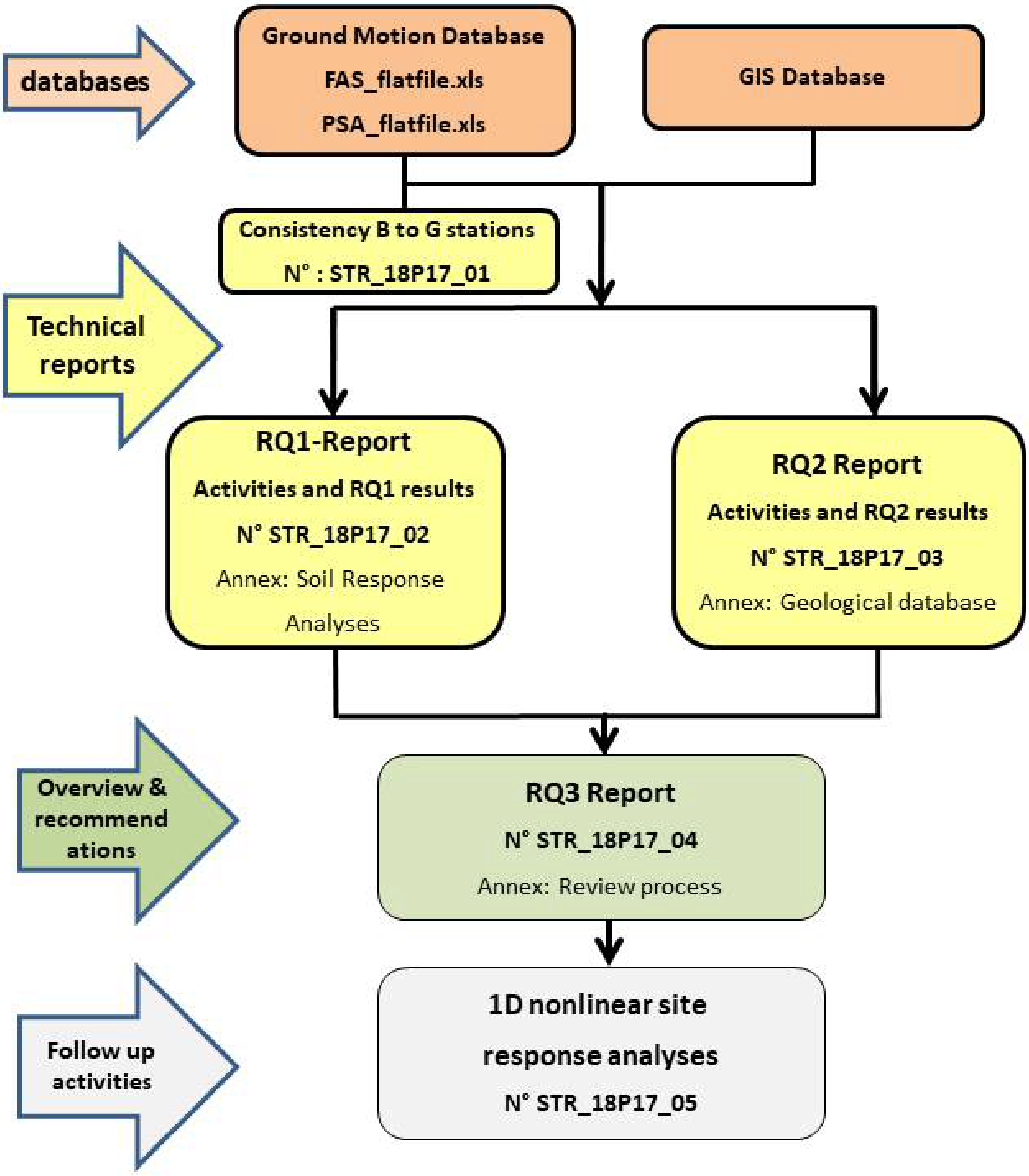

Figure 1-4 : KEM 04 reporting structure

The documentation has been designed so that the data analyzed and the databases generated by the project are traceable. These data (databases inFigure 1-4) are provided in digital form. Two databases have been prepared at an earlier stage of the project:

- The GIS database contains the digital elevation models of the geological units considered in the construction of the 3D geological model to conduct the physics-based simulations
- The ground motion database is made of two project's flatfiles:

- FAS-flatfile.xls includes the S-wave window smoothed acceleration Fourier Amplitude Spectra that were used to conduct the generalized inversions as the tools to determine key parameters useful for the simulations (RQ 1 report). The flatfile is made of 4 075 records from 23 events with magnitudes ML from 2.0 to 3.4, at epicentral distances between 1.15 km and 33 km, recorded at sensors located from top surface in free field to – 200m.
- PSA-flatfile.xls contains all the ground-motion intensity measures (GMIMs) used to conduct the data analysis and comparisons with the GMMV5 presented in the RQ1 report.

Other numeric deliverables like short movies refer to demonstrative results of 3D simulations with SPEED that have also been post-processed in a homogeneous format using specific post-processing tools associated with SPEED software. These tools allow generating ground shaking maps, snapshots of simulated wave-field and movies of seismic wave propagation in the target area that can be used for communication purpose.

The remainder of the documentation is prepared in the form of reports (Table 1-1):

- The technical reports related to the analysis of the recordings and of the coherence between networks B and G and to each of the research questions RQ1 and RQ2,
- The current RQ3 report which presents a summary of the project and the main recommendations arising from it
- A report corresponding to the achievement of one of the RQ3 recommendations to conduct 1D nonlinear soil response analyses, engaged toward the end of the project.

Table 1-1: List of reports.

Report N°	Content
In preparation	An "umbrella report" written in Dutch and English is in preparation as a communication document, summarizing the scientific works carried out within the KEM04 project and the results obtained.
STR_18P17_01	This report investigates the consistency of the seismic records at B and G stations that was a major concern identified at the beginning of the project and that led to the decision of avoiding the use of B-stations records in the continuation of the project.
STR_18P17_02	Report summarizing the activities conducted and the results achieved within the Research Question 1 (RQ1): • Ground motion data collection, processing and compilation of the project ground-motion flatfile; • Analysis and characterization of Groningen ground motions; • Evaluation of performance of GMMV5 based on independent data collected in the project; • Development of ground motion simulations adopting a complementary approach (Empirical Green's Functions, EGF) to the GMM V5 and to the

	physics-based simulations adopted in RQ2.
STR_18P17_03	Report summarizing the activities conducted and the results achieved within the Research Question 2 (RQ2): • Development of a 3D wave propagation velocity model for the Groningen area, including the shallow subsurface soil, based on the rich existing geological, geophysical, geotechnical and seismological data • Physics-based simulations of seismic wave propagation of selected induced earthquakes to reproduce the observed key features of the ground motion using the 3D numerical model and an open-source computational platform (SPEED) • Scenario and sensitivity studies to address specific questions, related to the effect of depth and shape of Zechstein Salt inclusions, to the effect of the heterogeneities of near surface geology such as the underground Peelo valleys, and to the ability to reproduce the observed features of recorded ground motion, such as peak values, frequency content and duration • Comparisons between simulated ground motions by EGFs, 3D Physics-based model and ground motions predicted with the Groningen GMM V5
STR_18P17_04	Report summarizing the activities conducted and the results achieved within the Research Question 3 (RQ3): • Based on the results exposed in the RQ1 and RQ2 reports, this report offers an overview of the project and suggests possible improvement strategies in GM modelling and recommendations for the evolution/improvement of the ground motion component of the Groningen hazard and risk assessment model as result of the RQ3 activities. • The RQ3 report identifies certain actions that would allow progress to be made in reducing the uncertainties associated to the ground motion prediction model. Insofar as these or part of them would be implemented, it will be possible to supplement the current documentation with a new study/action report to complete the "follow up activities" section of Figure 1-4
STR_18P17_05	This report presents the 1D equivalent linear and nonlinear site response analyses performed at five selected G-stations to compare conventional methods of estimating nonlinear site response with the results calculated using the EGF approach (RQ1) and the 3D physics-based simulations with SPEED (RQ2).

These recommendations detailed in the next chapters rely on the main observations and conclusions based on an inter-comparison of the RQ1 and RQ2 researches that are summarized in chapter 2. The RQ3 opens discussions on:

- Actions that would allow a better understanding of the origin of the differences between observations, the GMM predictive model and predictive models based on simulations
- Additional investigations or future research actions in ground-motion modelling for earthquake hazard and risk studies and notably actions that could be implemented to improve the ground motion component of the HRA or to implement the findings of KEM04 into an HRA perspective
- Potential consideration of EGF and 3D Physics-based simulations as complementary tools for the GM hazard assessment as component of the Groningen risk model.

2. Main lessons from RQ1 and RQ2 for the improvement of the ground motion model

One of the main results of the study is the remarkable similarity of certain observations and conclusions obtained by implementing comparisons between predictive models and recorded ground motion and using two fundamentally different methods (EGFs and SPEED simulations).

The comparisons explored in time and frequency domains, between the two simulations approaches and the GMM, evidence that the simulation approaches are very complementary to the GMM. They offer tools that are useful to address ground motion features due to the nature of the anthropic seismic activity and to geological features of the ground model, that are sometimes difficult to capture in a generic ground motion prediction equation used to implement probabilistic seismic hazard assessment.

A major interest of the approaches is to not only predict the peak values of the ground motion (PGA, PGV, PGD) and duration, but they are well appropriate to obtain a description in the time domain, for both the horizontal and vertical components. The time histories that can be generated from the simulation approaches could be used as direct inputs to the vulnerability studies.

The two next sections summarize the main outputs from RQ1 and RQ2 in the form of recap tables. The two first columns of each table identify and describe the main tasks conducted under RQ1 (Table 2-1) and RQ2 (Table 2-2). The third column summarizes the main observations and findings resulting from each research question and the last column identifies technical actions to improve the robustness of the ground motion predictions (reduction of uncertainties, robustness of the prediction). Based on this, the identified recommendations are described in detail in section 3. Irrespectively of which scientific team would execute the research work, the implementation of each action is intended to solve a pending issue, to better understand the origin of differences between predictions and observations, to decrease the uncertainties or to offer an alternative method to determine the ground motion component of the HRA.

2.1 Main outputs from RQ1 and implications for the ground motion model improvement

Table 2-1 presents a summary of the main activities conducted under RQ 1 and of the principal observations and findings from which sources of improvement of the ground motion component are identified. The reader is invited to consult the RQ1 report (STR_18P17_02) which offers complete technical justifications of this summary.

Table 2-1: Summary of the main RQ1 tasks, observations and findings and identification of actions to improve the robustness of the ground motion predictions and ground motion component of the HRA.

Item	RQ1 tasks	Main observations and findings. Consistency with RQ2 findings	identification of actions to improve the robustness of the ground motion predictions
1	Preparation of the GM databases	- Identification of inconsistencies between B and G stations. - Attenuation of high frequencies at B stations. - 2 Flatfiles where records are described by various GMIMs, available for a wider scientific community to conduct additional treatments or statistical analyses	- Investigate if attenuation of high frequencies at B stations has an impact on GMM versions posterior to V5
2	Evaluation of GMM V5 with the project flatfiles through a residual analysis	- Short-period spectral ordinates particularly at short distances (<5km) are underestimated by the median GMMV5 (also observed in RQ2 simulations)	- Verification if posterior versions of GMM (e.g., V6) show a similar trend. Additional comparisons with GMM V6 or subsequent versions (also use any new recordings) to confirm if observed trends from RQ1 &2 are the same - Better understand if a potential bias is introduced in V5 and posterior versions due to potential issues at B stations (sensors installations conditions, SSI). - Better investigate the origins of the bias at short distances
3a	Estimation of source and attenuation properties using non-parametric generalized inversion technique	- Fast attenuation of ground motion in Groningen confirmed in the first few kilometers. Rather good agreement with GMMV5. Greater difference for distance > 10km - No significant difference in attenuation properties between North and South of the Gas field	- Verification of the attenuation function in the posterior version of the GMM in the 10-15 km distance range
3b	Estimation of source and attenuation properties using non-parametric generalized inversion technique	- Inverted stress drop values relatively low compared to stress drop values from tectonic events. Consistent observations from comparable induced events. - Stress drops on average lower than in GMMV5. - Clear frequency-dependent rupture directivity for half of the events	- Verification if posterior versions of GMM (V6, V7) show a similar trend. - Appreciate the implications of stress drop differences w.r.t GMM-Vx - Investigate how source directivity could be better accounted in new GMM version: rupture directivity responsible for spatial variation of GM due to a source process. - In link with the seismicity model (production/depletion model) conduct scenarios based GM assessment
4	Analysis of V/H ratio	- V/H models for tectonic events not transposable to Groningen induced events at short hypocentral distances	- If relevant for the building stock or infrastructures, develop a GMM for the vertical component
5	GM validated Simulations using the EGFs approach (Zeerijp event)	- Demonstration of the relevance of the method for predicting GM (capturing path and site effects). Consistency with RQ2 physics-based simulations. - Poor agreement with GMMV 5 at short distances (underestimation of peak values).	- Offer a calibration approach of the GMM at short distances (small magnitudes). - EGF method relevant to conduct scenario-based ground motion assessment - EGF approach coupled with SGF for integration in a PSHA framework offering an alternative approach to conduct seismic hazard assessment.

Item	RQ1 tasks	Main observations and findings. Consistency with RQ2 findings	identification of actions to improve the robustness of the ground motion predictions
6a	GM blind Simulations using the EGFs approach for magnitudes higher than Mmax Obs (up to Mw 5). Surface conditions.	- Relevant approach for GM prediction with consideration of epistemic uncertainties on various parameters. - Good agreement with RQ2 physics-based simulations. - Limitations due to potential nonlinear effects in the upper 50 m. - Peak values on average larger than GMMV5, higher is the simulated magnitude. Consistency with RQ2 physics-based results.	- Requirement to better understand the development of nonlinear effects in the soil profile. (G0 to G4 stations). - Exploration of the reasons of the discrepancies with GMM V5. Verification of the trends observed when considering posterior versions of the GMM. - Possibility to use the EGF in the development of scenario-based GM assessments.
6b	Coupling of EGF approach with Soil response analysis.	- Nonlinear soil response in Groningen mostly related to large strains developed in the shallow-most few tens of meters. - To overcome the limitation of nonlinear effect in the EGF approach for large events, coupling EGF simulations at depth (using borehole EGFs) with 1D nonlinear soil response for shallow layers, is relevant.	- Requirement to better understand and consider the development of nonlinear soil effects in the upper part of the soil profile. - Requirement to explore the feasibility to develop the GMM at a horizon where nonlinear effects are not suspected.
6c	GM blind Simulations using the EGFs approach for magnitudes higher than Mmax Obs (up to Mw 5). NSB conditions (rock).	- Relevant approach for GM prediction with consideration of epistemic uncertainties on various parameters. - Better agreement with GMMV5, still for the branch of higher stress-drop value of the GMM.	- Development of EGF simulations at -50 or -200 where nonlinear effects are not suspected can offer additional constraints for the development of the GMM-Vx - Coupling EGF simulations at depth and implementing SRA, based on the new acquired SCPTs can provide useful dataset to better constrain the new GMM. - Explore the feasibility to extent the EGFs set to small magnitudes to predict the GM. - Feasibility to exploit a greater number of EGFs of smaller magnitudes than Mmax observed to develop ground motion maps (coupling with SGF from RQ2). - Development of Scenario-based GM maps - Integrate the EGF/SGF as a complementary approach of GMM in the PSHA.

2.2 Main outputs from RQ2 and implications for the ground motion model improvement

Table 2-2 presents a similar summary for the activities conducted under RQ 2. Detailed technical justifications of this summary can be found in the RQ2 report (STR_18P17_03).

Table 2-2: Summary of the main RQ2 tasks, observations and findings and identification of actions to improve the robustness of the ground motion predictions and ground motion component of the HRA.

Item	RQ2 tasks	Main observations and findings. Consistency with RQ2 findings	Implications for the identification of improvement factors of the ground motion model
1	Development of the 3D physics-based model and validation with real records (Zeerijp event)	- Model relevant to reproduce observations in a large area (20 km x 20 km) and up to 10 Hz, Horizontal and vertical components. - Capability to generate ground motion maps and time-histories of the horizontal and vertical components at any location of the modelled area.	- Possibility to conduct scenario-based GM predictions for any induced earthquake consistent with the source model - Requirement to conduct sensitivity analyses and perform additional treatment of uncertainties for a better evaluation of the ground motion range.
2	Wave propagation singularities related to 3D source-path and complex geological features effect of Peelo Valleys;	- Negligible effects, small aspect ratio heterogeneities and small impedance ratio. Contribution to GM variability limited to few percent.	

Item	RQ2 tasks	Main observations and findings. Consistency with RQ2 findings	Implications for the identification of improvement factors of the ground motion model
3	Wave propagation singularities related to 3D source-path and complex geological features effect of Zechstein salt dome inclusions	- No impact when only small irregularities are tested. - Large amplification effects observed for sharp topography. Such effects cannot be accounted by a generic GMM.	- Perform additional scenarios using SPEED (Location / Distance / Azimuth / Size) to better account for uncertainties both in the EQ scenarios and the 3D propagations effects. - More systematic analysis of the potential 3D effects to identify zones where an aggravation factor could be considered - Quantification of an aggravation function that could be applied to the GMM in areas prone to this 3D site-specific effect.
4a	Wave propagation singularities related to 3D source-path and complex geological features simulation of a Mw5 scenario, and quantification of non-linear soil response effects in 3D	- Capability to develop GM estimates (Maps, Peak values, time histories, horizontal and vertical components) at any point of the 3D model - Possibility to determine V/H ratios (consistent with RQ1 results). - Near source effects consistent with RQ1 residual analysis and EGFs simulations	- Production of GM maps for scenario-based induced scenario considering finite-fault models consistent with the seismicity models - Additional constraints to calibrate the GMM at short distances: SPEED and EGFs numerical tools efficient for earthquake ground motion simulation in near-source condition to better constrain the development of the GMM at short distances - Produce as necessary alternative Scenario-based GM maps - If of relevant interest for the risk model, possibility to develop specific V/H ratios
4b	Wave propagation singularities related to 3D source-path and complex geological features simulation of a Mw5 scenario, and quantification of non-linear soil response effects in 3D	- Effects of the non-linear visco-elastic model implemented in SPEED lead to moderate deamplification versus linear model (decrease in the order of 15%-20%)	- Need to better understand the development of nonlinear effects in the upper 200 m (see report STR_18P17_05). - Need of better calibration of nonlinear models on local experimental data and consideration of epistemic uncertainties related to different numerical approaches and different soil constitutive models
5a	Comparison to EGFs and GMM V5	- Overall, higher predicted peak values than GMM-V5 especially at short distances. - Better agreement with GMM-V5 in terms of PGV than of PGA - Agreement of SPEED and EGFs in terms of trend of PGA decay with distance, although EGFs predictions for Mw5 are higher than SPEED.	- Need to redo comparisons with new version of the GMM to verify if the short distance trend still observed.
5b	Assumption of 1D wave propagation in GMMV5 soil response	- Magnitude-Distance dependence of the amplification functions as a possible consequence of non-1D wave propagation in the last 800 m	- Need of verification of the assumption of 1D vertically wave propagation in the top 800 m - Conduct 1D equivalent linear and nonlinear site response analyses and compare with 3D simulations to verify at which depth de assumption of 1D propagation is applicable (see report STR_18P17_05). - Verify if the physics-based model capture the nonlinear effects at large strains using independent SRA and verify the effect of damping at large strains - Development of the GMM at a reference depth closer to the ground surface and better constrained with G records at depth, minimizing the deconvolution effects and the non-vertical wave propagation effects.
6	Snapshots and tools for diffusion of information	- Capability to develop demonstrative maps for various plausible earthquake-induced scenarios	- Preparation of demonstrative communication tools

3. Suggested recommendations and identified actions to improve the ground motion component of the risk model

In the PSHA developed as component of the HRA model (Van Elk and Doornhof, 2017), the ground-motion prediction equations of the GMM are used to provide the probability distribution of earthquake ground motions at a given site of the area, as a function of kinematics, source parameters, distance between induced and sites also considering the site conditions.

The model and the adjusted set of GMPEs adopted in the PSHA were developed over time by a high-level scientific team and was the subject of a considerable effort to tailor the model to the particularities of the geological and kinematic models linked to the configuration of the gas field: characteristics of the induced-earthquake sources, wave-propagation processes and site-response. Due to the parameterization adopted in the functional forms, and to the inherent difficulty of considering the varying complexity of the ground motions propagating in a 3D geological model, not all the 3D features can be addressed in such a model.

Although the GMM V5 has made use of this area-specific information, the model parameterization was still simple concerning the modelling of wave propagation effects:

- The stochastic ground motion model EXSIM (Boore, 2009) provides a crude approximation of the complexity of the wave propagation process
- The spectral amplification functions are obtained by spectral 1D deconvolutions of surface ground motion to NS_B horizon using area-specific amplification factors, based on the assumption of vertically propagating plane waves.

The empirical data recorded in the Groningen area are representative of magnitudes lower than 4.0. The post-treatment and the disaggregation of the probabilistic seismic hazard assessment have evidenced that the range seismic sources having a significant control on the ground motion hazard at the return period of interest was for magnitudes between Mw 4 and Mw 5 and epicentral distances lower than 5 km (Bourne et al., 2015, Bourne et al., 2018). In this range of magnitudes and distances, the GMM model is poorly constrained by local observations. The simulations conducted within KEM 04 and using either EGF or 3D crustal wave propagation model, provide additional and complementary means to estimate the site and path effects with independent methods for those sources in these ranges of magnitudes and distances.

One of the remarkable results of the KEM 04 project is the stability of the observations when considering independently:

- The residual analysis carried out in exploiting the database of recorded events although corresponding to low magnitude events
- The simulation methods, which are based on the semi-empirical EGF approach or the physics-based spectral elements modelling. For both types of simulations, EGF and SPEED predicted values are in fairly good agreement with the observations (Figure 3-1).

This consistency combined with the capability of the two methods to reproduce the observations of the largest earthquakes recorded at G stations so far (Mw 3.4), gave sufficient confidence that the simulation methods could be considered as reliable approaches for the prediction of ground motion generated for hypothetical stronger earthquakes than observed.

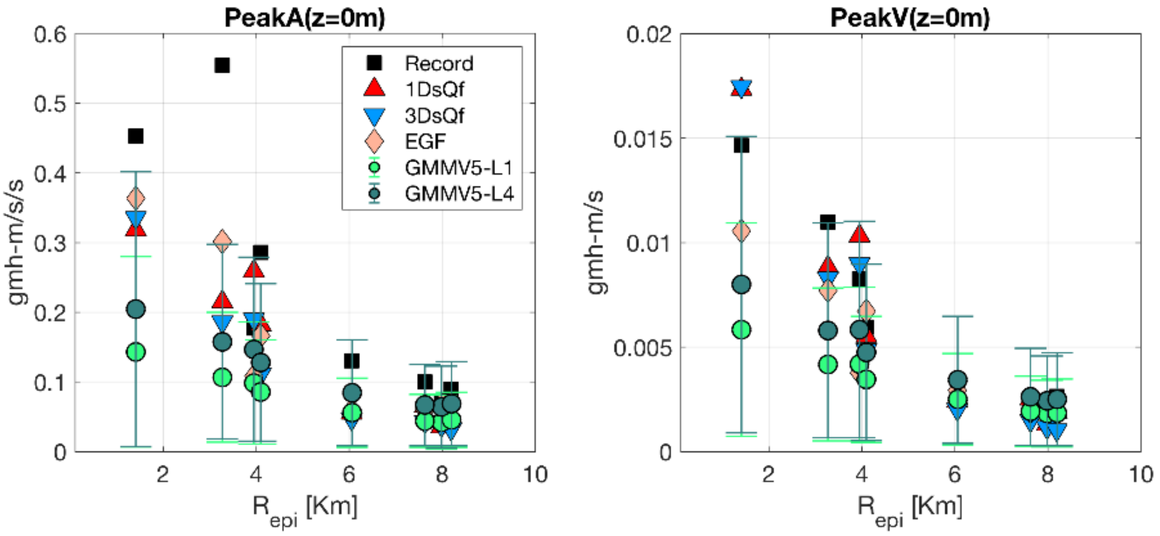

Figure 3-1 : Comparisons of the PGA (left) and PGV (right) values predicted at ground surface for the Mw3.4 Zeerijp earthquake. Predictions by EGFs approach, Physics-based simulations with SPEED (linear and nonlinear) and lower and upper stress-drop branch of GMM V5 (Refer to RQ2 report n° STR_18P17_03 for a detailed explanation and understanding of these results).

One of the most striking characteristic obtained in simulating earthquakes of higher magnitudes (Mw 4.5-5.5) and distances (< 10 km), in the range of the controlling sources as evidenced by probabilistic seismic hazard disaggregation, was the higher ground motions obtained with the two simulation approaches compared to the predictions by GMM V5 (Figure 3-2).

The large differences observed for the hazard dominant sources suggest the formulation of new and complementary actions and research and development efforts for better understanding the origin of the differences and for improving the ground motion component of the risk model.

Based on observations and conclusions detailed in the RQ1 and RQ2 reports, the recommendations are classified in two categories as a function of the level of scientific complexity to address and of the estimated duration for the execution of the corresponding actions and activities:

- Moderate effort actions (MoEA): these are actions for which the data are immediately available and for which the methods can be implemented to treat the identified subject with a moderate research and development effort. The estimated duration to implement the activities is between one and 6 months. The methodologies and tools can be applied without complex development and do not require a substantial research effort. Their implementation is assumed to improve the robustness of the ground motion model.
- Major effort actions (MaEA): these are actions that would require more significant research and development effort. The estimated duration to implement the activities is between 6 months and one year. Enter in this category the actions for which a methodological

development is required and the corresponding tools (software) need to be verified and validated.

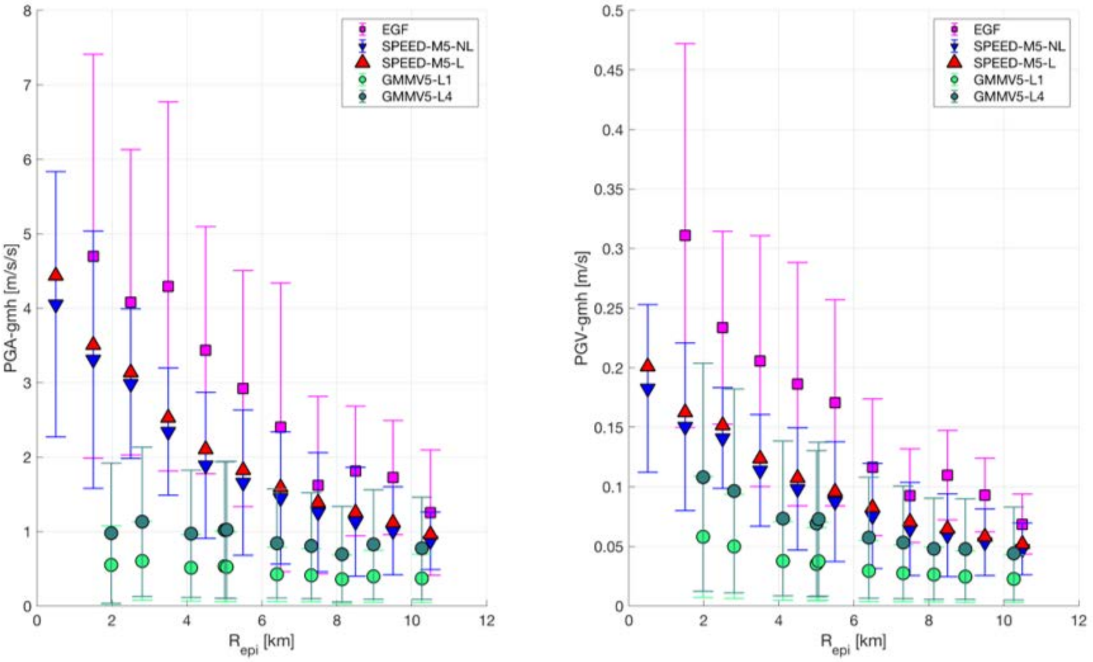

Figure 3-2 : Comparisons of the PGA and PGV values predicted at ground surface for a Mw5 hypothetical scenario. Predictions by EGFs approach, Physics-based simulations with SPEED (linear and nonlinear) and lower and upper stress-drop branch of GMM V5 (Refer to RQ2 report n° STR_18P17_03 for a detailed explanation and understanding of these results).

3.1 Recommendations requiring moderate effort actions

3.1.1 Comparisons to most recent version of the GMM (MoEA n°1)

As already mentioned in Chapter 2, comparisons were made considering version 5 of the GMM model.

One of the main observations based on the comparisons presented in the RQ1 and RQ2 reports in between the EGFs and physics-based SPEED approaches and the GMM V5, is a potential underestimation with the current GMM V5 of the ground motion predictions at short distances and especially at short spectral periods, (Figure 3-2), at the ground surface and at the reference NS_B horizon.

A similar conclusion is highlighted in the KEM02 project report (Evaluation, validation and improvement of the Site Amplification component of the Groningen Risk Model, Research questions 1 and 2, De Greef et al., 2019).

These consistent results lead to the conclusion that it is for the short distances domain (epicentral distance lower than 5-7 km) that adjustments/improvements of the current V5 model are expected to more properly reflect the peak amplitudes and attenuation observed in the recorded data and predicted by the simulation approaches.

In the same time and during the last months of the project, an interaction was organized with the experts of the GMM team, headed by J. Bommer, in September and December 2019. The open discussions and technical exchanges allowed to better understand the evolution and the direction taken in the development of the newer versions of the GMM.

We have understood from this interaction that compared to the V5 model, V6 has paid attention to:

- The consideration of the updated ground motion database, which include much more records and of higher magnitudes,
- The use of the records at the G0 (surface) stations of the G monitoring network that were not at all considered in the development of V5
- The site response model with consideration of larger low-strain damping values in the upper layers of the model than in V5

Given the importance for the HRA model to verify whether alternative and complementary methods evidence similar trends, thus improving the confidence in the ground motion model used in the seismic hazard assessment component of the risk model, an immediate action would be to re-conduct the comparisons between the predictions by EGFs and SPEED and the predictions by V6. This would allow more specifically appreciating if the observed discrepancies are reduced in the short distances and for magnitudes controlling the probabilistic seismic hazard, if yes in which proportion and for which spectral period, magnitude and distance ranges.

This action is also essential in the perspective of a scientific publication of the KEM04 results. As each time that a new model supersedes the former version, it is a legitimate and minimum expectation to appreciate how the new version compares with the older.

This action could cover different tasks according to the level of details that one expects to analyze. The main tasks that could be easily implemented are:

- The analysis and understanding of the GMM V6 through review of the new model documentation to understand the origin of the modifications compared to the previous version,
- The implementation of the GMM V6 model and of the verification and validation code procedures to ascertain that the predicted values for various scenarios can be reproduced without error
- The comparison between the observations, already available in the KEM04 project flatfiles, and the predictions by GMMV6. This would require to conduct again the same type of residual analysis as presented in the RQ1 report
- The comparison of KEM04 simulations already available (based on the two approaches EGF and SPEED) with GMM V6 predictions
- The preparation of a supplement to the current documentation like an addendum to the KEM04 reports and update of the recommendations.

More advanced treatments could be implemented to supplement the database with records and simulations and make the statistical comparisons between simulations, predictions and observations more robust:

- The project flatfiles extension to take benefit from the new records potentially collected in the future;

- Expand the comparisons not only to the G stations as done in the RQ1 report but also to the B stations after that the ongoing activities to identify soil-structure effects are completed.
- Run additional simulations (EGFs and SPEED) for an exploration of wider range of source-path-site effects between hypothetical location of induced earthquakes and sites. This last action would be of significant interest to ultimately compare the aleatory variability of the ground motion associated to the GMM and the variability offered by the simulation approaches.

3.1.2 Better understanding nonlinear effects (MoEA n°2)

In the Groningen area, the subsurface soil conditions above the base of the Peelo formation considered in the idealized 3D model (Figure 3-3) may have a significant impact on the predicted ground motion at a given site, through local site effects that are due to the soft soil conditions.

For the project, Vs-profiles developed by Deltares (2016) and Kruiver et al. (2017) were initially used to derive an idealized geological model in the upper 3km (Figure 3-3). Improvement in the upper 30 meters and a reduction of the uncertainties was made possible during the course of the project with the SCPT and CPT data performed at shallow depths (up to 30 m, Fugro report, 2019).

The soil-response analyses conducted to generate the calibration records at various depth (Appendix 1 of report n° STR_18P17_02) evidence that the transfer functions between NS_B interface and surface as well as between deep Gx sensors (x being between 1 and 4) and surface were mainly affected by the geotechnical units in the upper part of the soil profile: the soil amplification was observed in the upper part of the soil profile (0-50 m) whereas the amplification between the top of NS_B and the base of the Peelo formation was assessed to be very limited.

Because, the PGA amplitudes of the events selected in the project flatfiles do not exceed 0.07g the consideration of nonlinear effects was not a real issue for RQ1 and RQ2 tasks that focused on the comparisons between prediction by the simulation methods and the observations only available for small magnitudes. However, for magnitudes controlling the risks from vibratory ground motion hazard (Mw in the range 4.5 – 5.5), the question on how to address the nonlinear effects became more crucial, as the level on the ground motion at the base of the model enters in the domain where nonlinear effects have to be considered and the resulting amplification functions are frequency and input motion-dependent.

With the EGF approach, one of the potential issues when simulating ground motion for such magnitudes is that the linear assumption adopted in the EGF approach, when using small magnitude records as EGFs, could result in an overestimation of the observed motions. When comparing the SPEED simulation results obtained considering nonlinear and linear soil model, the nonlinear effects were estimated to have a moderate reduction impact (about 15%) on the ground motion estimates. Despite the fact that the SPEED simulation adopts a nonlinear soil model, the idealized upper part of the soil model was simplified to preserve the high computational performance of the 3D simulations in the entire modeled volume, which raised the questions of the signification of the moderate variability observed when comparing the results of the simulations obtained for both linear and nonlinear behaviors.

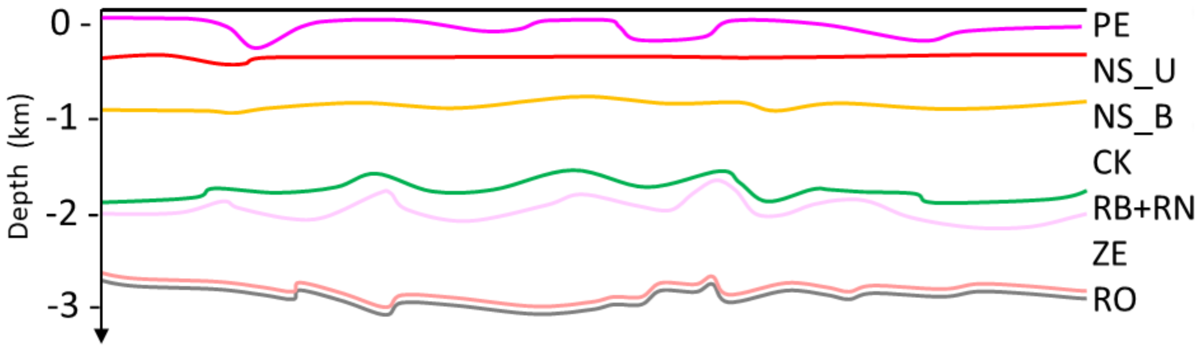

Figure 3-3 : Schematic cross section and main 3D interfaces considered in the 3D SPEED model. PE: base of Peelo formation. NS_U: base of Upper North Sea group. NS_B: base of Lower North Sea group. CK: base of Chalk group. RB RN: base of the Germanic TG. ZE: base of the Zechstein Group. RO: base of Rotliegend Group above LI: Limburg Group (Halfspace of the model).

The comparison of simulations obtained by SPEED when considering a linear elastic or nonlinear elastic model has concluded that the reduction of the ground motion amplitude was limited to 10% to 20%, likely related to the short duration of the moderate magnitude earthquake scenario considered.

A common conclusion based on the EGFs (RQ1 report section 7.3.2) and SPEED (RQ2 report sections 4.2 and 6.6) simulations as well as based on the soil response analyses conducted to prepare calibration records at the top of the NS_B horizon (appendix 1 of RQ1 report) was for the KEM04 team a requirement to:

- Better understand the development of nonlinear effects in the soil profile especially for magnitudes that control the vibratory ground motion hazard at the return periods of interest (i.e. for Mw magnitudes between 4.5 and 5.5). The recommendation was to conduct 1D equivalent linear and nonlinear site response analyses at 5 selected G-stations for Mw 3.4 (magnitude like Zeerijp earthquake) and a hypothetical Mw 5 scenario earthquake and to compare the results with both SPEED (considering linear and nonlinear behavior of the upper part of the soil profile) and EGFs simulations of ground motion at the ground surface and at depth, in terms of acceleration response spectra and site amplification ratios.
- To verify and cross-check with these results the nonlinear effects modelled by SPEED
- To minimize the potential bias due to the effects of non-vertical propagation of S waves and to estimate the depth where the assumption of 1D wave propagation is applicable
- To identify if an alternative target horizon depth could be identified where simulations and site response terms could be better calibrated and compared to empirical data.

A recommendation was made to conduct this new soil response analysis study in the linear equivalent and nonlinear domains to specifically address:

- The development of the nonlinear effects in the model.
- Their evolution with increasing magnitude and strain

- Their variability when considering input motions to the soil response analysis (SRA) at different depths of the soil profile above the NS_B
- If differences are observed when considering within ground motion inputs or outcropping inputs
- The consistency with the deconvolution/soil-response analysis performed in the GMM V5

As ground motion inputs to the SRA, it was suggested to consider the ground motions at the Gx vertical array sensors (G4 -200m, G3 -150 m, G2 -100m and G1 -50m) and at the NS_B horizon, generated by the EGF approach using the records at the various depths and by the SPEED simulations at the same depths. This exploration was suggested in considering 1. the recorded ground motions at depth as calibration records in the low strain domain and 2. ground motions predicted for higher magnitudes to explore the medium to high strain domain. The results are intended to measure the consistency and stability of the transfer functions at various control depths between the two approaches.

From G0 to G4 depth it was also planned to conduct systematic comparisons of the transfer functions obtained for both horizontal components of:

- The 1D equivalent linear and nonlinear soil response;
- The SPEED linear and nonlinear soil response

It was believed that such an approach would also allow a verification of the generated shear strain and its evolution at depth and an estimation of the damping for soft soils prevailing in the upper part of the soil profile, where nonlinear effects are likely to propagate.

As part of follow-up activities, the report STR_18P17_05 summarizes the 1D equivalent linear and nonlinear site response analyses performed at five select G-stations to compare conventional methods of estimating nonlinear site response with the results calculated using the EGF approach (RQ1) and the 3D physics-based simulations with SPEED (RQ2).

The site response analyses were performed using SPEED simulated motions at 200 m and 800 m depth for Mw 3.4 and Mw 5 and using the EGFs motions at the same depths for Mw 5. The results are detailed in the deliverable n° STR_18P17_05 and the preliminary conclusions should be kept in mind for implementing future ground motion assessment based on simulations approaches.

It was observed that:

- For earthquake magnitudes in the order of the largest observed (Mw 3.4 2018 January 8 Zeerijp earthquake), when strains remain low, linear, equivalent-linear and nonlinear results remain stable. This supports the idea that SPEED and EGF simulations can be used with confidence to develop various types of scenarios to assess ground motions at surface for various types of 3D geological configurations and size of events comparable to the Mmax observed so far.
- For increasing strains above 0.1%, the equivalent-linear and nonlinear soil response analyses result in lower ground motion in the upper part of the soil profile (Surface and depth of the G1 stations -50m) suggesting that SPEED results tend to overestimate the surface ground

motion, when the largest magnitudes are simulated. This is a source of progress in implementing the SPEED simulations for such magnitudes or an indication that a two step-approach could be implemented for the largest magnitudes, i.e., SPEED simulations at a depth where nonlinear effects are negligible, then equivalent-linear or nonlinear soil response in the upper 50 m of the soil profile. A similar trend was observed when considering the EGFs simulation for the Mw 5 event: results are consistent at the different depths of control between 50 m and 200 m, while lower spectral amplification is observed in the 1D soil response analyses due to higher damping in the upper surface than the damping captured in the EGF.

Interestingly when simulated input motions with SPEED are entered in the soil response model at 800 m and 200 m depth, differences observed at the surface suggest that 1D soil response analysis do not capture the 3D wave propagation effects that propagate between these two depths. This effect is not observed when considering the EGFs suggesting that the 1D deconvolution of the EGFs from surface stations to 800 m do not allow to capture as well the potential 3D effects.

For future implementation of site-specific induced seismic hazard assessment such as tested in the current project, some preliminary recommendations can be made:

- For the induced or triggered seismic sources that control the ground motion hazard at the return period of interest, there is a significant effort to better capture the nonlinear effects developing in the upper part of the soil profile. When the strain domain exceeds 0.1% the methods used to capture the nonlinear effects can be a source of significant uncertainty. This is true for the current GMM V5 used so far in the PSHA and for the two simulation approaches. Additional soil response analyses, especially for magnitudes that control the probabilistic ground motion hazard at the return periods of interest and at short distances, should be carried out to better evaluate the development of non-linear soil response effects. If engaged this would require a calibration of damping and modulus reduction curves based on in-situ investigations and tests.
- SPEED and EGFs approaches are appropriate to develop ground motions at depths between 50 m and 200m since nonlinear effects develop in the shallower soils. Both SPEED with and EGFs simulation can be well calibrated by the natural records at the Gx stations at least for the largest events that occurred in the recent years.
- Both SPEED and EGFs based approaches are appropriate to develop surface ground motion estimates as far as the magnitudes remain in the magnitude range of the maximum magnitudes recorded so far;
- 1D site response from this depth range to the surface, considering equivalent-linear or nonlinear models appears appropriate to capture the soil response in the upper part of the model as long as a site characterization is available. Significant progress has been done during the project to improve the shear wave velocity profiles close to the recording stations (Fugro, 2019). Attention should be paid in the future to improve the damping/modulus reduction curves that remain based on literature curves rather than soil-specific curves. Damping is of specific concern as the damping considered in the GMM V5 development as

well as in the simulations currently performed is only poorly constrained. Such data acquisition would allow a better estimate of the uncertainties related to the soil-constitutive properties and modelling in the shallow formations of the Groningen area, when nonlinearities are assumed to develop for magnitudes higher than the observed magnitudes that occurred so far.

- This also suggests an overall two-step approach with the perspective of better constraining the amplitude and effects of ground motion at surface: the development of a ground motion model based on one of the approach explored so far (classical GMM, simulation-based approaches) at a depth horizon where 3D wave propagation effects are suspected but nonlinear effects are not. Then a soil response analysis that could be conducted either in a deterministic framework or a PSHA model
- This also raises the question of developing the future GMM at a different reference horizon than the NS_B.

3.1.3 Extend the EGF approach to smaller magnitudes (MoEA n°3)

The simulation approach based on EGFs has demonstrated that it offers a complementary approach to the GMM and to the physics-based simulation to predict the ground motion for a variety of source to site configurations. Despite the fact that nonlinear effects in the upper part of the soil profile need to be accounted for when simulating large magnitudes, the method can be used for various applications including PSHA and DSHA (cf. 3.2.1).

The project flatfile (report STR_18P17802) contains records from 23 events with magnitudes Ml from 2.0 to 3.4, records at epicentral distances between 1.15 km and 33 km and from surface to – 200m. The raw database publicly accessible from the KNMI portal (http://rdsa.knmi.nl/dataportal/), contain much more recordings from B and G networks and this database is continuously enriched over time.

One of the recommendations is to extend the flatfile to lower magnitudes after verification that the signal to noise ratio for smaller magnitudes remains acceptable to consider the records as candidates for potential EGF.

The enrichment of the database would make it possible to benefit from a larger number of EGF representative of the peculiarities of the seismic ground motion between a larger number of induced seismic sources and sites.

This greater number of events would in particular allow a better characterization of the variability of the ground motion. Epistemic uncertainties were considered in the EGF-based simulations for a variety of parameters (stress drop, rupture dimension, slip distribution, position of the rupture over the hosting fault along the strike, position of the hypocenter along the strike on the rupture). However the uncertainty due to the choice of the EGF itself was only poorly addressed because the limited number of magnitudes above ML 2.0 in the same area and recorded at the same station. Increasing the number of EGFs would precisely offer a database with multiple EGFs to control, for earthquakes that have occurred at the same place in the 3D model, which variability is observed in the records and how they propagate when they are used as EGFs.

This action would provide a more robust set of ground motion parameters in completing the current database and in offering the possibility to develop additional ground motions for higher magnitudes.

This extended database of ground motion could be used in the future version of the GMM. It would be in any case necessary if the prototype tool suggested in 3.2.1 is implemented.

3.1.4 Adjustment factors of the GMM for specific features of the Groningen area (MoEA n°4)

Several sensitivity studies have been conducted with SPEED to address the potential impact of 3D ground model features of Groningen after that the approach was validated reproducing with accuracy the recorded motions for the 2018 Zeerijp event.

If the comparison to GMM V6 would confirm the trends observed for V5, i.e., the observed differences in short distance/spectral period ground motions, the recommendation would be to interface the results of the simulations and the GMM to better account for the ground motion characteristics in the distance and magnitude ranges that control the probabilistic seismic hazard assessment of the Groningen HRA model.

Among the tested configurations and heterogeneities, and despite the limited exploration of the uncertainties included in the simulation model, the 3D geometry of the salt domes of the Zechstein formation appears to have significant effect on the surface ground motion. Such specific features of the ground motions and local amplification effects that develop in specific areas of Groningen cannot be taken into account in a generic model based on 1D wave attenuation.

In case where significant amplification factors are expected in a given area, the simulation approaches could be used to develop frequency dependent aggravation factors to be applied to the predicted motion by the GMM.

The 3D geometry of the Zechstein formation is one of the more striking 3D heterogeneity for which such aggravation factors could be developed. In the simulations presented in the RQ2 report n° STR_FUG_18P17_03, the salt dome geometry in the Veendam area has been fictitiously translated in the model next the location of the Zeerijp event, evidencing significant amplification factors. As a limited number of SPEED simulations were conducted, the development of such factors would require a more careful consideration of the epistemic uncertainties as well as a control with the EGFs approach. No investigation of such effects was possible from the records available in the project flatfile, because no earthquake with magnitude greater than or equal to 2 did occur in the Veendam area where the sharpest salt dome geometry exists. This should be again explored if the database is completed with smaller magnitudes.

The topography of the Zechstein formation is shown Figure 3-4, with two cross-sections evidencing the sharp dome tested in the current study.

More systematic analysis of the potential amplification factors may help in identifying the areas where an aggravation factor to the predicted ground motions may be applied in relation with the topography. It was for instance observed that when the topography of the Zechstein is smooth, like in the Loppersum area, comparisons at several stations have highlighted a moderate increase in the peak values of the simulations obtained.

Due to the limited consideration of epistemic uncertainty in the 3D simulations so far, it is suggested:

- To verify, outside the Groningen area selected to conduct the KEM04 project, if the amplification factors resulting from the simulations are confirmed by empirical data. This would be of relevance for areas outside Groningen where shallow Zechstein salt domes exist and induced seismicity is observed.
- To perform, for a couple of induced earthquake scenarios consistent with the seismicity models, additional 3D physics-based SPEED simulations to verify the stability of the predicted amplification functions above the salt domes. The simulation should be based on representative configurations of plausible future events: magnitude, location and distance to the more sharp salt domes, also considering the azimuth coverage between the epicenters and the dome locations
- Verification of the impact of smoother irregularities of the top of the Zechstein formation
- Estimation of the aspect ratio of the 3D heterogeneities for which aggravation functions would need to be applied to the ground motion predicted by the current GMM
- Definition of aggravation functions, topography and frequency dependent hence locally dependent, that could be applied to the uniform hazard spectra resulting from the Groningen PSHA model

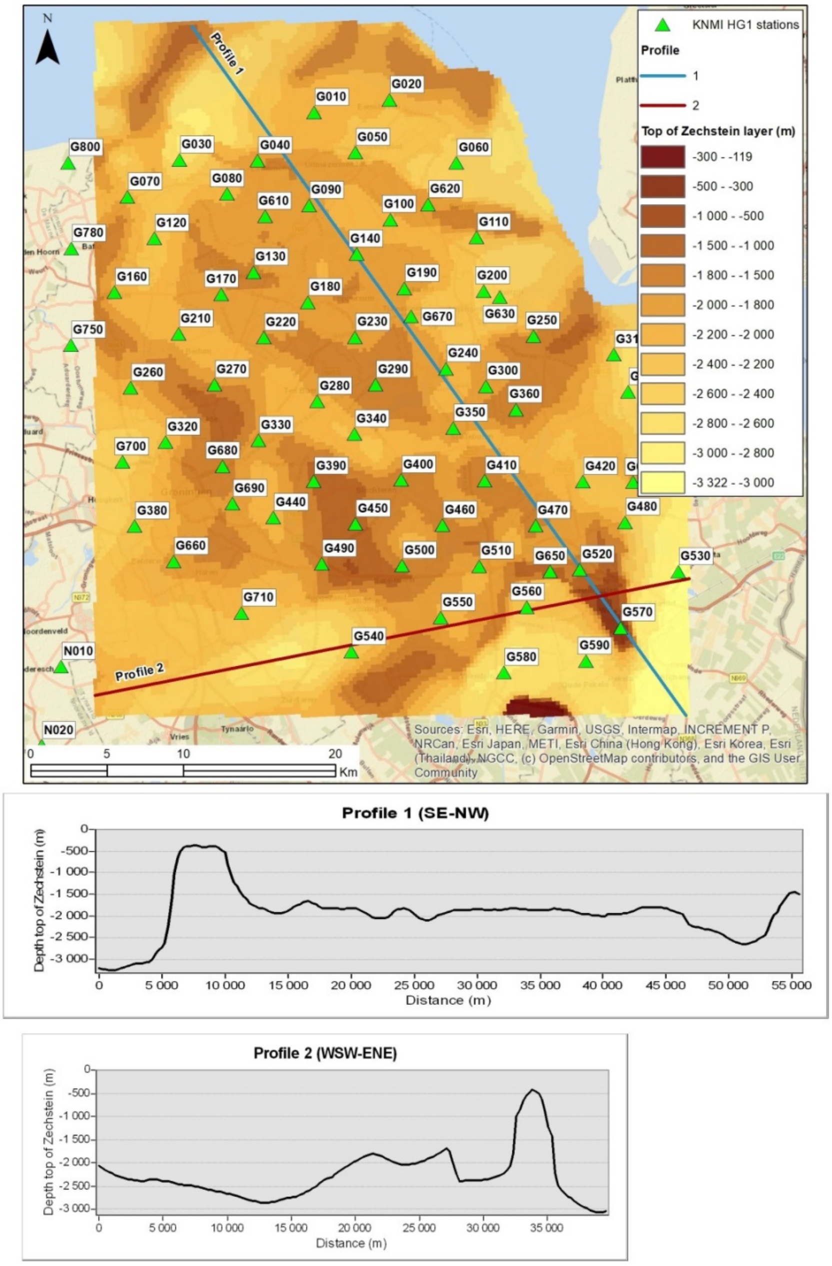

Figure 3-4 : Topography of the top of the Zechstein formation in the Groningen area. The sharp dome at the intersection of the cross-sections corresponds to the topography tested in the RQ2 report (STR_18P17_03, section 3.4.3)

3.1.5 Vertical ground motion (MoEA n°5)

If part of the building stock and assets located in the Groningen area are deemed sensitive to the vertical component of the ground motion, the V/H analyses carried out on both recorded data and simulations suggest paying attention in the development of a vertical ground motion model tailored to the specificities of the vertical motion due to Groningen induced earthquakes.

In such case, additional investigations should be implemented to develop a Groningen specific V/H model, because current V/H models for tectonic events seem not exportable to the Groningen case at distances to the rupture lower than 10 km, differences up to 50% being observed (Report STR_18P17_02, chapter 4). This could be due to the fact that the very short source-to-site distances of the Groningen context are not well represented in tectonic databases and/or to specific characteristics of induced events providing large P-wave energy at short distance.

Different tasks could be conducted:

- Verify using generalized inversion technics, the differences in attenuation properties when using the P wavefield and S wavefield
- Check the variation of the energy content with distance of the P wavefield and S wavefield
- Check if these variations are still observed in additional SPEED simulations for magnitudes in the range 3.5-5
- Development of a specific V/H ratio for short distances that could be applied in the PSHA

3.1.6 Installation setting of seismic stations (MoEA n°6)

One of the actions in RQ1 has been to analyze and select from the available data provided by the different seismic networks a set of records suitable to identify the characteristic features of free field ground motions and to prepare calibration events whose records are compared to the simulated ground motions. Apart from the issue regarding the error in the calibration settings affected to the G0 sensors (Dost et al., 2019), lessons could be drawn from these analyzes:

- Differences observed between seismic stations installed in free field and in structures at very short distances, suggest that stations installed in the structures even of small size, are affected by a reduction of high-frequency amplitudes potentially caused by structure and installation conditions-dependent or soil-structure interaction effects.
- When corresponding records are included in the database used to develop the GMM model, this has obvious consequences when the purpose of the GMM is to predict free-field ground motion.
- A preliminary screening of the station installation condition has been made in 2019 to appreciate to which extent the records can be biased by such interaction effects, and select the stations that can be considered as free field stations. This shall encourage, for potential future network extension, to properly define the installation conditions of the sensors if the purpose is to generate a free field records database.
- The installation conditions should also encompass the definition of soil conditions prevailing at the sensor locations and especially the Vs profile in the top 30 meters.

3.2 Recommendations requiring major effort actions

The comparisons presented in the RQ1 and RQ2 reports show that to predict ground motion for induced earthquakes, the simulation approaches are especially effective to address specific issues like the ground motion at short distances where nearby ruptures contribute significantly to the vibratory ground motion hazard at the site or like 3D features that impact the propagation of the wave field.

This could pave the road for implementing complementary hazard assessments, adopting either a deterministic or probabilistic framework, which could be beneficial for various applications: adjustment of the ground motion prediction equation for certain source to site configurations, implementation of scenario-based ground motion assessment to address the effects of theses configurations, development of alternative probabilistic approaches.

The ground motion model and the variability in the prediction of ground motion is a source of significant uncertainty in a seismic hazard assessment model. Due to the limited treatment of uncertainties in the physic-based simulations conducted with SPEED, there is still a requirement to better address the uncertainties and to conduct additional tests to envision applying the methods from an operational perspective of ground motion hazard quantification.

Methods for estimating ground motions in a PSHA framework generally include GMM based on empirical or stochastic GMPEs as in the Groningen HRA. Ground motion simulation methods, which are physics-based or rely on EGFs are also used for seismic hazard assessment purpose, more often in a deterministic framework, although their consideration in PSHA models has been experienced and can offer complementary and alternative ground motion estimates to the conventional GMPEs approach (Hutchings et al., 2015).

While GMPEs are typically developed to predict a ground motion measure, such as the horizontal or vertical response spectral acceleration, these alternative methods present the advantage to typically produce ground motion time histories from which any necessary intensity measure can be derived directly. Another interest of the physics-based and data-driven methods is to provide constraints on scaling behavior for parameters related to source and site properties that may control the ground motion and that are not always well-represented in the empirical or stochastic ground motion databases, such that the GMPEs may not be fully suitable to address specific issues that may control the ground motion estimates.

An important result of KEM04 is to demonstrate that data-driven and ground-motion simulation methods based on EGF or 3D simulations provide complementary ground motion estimates that can be used to:

- Address ground motion characteristics that are not fully considered in a GMPE model. Because the 2D or 3D geological structure differs from a homogeneous layered model, the simulation approaches offer the possibility to develop more realistic wave propagation effects either directly included in the EGFs or resulting from the physics-based simulations
- Develop ground motion estimates that can supplement the ground motion database and may help to refine and calibrate the GMPEs
- To develop ground motions for specific scenario events. The physics-based methods present the specific interest of addressing the ground motion that could be potentially generated by future scenario earthquakes for which specific parameters can be evaluated from the seismicity model (geometry of the rupture, stress drop, seismic moment, slip velocity function, rise time function)
- If a sufficiently large number of ground motions estimates are produced for the seismic events representative of the future seismicity model up to the maximum magnitude, they can constitute a sound basis to a probabilistic seismic hazard assessment.

3.2.1 Exploitation of the simulation approaches in a probabilistic framework (MaEA n°1)

The results of the simulation-based ground motion assessments have indicated that the simulation approaches have the potential to offer alternative ground motion estimates when source and complex 3D geological features exist. Different actions can be identified to bring the results of the KEM 04 study into a probabilistic framework.

As seismic sequences associated to various production scenario are available, and because the 3D geological model of Groningen is continuously enriched by additional site investigations as well as the rich database of induced earthquake records, all pertinent parameters are available to test simulation-based seismic hazard assessment to supplement the more conventional method.

3.2.1.1 Feasibility of introducing the EGFs into a PSHA model: Development of a Prototype.

If the easier and immediate action would consist in improving the existing GMM used in PSHA (section 3.1), notably to improve the short distances ground motion prediction, a broader use of the simulation approaches could be considered as a complementary tool to introduce the source to site propagation effects addressed by RQ1 and RQ2 in a probabilistic environment.

The two approaches EGF and SPEED have demonstrated their capability to reproduce some key characteristics of the propagating waves in the 3D space of the Groningen area. When empirical Green’s functions are used, the effects of the actual wave propagation are automatically included in the ground motion computations, which presents a significant interest for the potential reduction of the uncertainties in the ground motion estimates, provided that nonlinear effects are complementary addressed for the largest magnitudes. A simulation-based ground motion model included in the PSHA could offer an alternative tool for the prediction of hazard curves later on used in the seismic risk model.

Plausible fault rupture locations consistent with the seismicity model should be identified in advance (location and geometry of faults able to generate earthquakes with magnitude higher than the minimum magnitude of the hazard integral), which is a source of significant uncertainty as multiple seismicity models exist. To represent this variability the model parameters would ideally be modeled as random variables with due consideration of correlated parameters. To represent this variability a number of simulations would be necessary to obtain a robust estimate of the median ground motion and its variability about the median, as it is currently done in the GMM. While this appears possible when using the EGF approach, one of the limitations with the SPEED simulations would be the high computation-time effort to fully capture the variability. This is the reason why the physics-based approach would certainly find seismic hazard assessment applications much focused on scenario-based assessment or on objective to address source to site specific features, while the EGFs could be tested as a complementary approach to the conventional GMM, in a probabilistic environment.

The consideration of magnitudes smaller than ML 2.0 in the development of the project’s flatfiles, would certainly help in better addressing this variability. As suggested in the recommendation 3.1.3 the threshold in magnitude of the events whose records could be used as EGF should be determined, which assumes to verify for the different areas of Groningen, the range of frequencies where the signal to noise ratio is sufficiently high to qualify the records as candidates for being selected as EGF.

As the number of records candidate to be considered as EGFs appears to be sufficiently rich, at least in parts of the Groningen area, the development of a prototype is suggested to appreciate if the current GMM used in the PSHA could be replaced by a ground motion model based on EGFs, and how this would bring comparative ground motion hazard estimates than the current PSHA. For the larger magnitudes, and if necessary, a limited number of SPEED simulations could be coupled to the EGF simulations to offer synthetic Green's functions (SGFs), in areas not covered by the empirical database or to develop SGFs for magnitudes larger than the observed magnitudes.

In such a prototype, the physically based PSHA would follow a similar procedure as the conventional PSHA, except that conventional PSHA utilizes a ground motion prediction equation as propagation model while the simulation-based could use a wave propagation model based on EGFs from the recorded database as well as SGFs obtained from SPEED simulations.

The approach would be based on calculations of synthetic seismograms for all magnitudes/distances earthquakes representative of the different induced-seismicity models, to obtain ground motion parameters. This would require the prior development of synthetic induced-seismicity catalogues from the minimum and maximum magnitudes to be considered in the hazard integral, consistently with the existing seismicity models, themselves a function of production scenarios.

The feasibility of such simulation-based PSHA prototype could be addressed in a six-month research and development effort in implementing the following tasks:

- Identify from the existing seismicity models the predicted earthquake sequences and use existing or develop synthetic earthquake catalogues, consistent with the Groningen seismicity models, to consider spatial distribution of earthquake events based on the production scenarios for the gas field considered in the HRA ;
- Select a limited number of target sites where data are deemed sufficient to conduct the PSHA (EGFs number, site characterized with in situ data, etc.). The selection of a limited portion of the Groningen territory is intended to limit the calculation times while making representative the tested area to estimate the feasibility and interest of the method. 2 sites could be considered;
- Based on the recommendation 3.1.3 (it is anticipated that ML < 2 would need to be included in order to increase the coverage of the EGFs in the field), data processing for the earthquake records to be used as EGFs for the relevant sources
- Investigate the range and variability of the ground motion parameters using EGFs
- Definition of the parametric space for the EGF simulations, completed when necessary by SGFs: fault geometries, stress drop, rupture velocity, mechanism, depth, magnitude range and related uncertainties. Multiple EGFs should be used when available for each event in order to better account for the uncertainty due to the use of a specific EGF.
- Quantification of the simulated ground motion variability obtained with the EGFs and comparison with observations and predictions by GMM

- Simulation using EGFs finite-fault approach of the ground motions time histories based on the parameter space defined in the previous step. Simulations should be preferably performed at one of the depths of the G stations e.g., - 50 m or -100m depth where records are available for calibration and where nonlinear effects are assumed to be negligible. The scenarios could be selected randomly with varied independent parameters, and the corresponding waveforms could be calculated using EGFs and SGFs to generate a database of synthetic waveforms, for each typical scenarios included in the synthetic earthquake catalogue
- Conduct the 1D nonlinear soil response analysis for the selected sites of interest in order to define the simulated time histories at the surface (using EGF-based simulations at depth)
- The PSHA would then be developed by statistical treatment of the generated time-histories database instead of the conventional approach

Comparison of the median and centiles hazard estimates from the conventional PSHA using the current GMM and the EGF simulation-based PSHA would ultimately allow determining how the two approaches compare, and to quantify the gain in the reduction of the ground motion hazard uncertainty.

Identified limitations of the method could be:

- The generation of synthetic catalogue of induced earthquakes representative of the future evolution of the seismicity, which is production scenario dependent. This component would be however based on the existing predictive seismicity models considered in the current HRA;
- The determination of an optimal number of induced-earthquakes for the purpose of calculating all possible ground motions and generate a sufficiently robust database of synthetic waveforms from which hazard curves can be calculated. There is a need here to implement the procedure in a systematic way to capture the epistemic and aleatory uncertainty and the research should focus on how to limit the computation time especially for the SGFs calculations
- For magnitudes where the point source approximation is not valid, to estimate the uncertainty in the prediction of future ground motion generated by finite fault source, that requires to identify the range of source parameters for future larger induced- earthquakes than observed so far. A sufficient range of possible source parameters would be essential for an assessment of uncertainty. For that reason, it would be important to conduct a quantitative sensitivity analysis study by using different source parameters and appreciate the variability in the predicted ground motions.

Despite these potential limitations we believe that such an approach would offer the possibility to address source and site effects specificities that are otherwise averaged and smoothed when considering the conventional approach. The method would also offer the possibility to appreciate the potential differences or consistency between two independent PSHA approaches.

3.2.1.2 Considering the simulation results in a PSHA Bayesian update

The GMM logic tree is based on several branches of the GMPE to propagate the epistemic uncertainties. Inherent to the PSHA methodology, the reliability of PSHA outputs are always questioned, especially when the hazard assessment is conducted in an area where no observation or empirical record is available in the magnitude range which is considered in the hazard integral. This is typically the case for the Groningen area where the largest recorded event corresponds to a local magnitude ML 3.6 while the hazard at the return periods of interest is controlled by much higher magnitudes.

As in any hazard model, some choices had to be made like for instance the selection of the NS_B horizon to implement the deconvolution at a common target velocity horizon without real possibility to calibrate the model with recorded data. This choice may represent a major source of uncertainty in the GMM because no data exist at the NS_B horizon to control the deconvolution results. Different choices may lead to significant variability in the ground motion estimates that are difficult to quantify without empirical data.

PSHA including a testing phase of the PSHA outputs (mean and centiles of the distribution) against any available local observation has been recently recommended by the OECD/NEA/CSNI (OECD/NEA, 2015). The idea is to use data or observations not used in the PSHA model, to calibrate the model or part of the model, based on a Bayesian inference.

Such a PSHA testing and updating, could be based on the comparisons between the predictions by the GMM and by the EGF and SPEED predictions. Comparison between the predictions by the GMM and the two simulation approaches may offer a tool to help in the assignment of the weights to the different branches of the GMM logic tree. Among the branches considered in the LT, the branches closer to the prediction performed by EGF and SPEED would be assigned a higher weight compared to the branches leading to the highest differences.

In another way, the seismic networks deployed in the Groningen district have generated a remarkable ground motion database that keeps growing as time progresses. Due to the significant induced seismicity, the networks offer also the possibility to exploit observed data between two dates of PSHA realizations, so that a set of observed data not used in the tested PSHA could be used to weight the logic tree branches at least for part of the hazard curves corresponding to the highest probability of exceedance.

A task could be to appreciate how a Bayesian inference technique could be used in order to quantify the likelihood of the prior estimation (the estimation obtained prior the dataset is generated), and to conceive an updating PSHA tool, based on weighting scheme adjustment of the GMM branches of the logic tree, that could address:

- A Bayesian inference technique using the accelerations predicted by the PSHA model and the observed accelerations at the seismic networks
- A similar technique using direct comparisons between ground motions obtained with the predictive GMM model used in the PSHA and the ground motion predictions by EGF and SPEED.

In the framework of the project such techniques could be used either to adjust some components of the GMM (in the case of V5, the short distances and short spectral periods) or as a less subjective approach to weight the branches of the PSHA Logic Tree.

3.2.2 Scenario-based tools (MaEA n°2)

If the probabilistic approach is intended to provide the inputs to the risk model, the scenario-based approach remains a risk-informed tool to estimate the ground motions that can be due to source-specific earthquakes.

Ground motion generated by low to moderate induced-earthquake can be strongly felt by the population. Small but repeated damages can also cause a social trauma. It is therefore essential that the amplitude of the ground motion and their potential effects can be assessed with sufficient accuracy to communicate on the consequences of potential induced scenarios, that remain realistic given the potential evolutions of the production scenarios.

The two simulation approaches have demonstrated their capability to be used to conduct such scenario-based estimates, and we believe that it would be worth considering this scenario-based approach, especially in the zones of the Groningen model where 3D propagation effects may not be properly addressed in the current GMM.

The two methods tested in RQ1 and RQ2 could thus be used in some of the areas of the Groningen agglomeration where the GMM presents limitations in estimating particular 3D effects such as those evidenced in the simulations of the wave propagation effects due to sharp geometries of salt domes. With induced earthquakes located at shallow depth and in an inhabited area, the simulations conducted within KEM04 have also shown that we are still concerned with near-source effects, where the ground motion can by high, where directivity effects have been evidenced even for small recorded events but also with the variability in the energy content and the capability of corresponding ground motion to generate damages.

We suggest that EGFs and SGFs by SPEED could be used to quantify the range of ground motion characteristics that could be generated by different earthquake-induced scenarios that have a reasonable probability to occur in the future. This approach would offer the possibility to account for specific effects that are not accounted for by the current GMM model or accounted by smoothed proxies. Appropriate geological and seismological data exist for the determination of key parameters assigned to plausible scenarios that could occur in the future. The precise nature of the scenarios could be defined with the support of the KEM panel.

The approach would require:

- To determine, from the seismicity model, a limited number of well constrained earthquake-induced scenarios, that could be consensually determined by a group of specialists having been involved in the recent development of seismicity model. This determination could rely on the events observed so far, by the continuous survey of the seismicity migration over time and the predictive evolution based on production scenarios, by the analysis of the disaggregation as made available from the most recent PSHA model, and on the areas of Groningen identified at risk

- Perform the ground motion calculations based on the methods tested in RQ1 (semi-empirical) and RQ2 (simulation using physics-based model) with the appropriate level of uncertainty consideration. The objective would be to determine the ground motion that each of the tested scenarios would cause at the grid of calculation points, with account taken of the variability of the ground motion. The calculations could be done considering a target horizon of the soil profile where nonlinear soil effects can be neglected.
- Conduct the soil response analysis considering the enriched soil database and Vs profiles acquired since the origin of the project.

Compared to the PSHA approach, the interest would be:

- A ground motion assessment for plausible earthquake-induced scenarios. Care should be given to select scenario representative of relevant and representative cases in line with the seismicity model. For instance, Mw magnitudes in between the maximum magnitudes observed so far up to the Mw magnitude that represents 84% of the contribution of magnitudes from the disaggregation analysis. Mw 4, 4.5 and 5.0 could be tested in locations consistent with the observed migration of the seismicity in the last years and/or at location of the Groningen area where 3D effects are suspected. This would be very useful to assess the impact/rics for a credible worst case scenario.
- A more direct assessment for the ground motion and their characteristics (duration, frequency content) to generate damages on the specific building typologies prevailing in the Groningen area.

Such scenarios may also offer the possibility to control how plausible the probabilistic outputs are, especially for induced events whose location and size in an operating gas field are closely related to the evolution of the production model. The post-treatment of the probabilistic model would allow determining a return period or probability of exceedance of the scenario-based predictions. Alternatively, this would provide more insights of the plausibility of the probabilistic results by a measure of the difference between ground motions parameters due to deterministic set of scenario and probabilistic evaluations at a given return period.

3.2.3 Consider additional epistemic uncertainties in the physics-based approach (MaEA n°3)

Given the significant calculation time to implement 3D physics-based models, the treatment of epistemic uncertainties was voluntary limited to key sensitivity analyses with the objective to demonstrate the capability of the tested methods to address the research questions, rather than for practical and operational assessment. There would be a need to a more in-depth characterization of the uncertainties. Candidate parameters could be the seismic moment, the rise time function, the stress drop, the rupture velocity, the average slip.

In case the simulation methods would be used in one of the applications mentioned above, additional sensitivity analyses should be conducted to 1. Verify the impact of the choice of input parameters and 2. Better account for the epistemic uncertainties associated to the characteristics of the induced-seismicity scenarios and locations of the sites above specific 3D features of the ground model.

Regarding the EGF-based simulation approach, epistemic uncertainties have been considered for the source parameters (the slip distribution, the stress drop, the position of rupture over the fault along the strike, the position of the hypocenter). However most of the simulations have been conducted in considering a single EGF and no epistemic uncertainty was considered in the EGF itself. It would be worth considering several EGFs from recorded earthquakes having their location in the same volume of the reservoir and for a range of magnitudes.

These effects could be better analyzed in considering a completed database as suggested by the recommendation 3.1.4.

3.2.4 Alternative reference depth for the GMM (MaEA n°4)

A noticeable result of the 3D numerical simulations carried out with SPEED is the questioning of the standard assumption of a vertically propagating plane wave in horizontally layered media generally adopted in soil response analysis (RQ2 report, section 5.1.3) and adopted in the GMM V5 development for the 1D deconvolution of surface ground motions. As verified in the RQ2 simulations, such assumption was indeed not valid for the earthquakes occurring at 3 km depth. This result is also confirmed in the 1D soil response analyses developed in the report STR_18P17_05 report when comparing the SRA results when input motions are entered at different depths of the soil profile. The deconvolution approaches implemented to determine the EGFs at the NS_B horizon as well as the analysis of 3D wave field more generally questions the validity of the 1D vertically propagating waves for epicentral distances greater than 2 km.

To better account for the potential effects of the 3D ground motion features that propagate above the NS_B, one of the recommendations would be to select another horizon or another depth than the top of the NS_B horizon to develop a future GMM.

One of the issues with the GMM V5 is the absence of calibration of the ground motion at the NS_B interface with recorded data. The transfer functions analyses described in Appendix 1 of the STR_18P17_05 report show that surface ground motion is mainly affected by the waves propagation in the upper 50-100 m, e.g., at a depth where the G records (G1 geophones at -50 m and G2 geophones at -100 m) in the boreholes offer a possible calibration of the simulated ground motion at such depth and also provide EGF at depth.

The sensors of the vertical arrays are currently limited to a depth of – 200 m but they offer a remarkable suite of calibrations records at a depth where nonlinear effects appear limited and which is still significantly above the NS_B interface at -800 m, where no calibration record is available.

At the time the specific GMM development was conceived, the choice in developing the GMM at the rock NS_B target horizon was certainly commendable, but the counterpart was that deconvolution was needed to derive ground motions at NS_B, implying large uncertainties in the process and without the possibility to control or calibrate the results with recordings.

For many of the reasons advocated above (questioning of the standard assumption of 1D vertically propagating plane wave, nonlinear effects likely limited below the Peelo formation, availability of records at depths where stiff soil conditions prevail), it might be wiser to develop a future GMM for a stiff soil condition and at a depth where the Gx stations offer calibration records.

For this reason, we suggest to explore the feasibility of developing the GMM at a reference velocity horizon where the Gx sensors offer a set of calibration records.

3.3 Summary of recommendations

At the onset of the KEM 04 project, two research questions were posed to appreciate and to check how alternative methods based on data-driven analyses and simulations approaches would allow addressing local features in the induced seismicity sources and the 3D geological model that were difficult to address in the current GMM V5.

An important result of the RQ1 and RQ2 is that both EGFs-based and full 3D simulation of seismic wave propagation based on SPEED are suitable to reproduce with sufficient confidence the ground motions recorded during observed induced earthquakes. The applications of the approaches to predict ground motion for higher magnitudes than observed so far, also suggest that the approaches appear complementary to the current GMM V5.

The choice of implementing these recommendations (Table 3-1) may depend on the more general objectives pursued within the framework of the KEM Panel.

Some of the actions are of significant scientific interest in an attempt to reduce the uncertainties in our ability to better predict the seismic ground motions (MoEA 1, MoEA 3, MoEA 6, MaEA 3, MaEA 4), to reduce the potential over- or under-estimations (MoEA 2, MoE 5, MaEA 3, MaEA 4), to gain in the reliability of the predictive model (MoEA 4, MaEA 2) and to offer alternative methods of prediction of the ground motion (MoEA 3 and MaEA 1, MaEA 2).

Other actions are of interest to anticipate the horizontal and vertical ground motions that could be felt in case of future induced earthquake of given characteristics throughout the area of interest and to further predict the potential risks (MaEA 2). The simulation tools developed under RQ2 allow for conceiving and preparing demonstrative communication supports.

Given the variable research and time efforts to conduct the corresponding tasks and actions, the decision was taken to differentiate the nature of the recommendations and corresponding actions, as a function of the level of research and development efforts to address the scientific issue and of the duration to execute the actions. Moderate effort actions (MoEA) are identified as the activities that could be conducted in a limited time frame (less than 6 months). They would rely on the use of available data and results obtained so far using available methods and tools, either to solve one of the identified issues/questions, to conduct seismic ground motion assessments for particular configurations, or to perform additional sensitivity analyses. Major effort actions (MaEA) refer to tasks and actions that would require more substantial research and development efforts, more time (6 months to 1 year) based on more detailed analysis and additional simulations, the benefits of which should be assessed according to the general objectives of risk management of the KEM panel. They are also intended to transpose the RQ1 and RQ2 results into practical improvement or reduction of the uncertainties in the seismic hazard assessment for the Groningen area.

Table 3-1: Summary of the recommendations.

N°	Recommendation	Objectives and implementation
MoEA 1	Comparisons to most recent version of the GMM	Confirm the observed trends between simulation-based approaches and GMM and between data and GMM. Can be engaged as soon as a new GMM version is available.
MoEA 2	Better understanding of nonlinear effects	Focus the consideration of nonlinear effects where they develop in the ground model (upper part of the soil model, improve the parameters of the constitutive soil models). Require a two-step strategy: simulation-based approach or ground motion prediction equation at a reference depth in the 50 m to 200 m range then a soil-response analysis.
MoEA 3	Further improvement of the EGF approach	Extension of the EGFs database to implement PSHA or scenario-based simulations with consideration taken of uncertainties in the EGF. Require to extend the flatfiles to smaller magnitudes and treat the corresponding records.
MoEA 4	Adjustment and aggravation factors of the GMM for specific features of the Groningen area, like significant topography of the Zechstein.	Better consideration of 3D features not accounted for in the current GMM. Require more extensive use of the physics-based simulations developed under RQ 2.
MoEA 5	Development of an area-specific V/H model for the definition of vertical ground motion	For structures/components sensitive to vertical ground motion, offer a more suitable alternative to V/H inferred from tectonic events. Require additional attention to vertical component of induced events records.
MoEA 6	Installation setting of free-field sensors	Verification of the installation setting and clear differentiation between ground motions considered as free-field ground motions and ground motions affected by soil/foundation or soil/structure interaction.
MaEA 1	Interface and integrate simulation approaches in a probabilistic framework	Alternative probabilistic hazard assessment to the conventional PSHA. Typically a research and development action that would require that MoEA 3 is conducted.
MaEA 2	Conduct Scenario-based seismic hazard assessment	Evaluate the ground motions for plausible induced-events that may occur in the future. An input to scenario-based risk assessment. Develop communication supports to inform about the levels of ground shaking.
MaEA 3	Consider additional epistemic uncertainties in the simulation approaches	Better quantify the impact of uncertainties in the physics-based SPEED approach. Appreciate the variability from simulation-based methods compared to the variability from GMM.
MaEA 4	Alternative reference depth for the GMM	Minimize the effect of the assumption of 1D vertically wave propagation in the top 800 m outside the epicentral area. Additional constraint by G records at depth. Minimize the 3D effects between NS_B and reference depth. Seen as a major step in the reduction of uncertainty.

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5. Appendix 1: review process

KEM04 : DATA-DRIVEN STUDY ON SEISMIC STRUCTURAL FEATURES OF GRONINGEN GROUND MOTIONS.

Appendix 1 : Internal Review process

Document N°: STR_ 18P17_04

	Authors	Verification	Approval
Date	27/12/2019	02/01/2020	03/01/2020
Name	G. Ameri, R. Paolucci, A. Giannakou, C. Martin	C. Martin	G. Ameri

Version	**Date**	**Status**	**Description**
0	03/01/2020	final	Comments from internal reviewers and answers

Table of contents

1. Review process

Two reviewers were selected at the project's onset and have not been involved directly into the KEM04 research questions. Collectively the two reviewers cover all the complementary disciplines to provide advised comments on the outputs of the research questions including regional experience.

1.1 Reviewers background

The external reviewers were selected based on several criteria: (1) past experience on induced-hazards and risk assessment, (2) knowledge of data, methods and technical approaches and (3) balanced composition between in-country and international experience.

The two reviewers are Jean Savy (Savy Risk Consulting) and Ruben Jongejan (Jongejan Risk Management Consulting).

Dr. Savy has more than 40 years of experience performing and overseeing research, development and validation of analytical and experts' consensus methods in the areas of natural and man-made catastrophe hazards, risk and mitigation decision making. He has specific experience in the management of research and development projects, Probabilistic Seismic Hazard Analysis for critical facilities (PSHA), Probabilistic Hazard analysis for flood, wind and terrorism and Probabilistic Risk Analysis (PRA) and mitigation. Jean Savy is a recognized expert in the use of probabilistic techniques for the characterization of seismic hazard and risk for critical facilities. He has served on multiple peer-review panels for critical projects. He used to work on methods of integration of experts' knowledge to assess epistemic uncertainty in probabilistic hazard assessment.

Dr. Ruben Jongejan has multiple specializations in quantitative risk analysis and probabilistic design. He recently conducted several advisory missions to the Dutch government and was coordinator of an assessment of the seismic performance of the flood defenses at Eemshaven in the Province of Groningen and he use to collaborate with the GR-8 team in Holland, on addressing complex earthquake problems in the context of the Dutch flood defense codes. The experience of Dr. Jongejan was seen as added-value to the project for guiding the discussions and recommendations and to appreciate the feasibility of bringing the simulations-based approach into a probabilistic framework consistent with Dutch standards.

1.2 Process to conduct and reply to the review

Preliminary and uncomplete draft reports were sent to the reviewers at end of September 2019, for them to become more familiar with the content of the research activities conducted within RQ1 and RQ2.

The draft versions of the final reports were then sent on November 7, with the objective to receive from the reviewers an initial feedback by email, before the KEM Scientific Expert Panel meeting of November 12, 2019.

The reviewers were requested to provide the team, with written comments and requests for additional information when necessary. In particular, it was requested from the project side that the comments would be formulated in such way that (1) the reviews would be included in the final version of the project report (2) potential deficiencies with respect to the initial objectives of the research activities are identified (3) advice on how to put in perspective and take benefit from the research findings in the risk assessment program for the Groningen area are suggested.

The experts submitted their written comments on November, 25 and November, 26. The reviewers' reports were sent to the technical leaders of the project for their considerations.

The answering process has been as follow:

- Analysis of the comments and organization of a conference call to distribute the answering activities

- Preparation of written answers in the documents provided by the experts (the corresponding documents are presented in the sections 2 and 3 of this appendix
- Consideration of the comments in the revised versions of the reports.

The team has either submitted a response to the comment, or a demand of clarification to the reviewer depending on the complexity of the request. The technical team tried to provide a written clear, unambiguous resolution of the issues/questions raised in the comments. The answers as presented in sections 2 and 3 were provided to the reviewers for their information. It is not expected to conduct another round of questions/responses.

In the next sections, the original comments/questions are in black color and the answers in red.

2. Comments/Questions by R. Jongejan and answers

MEMO

From: Ruben Jongejan*
To: Gabriele Ameri (Seister SAS), Christophe Martin (Seister SAS), Jacob Chacko (GR8 GEO)
Date: 26 November 2019
Version: 2
Subject: Review of KEM04 reports RQ1 and RQ2

* Jongejan Risk Management Consulting B.V., Schoolstraat 4, 2611HS, Delft, The Netherlands,
Ruben.Jongejan@JongejanRMC.com, +31 6 1499 6316

1. Introduction

This memo summarizes the results of an internal review of the reports written within the context of the KEM04-study "a data-driven study on seismic structural features of Groningen ground motions". This review deals specifically with the stochastic nature of ground motions and the potential use of research findings in future PSHAs and HRAs. Please note that the details of ground motion modelling are outside my area of expertise.

The document is organized as follows. Sections 2 and 3 summarize comments and suggestions related to the reports for research questions (RQ) 1 and 2. Section 4 deals with potential avenues for using the computationally expensive 3D numerical model from the RQ2-report in future PSHAs and HRAs. Minor (general) comments and suggestions are given in section 5. Suggestions that are outside the scope for the present Task Order could perhaps be useful as recommendations for follow-up activities.

2. RQ1-report

The following comments and suggestions concern "Activities and results of RQ1 Document No.: STR_FUG_18P17_02, Draft Final Report, 07/11/2019".

1. In chapter 5, GMMV5 is compared to observations. The residuals are the differences between the natural logarithms of observed and predicted spectral accelerations (PSA). According to the text on page 29 "(…) the PSA from the GMMV5 in Eq.(1) is computed as a weighted *mean* of the 4 branches considering weights as specified by Bommer et al., (2018), i.e., L1=0.1, L2=0.3, L3=0.3 and L4=0.3." (italics added). Yet Figure 6.1 from Bommer et al. (2018) shows *medians* (reprinted in Figure 1). While the sum of the probability-weighted means of different distribution equals the mean of the composite distribution, this is not the case for medians.

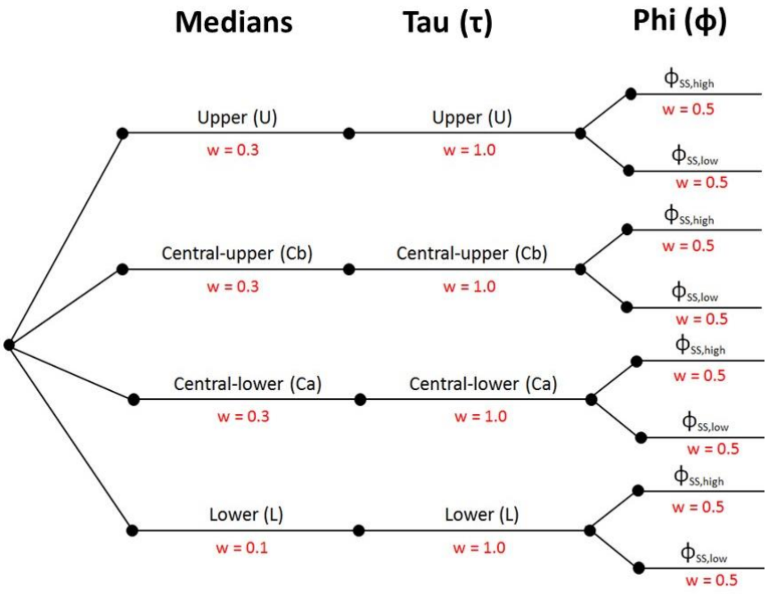


Figure 6.1. Logic-tree structure for model for motions at the NS_B horizon

Figure 1. Logic tree in GMMV5 (from: Bommer et al. (2018): page. 67)

A sum of probability-weighted medians could be greater or smaller than the median of the composite distribution. Put differently, the “mean median” is not the “true median”. This could be a rival explanation for the observed differences between median predictions and observations. To be able to unequivocally conclude that GMMV5’s median predictions are biased, it would be good to establish the true median predictions of GMMV5 as a basis for comparison.

Numerical experiment to illustrate the above

Consider two lognormally distributed stochastic variables, X_1 and X_2, with the following means and standard deviations of their natural logarithms: $\mu_{\ln(X1)}=1$, $\mu_{\ln(X2)}=2$, $\sigma_{\ln(X1)}=\sigma_{\ln(X2)}=0.3$. Now, let us introduce a new stochastic variable Y which is equal to X_1 with probability p_1 and equal to X_2 with probability p_2. Assume that $p_1=p_2=0.5$. The probability density functions of X_1, X_2 and Y are shown in Figure 2 below. The medians of X_1 and X_2 are equal to exp(1)=2.71 and exp(2)=7.39 respectively. The probability-weighted sum of the medians of X_1 and X_2 thus equals 0.5 x 2.17 + 0.5 x 7.39 = 5.05. Yet the median of Y equals 4.48.

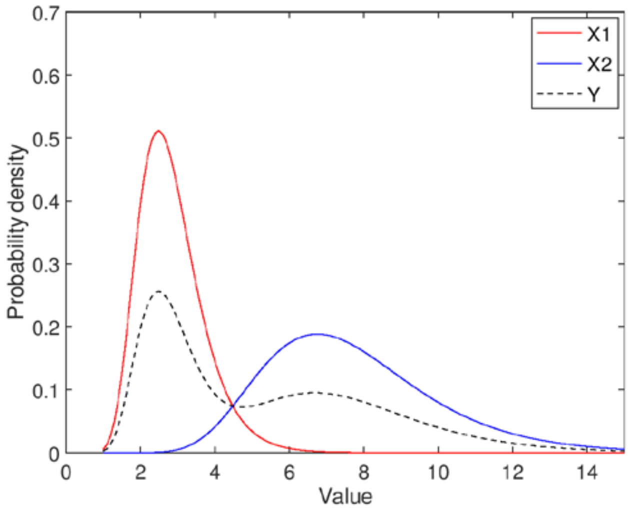
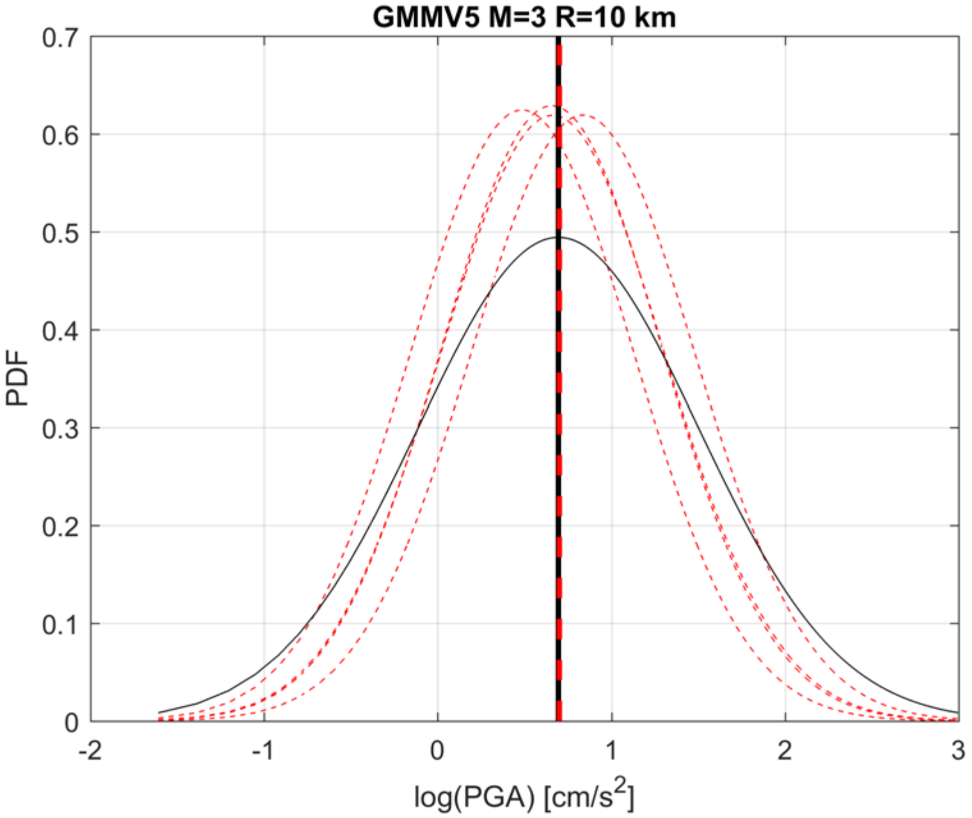


Figure 2. The probability density functions of the stochastic variables from the numerical example.

R1. We agree that the weighted mean of the four branches of the median predictions by GMMV5 is not equal to the median of the composite distribution with proportions defined by the L1 to L4 weights. However, in this specific case, the two quantities are very close due to the proximity of the predicted distributions from the four GMM branches for the magnitudes of interest for the residual analysis. This is shown in the following example were the weighted mean of the PGA as predicted by the L1 to L4 branches for a M=3 at 10 km (in red) is compared to the median of the composite distribution (in black). The two values are very close (2.0145 and 2.0031 cm/s^2) and such small differences are negligible for the purpose of the residual analysis.



2. Considering the difference between means and medians, it would be good to more clearly state throughout the report that only GMMV5-*median* predictions have been considered. For instance, it is somewhat confusing that the text on page 34 says that "*on average* the GMMV5 underestimates the observed short-period spectral accelerations". If a median is on average too low, the median could simply be said to be too low.

R2. This is clarified in the revised version of the report.

3. In PSHAs and HRAs, uncertainty matters. GMMV5 is essentially a probabilistic model. It would therefore be interesting to also consider other statistics, such as the mean and standard deviation of GMMv5 prediction errors. This would give a more complete picture of the accuracy of GMMV5 when used in a PSHA or HRA.

R3. The additional analyses mentioned by the reviewer would certainly be interesting but we stress that:

- The analyses are limited to the maximum observed magnitude in our dataset which is ML=3.4. Hazard and risk calculations are performed considering ML≥3.5. As a consequence it is difficult to assess the implications of the residual analyses for PSHA and HRA.
- The GMMV5 has been replaced by the V6 and V7 is currently under development. The simple residual analysis reported had the main purpose of understanding the behavior of the GMMV5 with respect to

an independent set of surface data. There are good chances that V6 would not show the same issues as V5 in the short period range because events have been added and errors removed. Thus, we are hesitant is putting more effort in analyzing V5.

4. Chapter 7 shows that the simplified EGFs-approach outperforms GMM V5. Is this due to the differences between some fundamental properties of these models or is this due to model calibration (i.e. the use of different data sets, with the one used for calibrating GMM V5 containing errors)? A discussion on the probable causes of the observed difference in performance could be useful for future work on ground motion models for Groningen.

R4. Part of the better performance of the EGF approach is certainly due to the fact that we are comparing the GMMV5 which is a probabilistic model to estimate the GM over the entire field with a deterministic prediction for the Zeerijp earthquake, using a specific EGF for that specific event (i.e., simulating another event would require a different EGF). Furthermore the Zeerijp event is not considered in the development of the GMMV5. Indeed we included the GMMV5 in the comparison as a reference only and it is expected that the EGF simulations provide better results. A discussion on the probable causes is added in the revised version of the report.

3. RQ2-report

The following comments and suggestions concern "Activities and results of RQ2. Document No.: STR_FUG_18P17_03, Draft report, 05/11/2019".

1. The M3.4 Zeerijp earthquake of January 8, 2018 was selected as a basis for both calibration *and* validation. What is the reason for not using different earthquake events for model calibration and model validation, e.g. the Zeerijp earthquake for calibration and the M3.4 Westerwijtwerd earthquake of 22 May, 2019 for validation?

R.1 – We did not take on a true calibration of our model, as we used the data and information available from NAM reports and KNMI website, agreed within RQ1. The only parameter for which no available information was given was the Q factor, for which we performed a calibration using data from a set of 6 different events (see Fig. 2.3 of RQ2 report). The validation of the model was performed with the M3.4 event that was not therefore considered for calibration.

2. Some additional explanation on the generation of the 3D random field of seismic wave velocities would be helpful (section 3.4.4). From what I understand, seismic wave velocities have been modelled as spatially variable in the horizontal plane and perfectly correlated along the vertical, with a decreasing standard deviation from ground level to a depth of 120m. Is that so? What effect would the authors expect from real-life variability towards the surface (i.e. the same standard deviation as a function of depth but autocorrelations smaller than one)? It could be interesting to add this to the discussion.

R.2 – The spatial correlation has been modelled in the horizontal plane but, for each depth, a different correlated stochastic field has been generated independently. The resulting layers are not perfectly correlated, because they are realizations of different lognormal probability distributions having as the mean value (function of the depth) the homogeneous velocity model described in the report and a standard deviation linearly decreasing with depth, modelled as so in order to have a smooth passage from a homogeneous to a heterogeneous field. For clarity, this section is enriched by a better explanation and discussion in the text of the revised version of the report.

3. The PGV, PGA and PGD (vertical and horizonal) obtained from a realization of the random field of seismic wave velocities are all smaller at the two selected stations than those obtained from average velocities. Because of the random nature of a random field, it would be interesting to see whether the

results for additional realizations of the random field (and/or additional stations) are similar or very different.

4. It would be interesting to compare simulation results for different realizations of the random field from section 3.4.4 to simulation results for different realizations of a uniform stochastic model (i.e. a random field that assumes perfect autocorrelation[1]). Such a comparison would make it possible to draw conclusions about the effect of spatial variability on the distributions of PGV, PGA and PGD.

R.3-4 – The computational burden of the SPEED simulations, as well as of the simulation of random fields for such large models, has been considered excessive for carrying out a specific sensitivity analysis that, in addition, is out of the scope of the work. On the other hand, we agree that a more robust sensitivity study on the influence of the spatial variability of the mechanical properties on the ground motion response of the field would be of interest for further developments of the model.

4. Using computationally expensive 3D numerical models in PSHAs and HRAs

From our introductory meeting on the 12th of November, I understood that the 3D numerical model (SPEED) for Groningen (20x20km) is too computationally expense for use in probabilistic seismic hazard analyses (or HRAs) that rely on numerical integration or crude Monte Carlo for computing probabilities. In that case, millions of model runs would be required. If more than e.g. 20 model runs already become prohibitively time-consuming or costly, even more efficient sampling techniques such as importance sampling will not provide a way out. Also, the development of a sufficiently accurate multivariate response surface (essentially a lookup table with interpolation) will not be feasible for the whole of Groningen with only 20 model runs.

It might be feasible to compute the exceedance probability of a particular importance measure at a particular location or the failure probability of a particular building with only 20 model runs using highly efficient, approximate probabilistic methods such as SORM or FORM. These methods would be unsuitable for the whole of Groningen, however. Note also that the use of more efficient, approximate probabilistic methods may not be acceptable to all stakeholders, even if this were to make it possible to use 3D-models that are able to more accurately describe the physics of earthquakes. At present, TNO uses numerical integration for probabilistic calculations (PSHA, HRA), NAM uses crude Monte Carlo. Both methods are “level III” (exact) probabilistic methods.

The 3D numerical model could perhaps be used as follows for improving future PSHAs or HRAs:

1. Direct use of the 3D numerical model in probabilistic calculations:
   a. Stacking models (“vertical combinations”):
      Run times could be reduced by not modelling the entire top 5km with the 3D numerical model but by avoiding the near-surface. The output of the numerical model would then form the input for a less advanced model.

   b. Parallel use (“combinations in the horizontal plane”):
      By using the numerical model only for small areas where less advanced models (e.g. GMM V5 or later version, EGFs-approach) do not provide satisfactory results, run times could be

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[1] The exact seismic wave velocity at a particular point in space is uncertain. A simulation based on average values of seismic wave velocities is essentially a simulation for a realization of a random field that assumes perfect autocorrelation (the field could also be populated with e.g. 95% or 1% values rather than averages throughout). As such, section 3.4.4 is not about comparing stochastic and deterministic models, but about comparing the effect of spatial variability in stochastic models.

reduced. However, for areas as small as e.g. 1 km^2, approximate probabilistic methods would probably still be required to be able to calculate seismic demands for small exceedance probabilities or small failure probabilities.

   c. A combination of a and b.

2. Indirect use:
   a. Gaining a deeper understanding of key phenomena:
   The 3D-model could be used in studies aimed at better understanding particular prediction errors and/or for identifying phenomena that warrant careful consideration in the (further) development of less advanced models. The RQ2 report provides several examples of this.

   b. Generating synthetic observations for model calibration or evaluation:
   The 3D-model could perhaps be used to generate synthetic (uncertain) observations for particular low-probability events that could then be used alongside actual observations in the calibration or evaluation of less advanced models. To generate informative synthetic observations, the selected events should be relevant to particular design loads (from the NPR) or failure probabilities (from the HRA).

R.5 As a matter of fact, the 3D model was not intended for a 'direct use' in PSHA. Besides, it was prepared for an 'indirect use', e.g. a better understanding of phenomena related to wave propagation, site or source effects, through visual inspection of maps, time histories, spectra…for different scenarios.

5. Minor comments and suggestions

1. The performance of alternative models has been evaluated by hindcasting historic events, i.e. by looking back, not by looking forward. Are there particular phenomena related to the seismic structural features of the Groningen ground motions that could change or become (more) important because of the rapid decrease in gas production? Could those be relevant for model development? If so, it would be good to add this to the discussion or recommendations.

R.6 This comment will be considered in the revised version of the report RQ3 volume.

2. The development of standardized fact sheets that summarize the key features of the available Groningen ground motion models would be useful for communication purposes.

3. Typos:
   - RQ1-report:
     - Page 42: "a quit strong bump" → "quite a strong bump"?
     - Page 52: "in only model as", "has been declined"
     - Page 65: "du to"
     - Page 69: "provide(s) strong complementarity with" → "complements"
     - Page 69: "Identify" → "Identifying"
     - Page 69: "a number of analysis" → "a number of analyses"
   - RQ2-report:
     - Page 31: "$\sigma(z_{max})$" → "$\sigma(z_{min})$"? (see also figure 3.15)
     - Page 40: "convenient" → "adequate"?

R.7 – Comments and suggestions have been accounted for in the revised version.

References

Bommer, J.J., B. Edwards, P.P. Kruiver, A. Rodriguez-Marek, P.J. Stafford, B. Dost, M. Ntinalexis, E. Ruigrok & J. Spetzler (2018). V5 Ground-Motion Model for the Groningen Field. Re-issue with Assurance Letter. Report prepared for NAM, March 2018.

3. Comments/Questions by J. Savy and answers

Review of documents KEM4-RQ1 and KEM4-RQ2

Reference Documents:
RQ1: KEM4: DATA-DRIVEN STUDY ON SEISMIC STRUCTURAL FEATURES OF GRONINGEN GROUND MOTIONS. Activities and results of RQ1.
Document N°: STR_FUG_18P17_02, 5/9/2019,
herein referred to as "the RQ1 Report", or simply "RQ1"

RQ2: KEM04: DATA-DRIVEN STUDY ON SEISMIC STRUCTURAL FEATURES OF GRONINGEN GROUND MOTIONS. Preliminary report on activities and results of RQ2.
Document N°: STR_FUG_18P17_03, 5/11/2019,
herein referred to as "RQ2".

Review by Jean Savy, SRC
November 25, 2019

1. Introduction

Most PSHA (Probabilistic Seismic Hazard Analysis) studies use simplified ground-motion prediction equation models (GMPEs) to estimate probabilistic seismic hazard, to develop design parameters, and to estimate specific risk associated with earthquakes consequences. GMPEs (earlier called Attenuation models) started without much specificity to the regional geophysical conditions, types of earthquakes, or local soil conditions. Nowadays GMPEs such as GMM V5 attempt to include as much details and specificity with use of all the geophysical and local information available in the Groningen region. The general questions RQ1 is exploring is whether there are some specific aspects of the region that are not included in GMM V5, whether there are aspects that cannot be included in a simple empirical model, and finally whether the proposed GMPEs could be improved or complemented with help from alternative methods of analysis, such as with help of physically-based 3D simulations.
This last sentence describes the general questions KEM04 is exploring, not only RQ1 but also RQ2.

The work described in RQ1 proposes to test configurations that are not usually accounted for in modern ground-motion prediction equations (GMPE). It includes four main parts in which a variety of methods and tools are used and tested for the purpose:

a. Collection and processing of data

b. Comparison of GMM V5 estimates with the available data
c. Selection of an appropriate calculation software a development of a 3D model
d. Comparison of estimates with GMM V5

RQ2 uses the same tools as RQ1 to investigate the effects of general topography, shape and depth of Zechstein salt inclusions and Peelo valley.

RQ2 does not use the same tools as RQ1.
RQ2 uses 3D physics-based numerical simulations. RQ1 uses EGFs-based simulations. These methodologies are fundamentally different.

2. General comments on RQ1

1. Overall, the rapport is well constructed and the choices made as to the tools and techniques to answer the questions asked make sense and are professionally conducted. The first question I have is regarding the estimates of depth in the data. Table 2.2 (and Fig. 7.1 page 37) only show depths to be 3 km which seems suspicious and could be just a default value due to the uncertainty in the determination. Since this could have an impact in the study, and on the results, it would be prudent to investigate this further.

   R1. The large majority induced earthquake occurred in Groningen are located into the reservoir which is in the Rotliegend formation located at about 3 km depth having a thickness of few hundred meters. The relocations performed by KNMI (Spetzler and Dost, 2017; van Stiphout, 2018) confirmed that most events indeed occur at reservoir depth. The figure below shows the best solutions for depth of several events between 2016 and 2018 obtained by van Stiphout (2018). Most of the events have a depth of 3km with few events in the range of ± 200 m. This uncertainty should have a negligible impact on the results.

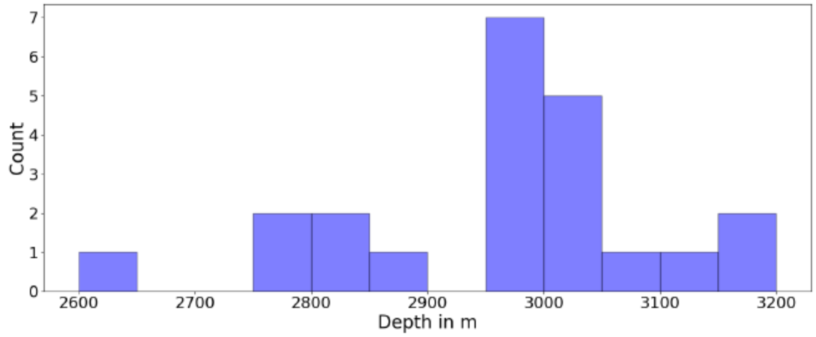


Figure 4.35: Histogram with bins of 50 m showing the mean depths for inversion for Zeerijp and Appingedam with $M_L \geq 1.5$.

   We also point out that for the 2018 Zeerijp event we indeed considered the relocation by van Stiphout (2018) in the RQ1 and RQ2 simulations (this is now specified in the revised version of the report).

2. The calculations are performed without consideration of the epistemic uncertainty on the parameters, consequently it is difficult to appreciate the differences with the GMM V5 model.

R2. To which calculations is the reviewer referring to? In case of the EGFs simulations for Mw=4.5 and larger magnitudes, we do not agree with the reviewer's comments. As clearly stated in page 59 of RQ1 report, several epistemic uncertainties are considered in the EGFs simulations, namely:

- The stress drop (which also controls the rupture dimension)
- The slip distribution;
- The position of the rupture over the hosting fault along the strike;
- The position of the hypocenter along the strike on the rupture.

There is definitely additional work that could be done to include epistemic uncertainties in e.g., the EGF itself (for example selecting multiple EGFs). This is one of the recommendations suggested in RQ3.

3. The validity of the assumed linear behavior is not clearly confirmed for at least 1 case as it appears in fig. 5 and 6. (see p73-74). To do so would require an estimate of the strain at the different depths. Since the frequencies of interest are in the 2 to 10 Hz range, it would be better to show all these figures with frequencies in the x-axis, to see the differences more clearly between the calculated and observed spectra. At least, more discussion is necessary to explain why the linear assumption is acceptable in the view of the comparison in fig. 5.

   R3. The shear strains that develop in the site response analyses for the earthquakes considered are low (i.e. less than 0.02%) and within a range where the linear assumption is considered to be appropriate. This has also been verified in comparisons between linear and equivalent linear site response analyses results for the Mw 3.4 2018 January 8 Zeerijp earthquake where results are essentially the same.

   This is one of the recommendations of the RQ3 that comparisons are undertaken as a KEM04 specific additional work to investigate more in details the nonlinear effects at some stations. This additional work and corresponding report will be part of the project's documentation.

   The differences between the recorded motion at the ground surface and the motion estimated by linear site response observed at some stations are more likely attributed to the idealized material properties used (i.e. shear wave veloctity, modulus reduction and damping curves) rather than the linear assumption.

4. Since we are looking at comparisons with GMM V5, which I have not seen, it would be very useful to have a description of that model at the beginning of the report, with all the relevant parameters that are used in the comparison, and ranges of applicability. An appendix would also be appropriate. This is an important point as we want to make sure that appropriate same-case comparisons are made. Including all types of uncertainty in the calculations should be an imperative of further work in this project. Deriving an estimate of uncertainty in the development of empirical models is primarily driven by the observed data. It is much more difficult to do so with physically-based simulations as many parameters in the calculations are not very well known, thus leading to possibly large ranges of uncertainty in the predictions.

   R4. The GMMV5 report is publicly available and can be accessed from the NAM web-portal. The GMMV5 is a complex model that requires a detail description to be able to understand the main assumptions and parameters used in its development. We believe that the best understanding of the GMMV5 can be obtained by the original report (Bommer et al., 2018) and that any attempt to simplify or summarize it will likely result in a less clear description. Thus it was our deliberate choice to do not include any further description of the GMMV5 in our report.

5. Characterization of V/H ratio is an important product of this work, but its usefulness is limited by the lack of estimation of epistemic uncertainty in its determination.
   R5. First we have to stress that the vertical component of the ground motion is not currently used in the Groningen HRA. So the V/H results are certainly interesting but we would not classify them as an "important product" of KEM04. For this reason, our aim was not to develop a V/H model to be used in the HRA that certainly would have required the quantification of uncertainties. We rather wanted to evaluate the V/H observed from earthquake recordings in Groningen in order to compare them with current V/H models. In this sense uncertainties can be appreciated from figure 4-3.

6. In section 6.4 "M_w5 scenario and non-linear effects in soil response » the statement "in the epicentral area, peak values of earthquakes ground motion significantly larger than predicted by GMM-V5 are found. » is not supported in a robust fashion, due to the issue mentioned regarding the validity of the depth estimates in the observed data, and due to the lack of uncertainty estimation.

   R6 (RQ2) The statement is related to nothing but what obtained from the simulations based on a specific scenario, using input parameters consistent with what considered for development of GMM-V5. Of course, if we will be requested to extend the number of scenarios to a wider range in order to account for the various epistemic uncertainties (not only hypocentral depth!) we shall do it, but presently this was out of our scope.

7. Question about magnitude units. All observed data are in M_L, and all the simulations are in M_w. Presumably GMM V5 is also in M_w.
   What was done to convert from one to the other when it was necessary, and in that case, was the uncertainty in the conversion included? A discussion is needed on this issue.

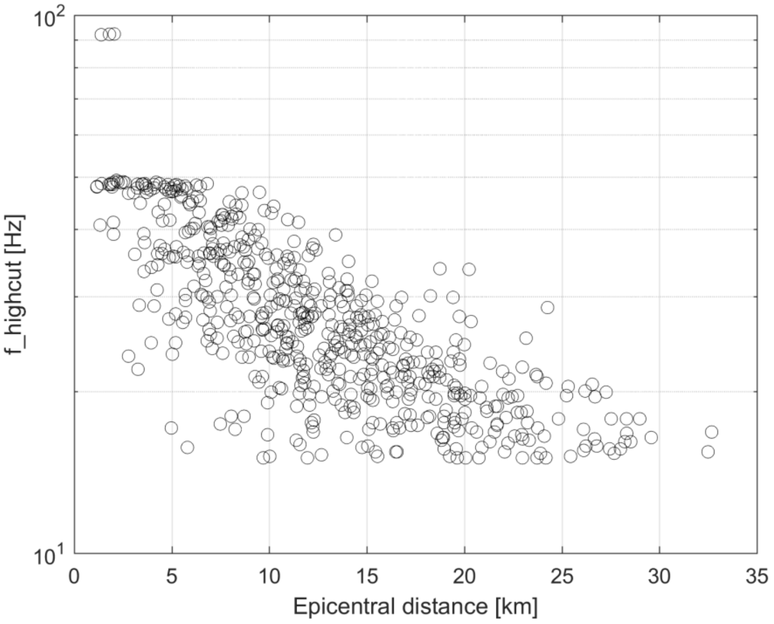
   R7. For Groningen, and upon advice of KNMI, the equivalence ML=MW holds, at least for Mw > 2.5. (see Dost et al., 2019)

3. Other comments on RQ1

8. Page 19, section 3.4: "The maximum usable spectral frequency is defined as 100 Hz but only records with f_highcut >= 15 Hz (the frequency of the high-cut filter) are used for the calculation of the PSA ratios in order to have a reliable estimation of PGA."
   Can you explain how the estimate of the PGA is more reliable if the frequency energy above 15 Hz has been removed from the record?

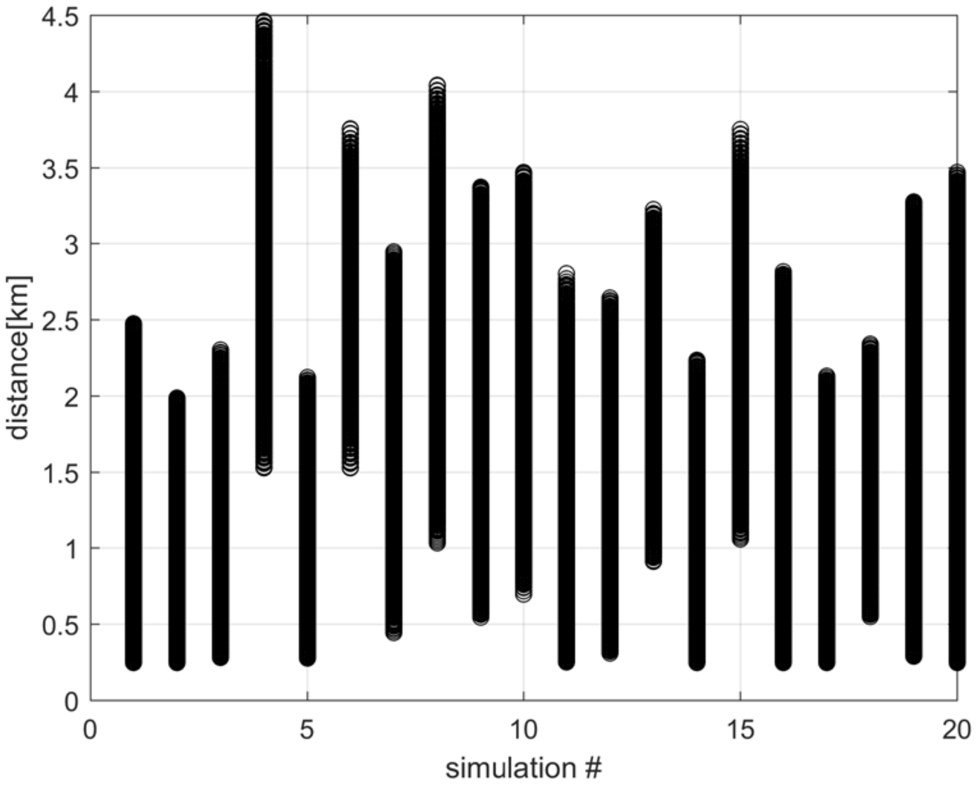
   R8. There is a misunderstanding here. In the report it is written that only records with high-cut filtering frequency ≥ 15 Hz are considered for response spectra calculations.

This doesn't mean that the records are all filtered with high-cut frequency of 15 Hz. The figure below shows the values of f_highcut for the processed G0 records.



9. Page 48, fig 7-10: Could the variations in the azimuth be also due to propagation in 3D going up and down in the fault surface at an angle of dip?
R9. The considered directivity function shows variations in the horizontal plane thus accounting only for along-strike directivity. Surely a component of along-dip directivity may be considered.

10. Page 57-58, Finite fault approach simulation with EGF, Green function correction: can we get a full description of the application for the blind simulation of the M_W=4.5 and M_W=5.0 events. What events were used as EGF, their ML and estimated Mw, depths (I suppose 3km). How far they were initiated from the points used in the simulation. Can the level of correction be given, in simple terms?
R10. A table with EGFs parameters has been included at the beginning of section 7.3.2. Generally speaking, the EGFs are used in the simulations on sub-faults that are relatively close to the original location of the EGF. This is due to the relative small dimensions of the rupture and the fact that the depth of the top of the rupture is fixed to 3km. The figure below show the distance between the original location of the EGF and the sub-fault to which the EGF is applied in the simulations (for the Mw=5 scenarios).
The distance-correction applied to the EGF is defined in terms of geometric spreading and anelastic attenuation (Q) based on the GIT results. The attenuation is computed combining a piece-wise geometrical spreading function (with a hinge distance at 7 km and corresponding decay rates of -1.55 and -1.0) with a frequency independent quality factor, Qs=220. This attenuation function is similar to the one used in the development of GMMV5 but it provides slightly better fit with the GIT nonparametric attenuation functions.



11. Since all the observed events are assumed to initiate at depth of 3km, and the blind simulations are for a M4.5 and M5.0, which rupture at greater depths, is that a problem?

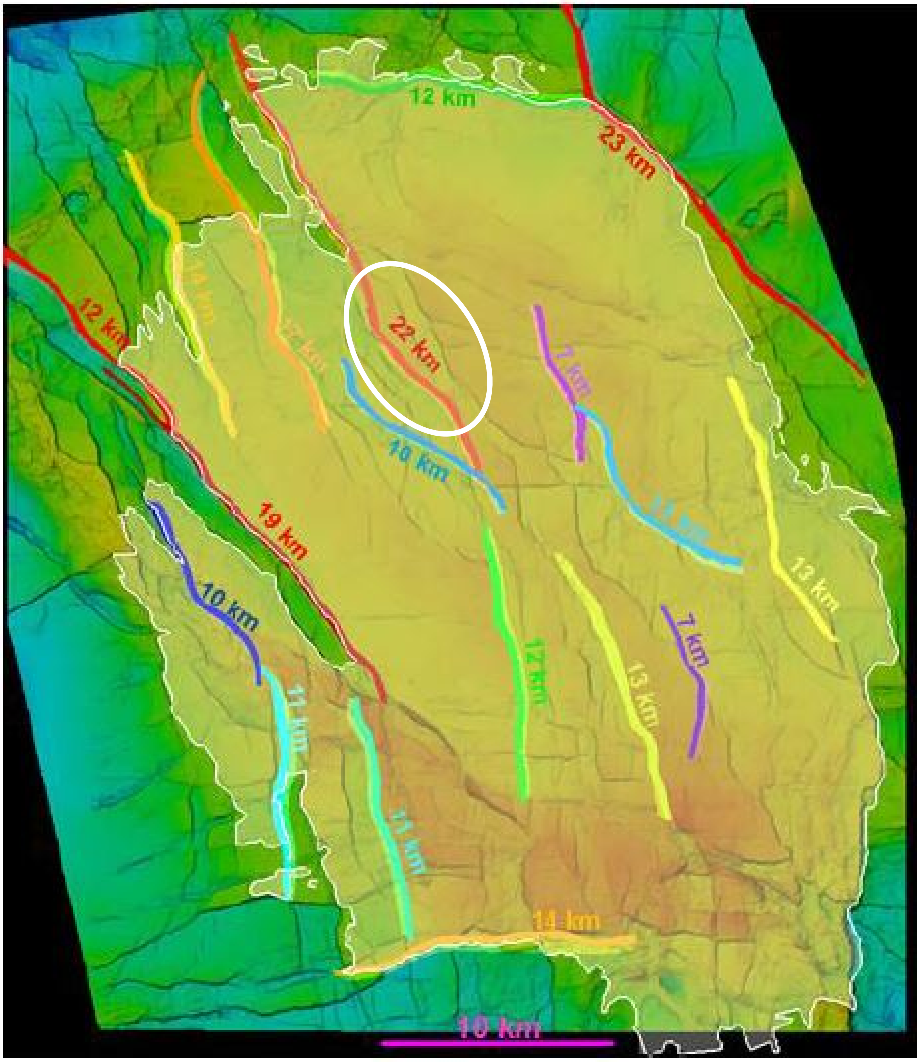
    A discussion on that issue is necessary.

    R11. We do not think that the issue mentioned by the reviewer is a "problem" but it certainly needs to be handled. The way we handle the distance correction of the EGF is detailed in the previous reply (R10). Furthermore, the difference in the Vs in the source region, which increases with depth, is also taken into account (as explained on page 59 of RQ1 report).

12. A M5.0 is outside of the range of magnitude likely to be induced by the gas exploitation and it would probably be of a different regime than the induced events (maybe a yet unknown blind fault). It is difficult, albeit not very possible, to predict the likely location and propagation direction of such an event. Consequently, I think at least two options have to be considered. One which would be the worst possible case (something akin to a precautionary case), and a second option would be to perform a full PSHA, that is, to include all possible events like in all present-day PSHAs, with full consideration of epistemic uncertainty. Clearly, the blind simulation presented in RQ1 is not akin to a PSHA. What were the criteria to decide of its location and fault properties (aside for its magnitude)?

    R12. First we would like to stress that it was never meant to be the purpose of RQ1 to produce a PSHA based on EGF simulations. The aim was to test such approach for several realistic scenarios in Groningen.

In this respect, the location and fault properties were defined based on the available information from the number of studies conducted in the area in the last years. The figure below (from NAM, 2016) shows a map of the longest faults below the reservoir (affecting the carboniferous) that could host large-magnitude events. The fault assumed to activate in the EGFs simulations in Zeerijp in marked in white. The dip (70°) and fault mechanism (normal) are assumed consistent with the GMMV5 simulations.



13. ANNEX 1 – Deconvolution page 65, section 11.1:

Item 3. Was the assumption of linearity fully checked by examining the strain levels in STRATA? And do we have material properties of the material at the locations of the wells? Do we have reliable degradation curves for G_0 and Damping as a function of strain to be used in STRATA?

R13. The linearity assumption was checked with the levels of maximum strains that develop (which are less than 0.02%) and was considered to be valid. As mentioned above additional site response analyses were performed using equivalent linear and nonlinear approaches and for the recorded motions it was shown that results between linear and equivalent linear analyses were essentially the same. Seismic CPTs were performed at the locations of the stations up to about 30 m depth and they were used in the development of idealized shear wave velocity profiles at the stations. For larger depths the soil model described in Bommer (2018) was used. For the equivalent linear/nonlinear site response analyses performed as part of the additional scope, since no site-specific cyclic laboratory tests are available for the region-wide study, shear modulus resuction curves and damping published in the literature were used as described in detail in Bommer et al. (2018) which contain detailed description of the soil model for Groningen (for example Darendelli 2001 MRD curves were used for clays and Menq 2003 for sands).

14. Editing, typos etc.

Although the report is well written and put in good form, the following are only some of the typos, misspelling and other things noticed, that need correcting:
~~*page 10*, penultimate line of the first par., replace “in only model” by “is only modeled”~~
~~*page 18*, section 3.3 , 4th line: duplicate “to to “~~
~~*page 24*: “We can observe that at such very short distances the P-waves amplitudes in the vertical direction exceed the S-waves amplitudes in the horizontal direction. We can also note that in some cases the P-waves amplitudes also exceed the S-waves ones in the horizontal direction.” Is that what you wanted to say? It is not clear what the second part of the sentence means.~~
page 30, first line: duplicate “others others”
page 34, section 6.4, first line: replace “done” by “taken”
~~*page 35*, section 7.2, 5th line: should “will be performed” be replaced by “was performed”~~
~~*page 44*, figure 7.7. Vertical bars are mentioned in the cation, but there are none that can be seen in the figure itself.~~
~~*page 48*, third line: replace “...we obtained da rupture...” by “...we obtained the rupture...”~~
page 48, caption of figure 7-10: “XX” needs to be replaced by the actual eq. number in the text. 9?
~~*page 50*, section 8.1 second line: suggested to remove “to some extent”, to obtain” ... GMMV5 that are limited...”~~
~~*page 50*, section 8.1, 5 lines before the end, “simulated” should be replaced by “simulate”~~
~~*page 50*, section 8.2, 3 lines before the end: replace ”... the site response in only model as...” by “...the site response is only modeled as ...”~~
~~*page 61*, 10 lines before end of page: replace “...(with same ML of the Zeerijp on)” by “...with the same ML as that of the Zeerijp one)”.~~
~~*page 61*, two lines below that above, replace “...would have help to better understand...” by “...would have helped to better understand...”~~

4. General comments on RQ2

Most of the general comments made above on RQ1 directly apply to RQ2. i.e. lack of epistemic uncertainty accounting, questions about depth of the earthquakes, etc.., which are not repeated here unless the add to the review. There are a few additional comments, including some on the deconvolution exercise.

R14. As an introductory clarification on the objectives of the 3D physics-based numerical simulations (3DPBNS) carried out within the RQ2 activities, it should be pointed out that 3DPBNS were planned to quantify the effects on ground motion related to 3D source-path and complex geological features, with specific attention to (i) effect of Peelo Valleys; (ii) effect of Zechstein salt dome inclusions; (iii) effect of different assumptions on Q-factor; (iv) stochastic heterogeneity of shallow soil properties; (v) simulation of a Mw5 scenario, and quantification of non-linear soil response effects in 3D.
Based on such evaluations, and on the comparison with the available GMM when appropriate, RQ2 was further expected to contribute to recommendations for the evolution/improvement of the GM component of the hazard and risk model.
With these objectives, the main steps of RQ2 activities were as follows:(a) development of a numerical model for of the Groningen area; (b) selection of the Mw3.4 Zeerijp earthquake as validation case; (c) Sensitivity analyses; (d) comparisons with GMM-V5; (e) synthesis of results and recommendations.
In this perspective, there was no plan in RQ2 to construct an alternative GMM, that would have required a careful evaluation of epistemic uncertainties, as underlined by Reviewer 2. The Vs numerical model was borrowed from that of Deltares, while a calibration of the Q model, in amplitude and frequency, was made in order to obtain a best fit to recorded spectral amplification functions. Sensitivity analyses were then carried out in order to answer the questions posed in RQ2.
As from the detailed answers to the reviewers remarks, we believe that many of such remarks originated from the misunderstanding of the role of RQ2 activity and of the results of numerical simulations. For this reason, it was decided to explain, within a common introductory section of the KEM04 reports, the objectives of the whole KEM04 project and how the different activities have interacted to pursue such objectives. This can be found in the final documentation.

15. The figures are often difficult to read and therefore difficult to understand because the colors are not different/contrasted enough for the reader to appreciate and in other figures the labels are so small that they cannot be read.

R15. We agree on this point. A comprehensive revision of the figures is being taken into account and will be addressed directly in the revised version of the report.

16. Before embarking in complex set calculations for the purpose of comparing different ground-motion models, GMPEs and methods, it is necessary to set the stage by explaining how the results will be used. In particular, it is necessary to identify the frequency range of interest for the purpose of doing a risk analysis. I assumed that in the present case we are mostly interested in the range of 2 to 10 Hz for the general built environment. Complex mechanical facilities or equipment might be sensitive to higher frequencies, such as chemical, or nuclear facilities, and some of the local

infrastructure, such as bridges, or tall buildings, might require information at lower frequencies, albeit at periods up to several seconds.

R16. As set in R14, objective of RQ2 was to give an answer to specific questions posed within KEM04, not to perform a risk analysis. Simulations beyond 10 Hz where out of concern in this task of the project.

17. The use of the open-source piece of software (SPEED) calls for a robust demonstration that it has been validated and verified by an independent entity. The text states that it has been done but it gives no reference to prove it. In the study there is later a verification by comparison with Hisada and Bielak's code, but this is for a very specific case only and does not constitute a validation.
R17. The open source code SPEED has been thoroughly verified within international benchmarks and amply validated based on different earthquakes, such as Christchurch (2011), L'Aquila (2009), Po Plain (2012), Norcia (2016). Specific reference to related papers will be addressed in the revised version of the report.

18. In figure 2.1 it is mentioned in page 7, section 2.1, that the computational domain is shown by a "black rectangle". Should it be a "red rectangle"?
R18. We agree, this has been corrected in the revised version of the report.

19. Table 2.2: Some explanations are needed on the estimates of depth. Are they all, really 3 km? What is the uncertainty?

20. What would be the impact of accounting for that uncertainty in the results of the study?
R19-20. Data are taken from the KNMI portal. The uncertainty of depth values of such earthquakes is of no relevance for our task.

21. Page 12, section 2.4, line 4: The size of the mesh has to be smaller to allow propagation of higher frequencies. Should the beginning of the sentence "The minimum mesh size was calibrated to correctly propagate frequencies up to 10 Hz…" be replaced by "The maximum mesh size…", or simply by "The mesh size was calibrated…"
R21. The right term is "minimum mesh size". Some clarification will be added in the revised version.

22. Page 13, section 2.5: There is no mention of the rupture propagation for the finite length fault rupture for M5.
R22. Details are provided in Figure 4.1.

23. Page 19, section 3.3, figure 3.5: Comparison is made between an observed record located at 1.41km of epicentral distance, with a simulation that uses a depth of 3km. As mentioned above, the reliability on this depth estimate is not demonstrated, and this casts a negative shade on the comparison, which otherwise is declared in the text to be very good.
R23. We do not understand this point and we do not see any negative shade on what we did. Depth is provided by KNMI as a best estimate, as well as the other focal parameters

(strike, dip, rake, and Mw itself). It is not our task to provide sensitivity to these parameters, but to make a validation with these values.

24. Page 31, section 3.4.4: There is no good explanation as to why we observe anomalies in the spectral ratios in figure 3.17 around 3Hz and 8Hz. Could it have something to do with the correlation distance used in the stochastic model of the velocity, and the dimensions of the mesh? Was there a sensitivity study to see how that pair-combination affected the results?
R24 Sensitivity studies on the impact of the correlation distances was beyond the scope of the work: we considered the best estimate as provided by the observed spatial variability of Deltares data. Nonetheless we agree on the need of a future clarification on this issue of relevant theoretical and practical interest.

25. Page 40, section 4.1: "As one of the purposes of this study is the comparison with the GMM-V5 predictions, the geometric parameters of the finite-fault rupture scenario were selected consistently with the EXSIM simulations performed for the construction of GMM-V5 [4]." Since the development of GMMV5 was for the entire area of study, its development, which I assume would have included a number of simulations to cover the estimate of epistemic uncertainty.
Firstly, RQ2 should contain a description of the GMMV5 model and a description of the set of corresponding parameters that are used in this study (RQ2).
Secondly, there should be a description of the set of remaining epistemic parameters that are simulated in RQ2 and the epistemic uncertainty in the final results should be estimated.
R25 As explained in the introductory reply R14, the goal of RQ2 was to give answers to specific questions posed within KEM04 and not to introduce alternative GMMs nor to provide quantification of epistemic uncertainties. Still, we have carried out several sensitivity analyses on some modelling assumptions that pertain to such quantification (dependence of Q-factor on frequency, spatial variability of Vs, 3D vs 1D interfaces). See also reply R4 of RQ1 section.

26. Page 42, top of page: Refs. Rodriguez-Marek et al. (2017) and Kishida et al. (2009) are missing in the list of References.
R26. Thanks, we have added such references in the revised version of the report.

5. Other comments on RQ2:

None.

Respectfully submitted,

Jean Savy, SRC