



Continuation of KEM04 to adapt to GMM V7 (KEM36/ IUC202212048)

Phase 1 Report |

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Fugro	Project Management
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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.

On 14 July 2020 Fugro issued the KEM04 report: data driven study on seismic structural features of Groningen ground motions. It is available on the KEM website: <https://kemprogramma.nl/blog/view/37cfcc1c-c6fd-4b38-a173-32b8f8467933/kem-04-data-driven-study-on-seismic-structural-features-of-groningen-ground-motions-finished>

The KEM04 study not only resulted in insight into the relevance of salt domes and thickness of the Pleistocene geological layers, but also in a better understanding of the GMM V5 that was developed by NAM. The KEM04 team developed multiple 2D and 3D models to simulate earthquakes and compare results with recordings and GMM V5. Several recommendations were given to further develop the GMM.

Since 2020, NAM made a 6th and 7th (and final) version of the GMM. At the beginning of 2023, Fugro was awarded phase 1 of the KEM36 study, which is a follow-up of the KEM04 study. The KEM36 team consist of part of the former KEM04 team. Seister and Politecnico di Milano are the subcontractors that are responsible for the technical part of the study. For the results, we refer to the attachment Seister Report A, STR_FUG_23P07_01_02 and the comments by K. van Thienen-Visser received on 4th September 2023.

Report Seister

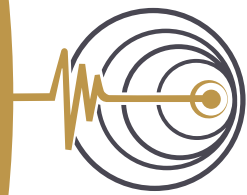
KEM36: Continuation of KEM04 study to
compare to GMM-V7. Phase 1

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1. Introduction and background

The KEM04 project investigated alternative approaches to model earthquake ground motions in the Groningen area, with particular attention to 3D effects. Part of the activity in KEM04 aimed at identifying 3D effects using recorded data from local earthquakes and part aimed at using 3D physics-based numerical simulations. At the time of KEM04, the latest GMM used by NAM in the hazard and risk model was Version 5 (V5). For such reason, during the KEM04, a series of comparisons were performed between ground motion estimates from V5 and observed data or simulated ground motions based on 3D numerical wave propagation. A series of recommendations were issued concerning potential drawbacks and issues of V5.

The objective of this new KEM36 project is to assess whether the issues we raised about V5 during KEM04, as well as the sources of improvement identified, have been addressed (and to what extent) in the most recent GMM V7 (hereinafter V7). Moreover, a series of questions are asked by the Ministry concerning several components of V7 (attenuation, soil response, source stress-drop).

In our proposal for KEM36 (in response to the Request for offer 202212048 'Continuation of KEM-04 to adapt to version 7 GMM'), we believed that it was not possible to address the three research questions (and in particular RQ1 and RQ2) appropriately within the time-frame and budget announced in the Request. For this reason, an alternative phased approach was proposed as follows:

- Phase 1 was conceived to address RQ 1 and part of RQ 3 within the time frame and budget asked in the Request. The Phase 1 scope of work should allow revisiting the results of KEM04 in light of V7 model but without conducting new 3D simulations.
- Phase 2 was conceived to address RQ 2 and the remaining part of RQ 3, with additional time and resources to be accomplished.

Only Phase 1 has been awarded by the Ministry and its results are summarized in this report. Decision on the award of Phase2 has not been taken yet and the foreseen activities (in case of award) are summarized in section 6 at the end of this document.

The Phase 1 scope of work consists of the following steps:

- analysis and understanding of V7 documentation (Bommer et al., 2022a);
- independent implementation of V7, with the necessary verification and validation;
- analysis of previous results produced by KEM04 and comparison with V7 (instead of V5);
- comparison of predictions from V7 with new observations available in 2022 (not used in V7).

2. Summary of main outcomes of KEM04 concerning GMM-V5

The KEM04 project lasted about 2 years and made use of the observed recordings and of advanced 3D simulation techniques to improve the understanding of the earthquake generated ground motions in Groningen. For convenience, we recall here the main outcomes of KEM04 concerning specifically V5, referring to the KEM04 final project report for more details.

The main points raised on V5 were:

- the issues related to short-period ground motions (and PGV) recorded at B-stations being lower than at G-stations;
- the input parameters for the EXSIM simulations at NS_B:
 - the rate of attenuation with distance in the range 7-15 km, that was not consistent with the results presented in KEM04 based on the nonparametric spectral inversion performed using the KEM04 dataset (Ameri et al., 2020);
 - the values of stress drop estimated for recorded events in KEM04 (Ameri et al., 2020), that were generally lower than those estimated in V5;

- the residual analysis presented in KEM04 pointed out that the observed short-period spectral ordinates at short distances were underestimated by V5;
- the ground motions from 3D physics-based simulations showed higher peak values than V5, particularly at short distances. This was also observed at NS_B horizon although the difference was less significant;
- the assumption of 1D vertical wave-propagation in soil response analysis in V5 (particularly in deconvolution to NS_B) was found questionable with respect to the non-1D wave propagation observed in the physics-based simulations, caused by the shallow depth of the hypocenters;
- the large soil nonlinearity developed in the V5 site-response model already at relatively low strains was also considered questionable in particular due to the absence of locally calibrated soil degradation curves.

3. Implementation of GMM V7

The main steps for the development of V7 remains largely unchanged with respect to V5 and presumably V6 (we recall that detailed analysis of V6 was outside the scope of KEM04), namely:

- (1) The observed recordings are first deconvolved to NS_B, in order to derive the seismological parameters for the EXSIM simulations;
- (2) A model for ground motion at NS_B is developed based on the EXSIM simulations for the required magnitude range;
- (3) The ground motions at NS_B are modified to account for soil response from NS_B to the surface based on amplification factors specific for each identified zone in the field.

3.1 Main modifications with respect to V5

Despite that the general scheme from V5 to V7 has not changed significantly, several important modifications are made in principal ingredients of the model. Discussing such modifications in details is outside the scope of KEM36; here we report the main differences that are of particular interest for the purpose of KEM36.

- The dataset of observations is expanded and a new processing procedure (Edwards & Ntinalexis, 2021) is applied in order to improve the data quality. The dataset used in V7 contains events with $M_L \geq 2.5$ occurred up to the end of 2020.
- A correction procedure is applied to recordings from three (3) B-stations located in basements for which soil-structure interaction (SSI) effects are identified. A clear assessment of the impact of the network on the GMM estimates is conducted.
- Vs profiles are available at almost all G stations used in V7. This allowed to use only surface recordings for the deconvolution to NS_B, whereas surface and boreholes recordings for B and G stations, respectively, were mixed in V5.
- Several modifications are made in the soil model (low-strain damping) and in the FAS inversion to derive input parameters for EXSIM simulations at NS_B.
- The functional form for the GMPEs at NS_B has been modified and the number and range of spectral periods is reduced to 10 up to 1.0 s, with no values between 0.01 s and 0.1 s.
- Scenario-dependent spectral amplification functions of soil response are introduced in V7, to account for differences in response spectral amplification in the linear range, owing to different frequency content of the excitation from the seismic source and to different propagation paths; this is shown to have a considerable impact especially on PGA (see e.g. Fig. 4.16 of Bommer et al., 2022a).
- Finally, though less important for KEM36, the logic tree structure to account for epistemic uncertainties is different in V7. Similarly to V5, four branches are used for median predictions. However, both epistemic uncertainties in the inter-event and intra-event variabilities are included in the logic tree in V7 (3 and 2 branches, respectively). 3 branches to account for

uncertainties in the site amplification factors (AF) are also included. We note that the weights of the 4 branches for prediction of median ground motion change with magnitude.

3.2 Implementation, verification and validation

The implementation of V7 was the first step of KEM36, in order to perform an independent evaluation of the model and to be able to compare the previous KEM04 results with the new GMM. V7 was implemented in Matlab and the code is available as supplementary material to this report.

We limited the implementation to the part of the model that is used for hazard calculations avoiding the elements (e.g., component-to-component variability, period-to-period correlation model) that are used for the risk assessment (referring to Table 9.3 in Bommer et al., 2022a).

The verification and validation (V&V) of the implementation is conducted based on the figures contained in the V7 reports (Bommer et al., 2022a, Bommer et al. 2022b). For sake of brevity, we will show here only few examples of such comparisons. Figure 3-1 shows examples of V&V regarding the distance and magnitude scaling of ground motions estimated by V7 at NS_B for three spectral periods ($T=0.01s$, $T=0.2s$ and $T=1s$). Figure 3-2 and Figure 3-3 show examples of V&V in terms of response spectra predicted at the surface for two zones and two magnitudes at several distances. In all these figures, the black curves superposed on the colored ones represent our implementation of V7.

We observe that the ground motion values from our implementation of V7 are coincident to those in the GMM documentation which allows validating our implementation.

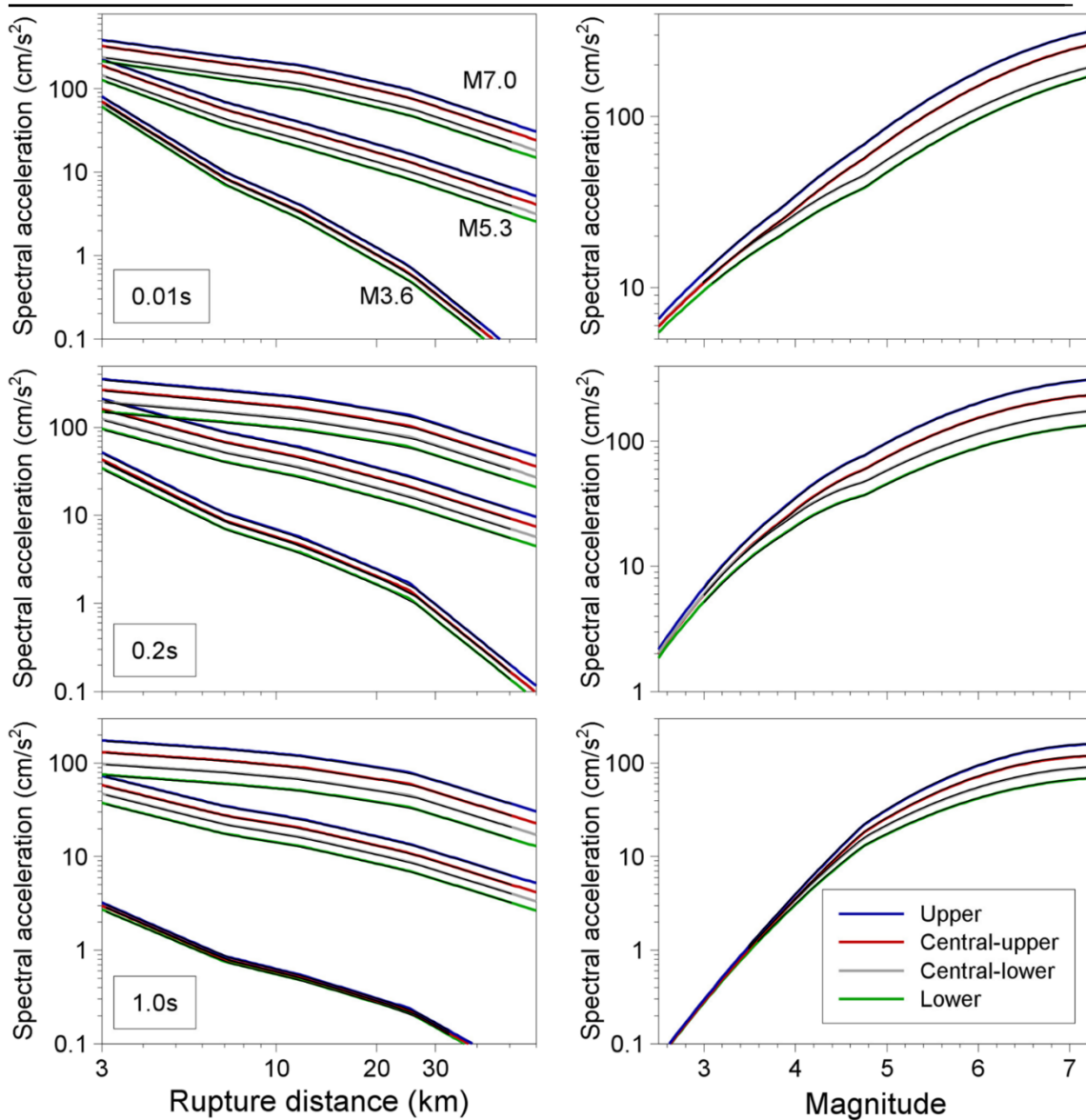


Figure 3-1 : V&V of the V7 model implemented in KEM36 for NS_B horizon. Predicted median spectral accelerations are shown at periods of 0.01 s (top), 0.2 s (middle), and 1.0 s (bottom) from the four models of the logic tree for various magnitudes as a function of distance (left) and as a function of magnitude for $R_{rup} = 5$ km (right). The black lines represent the implementation by KEM36 and coincide with colored lines in the original figure (modified from figure 12 of Bommer et al. ,2022b).

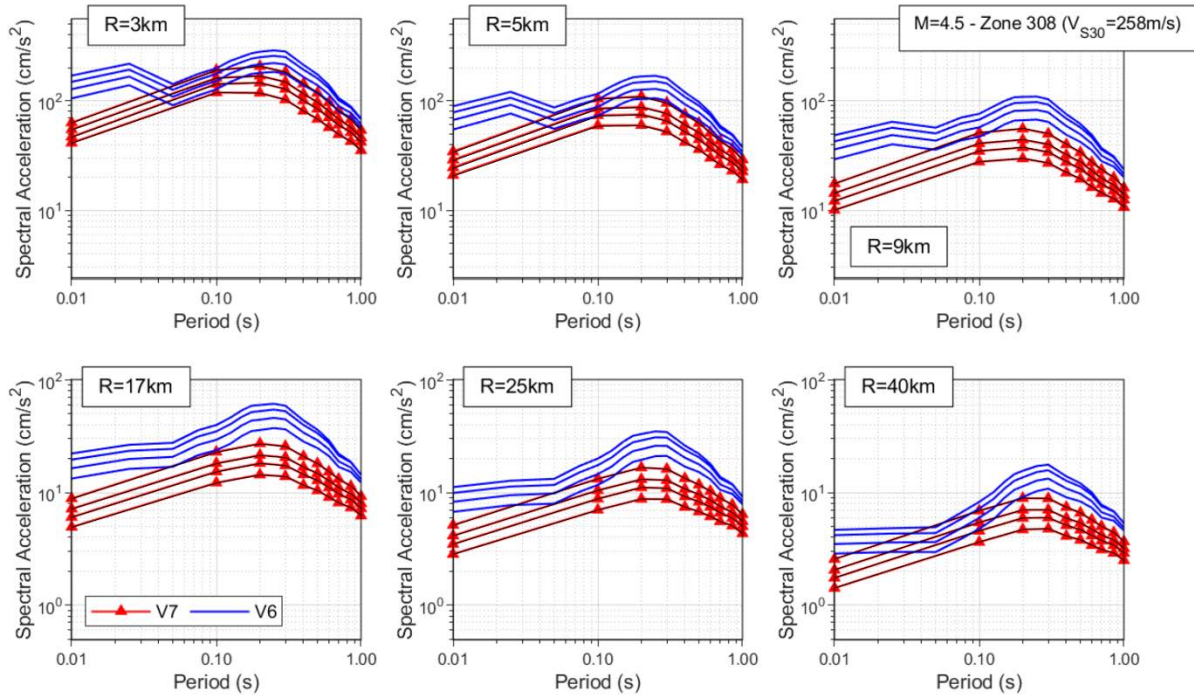


Figure 3-2 : V&V of the V7 model implemented in KEM36 for surface zone 308. Predicted median response spectra from the four models of the logic tree for $M_L=4.5$ at several distances. The black lines represent the implementation by KEM36 and coincide with red lines in the original figure (modified from figure 10.28 of Bommer et al., 2022a)

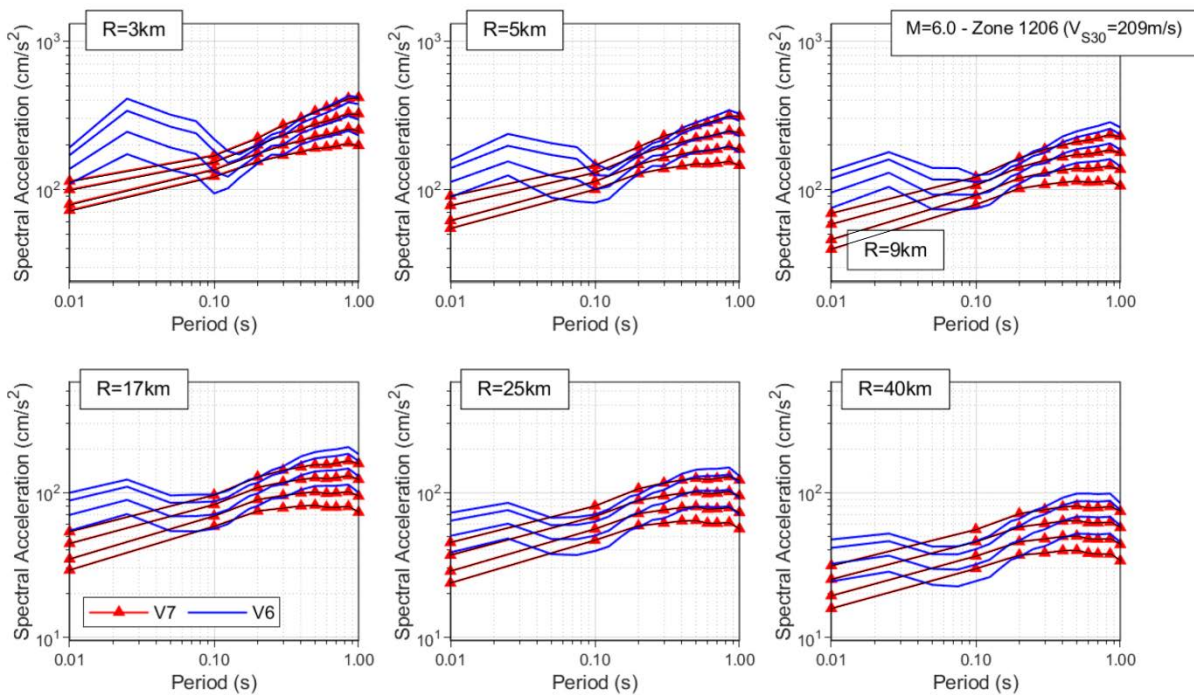


Figure 3-3 : V&V of the V7 model implemented in KEM36 for surface zone 1206. Predicted median response spectra from the four models of the logic tree for $M_L=6.0$ at several distances. The black lines represent the implementation by KEM36 and coincide with red lines in the original figure (modified from figure 10.39 of Bommer et al., 2022a).

4. Outcomes of KEM04 in light of V7

4.1 Installation setting of the B-network

In KEM04 we pointed out that short-period ground motion recorded at the B-stations was on average lower than that at G-stations; an effect that was not addressed in GMM-V5.

In V7 a substantial amount of work has been done in order to better understand this issue and to potentially solve it. In particular, it was found that SSI affects three B stations installed in buildings with deep basement. In this case, a correction procedure is applied to the recordings according to NIST (2012). On the other hand, for the majority of B stations, evidence of significant inertial or kinematic SSI effects on recorded motions was excluded by Bommer et al. (2022a), arguing that such effects were limited by the presence of a shallow layer of improved soil (with higher V_s) below the building hosting the B station. Therefore, no correction was made in the development of V7 to account for SSI effects and the full dataset of both B and G-networks was considered.

The impact of using network-dependent subsets of data in the model derivation is clearly shown by Bommer et al. (2022a) for PGV, pointing out the lower median prediction for the network-dependent model for the “B-new” stations (B stations installed after 2012). This is shown in Figure 4-1 where the PGV estimates as a function of distance for the model developed using the B-new recordings are lower than those provided by models developed using data from the other networks (G and B-old).

The implied bias of using different networks in the GMM V7 is also clearly acknowledged by Bommer et al. (2022a). In particular, the instrument bias effect on the ground motion model at NS_B is assessed in V7 by determining the fixed effects related to the instrument type in the regression. The results are shown in Figure 4-2 (from Bommer et al., 2022a) where the instrument bias is shown for the four stress-parameter branches as a function of spectral period. This figure shows clearly that there is a systematic difference between the G and B network (both old and new) for all stress parameters. The model for G stations tends to provide higher amplitudes than that derived from B stations, particularly at short periods. The GMM at NS_B is thus biased-low with respect to G station. However, because the GMM is adjusted for the combined bias of both B and G stations (without making the difference between them) in the model development procedure, the final bias with respect to G network is likely not large ($< 10\%$) for the average spectral acceleration measure. For the shortest spectral periods the underestimation is likely larger (between 10% and 20%).

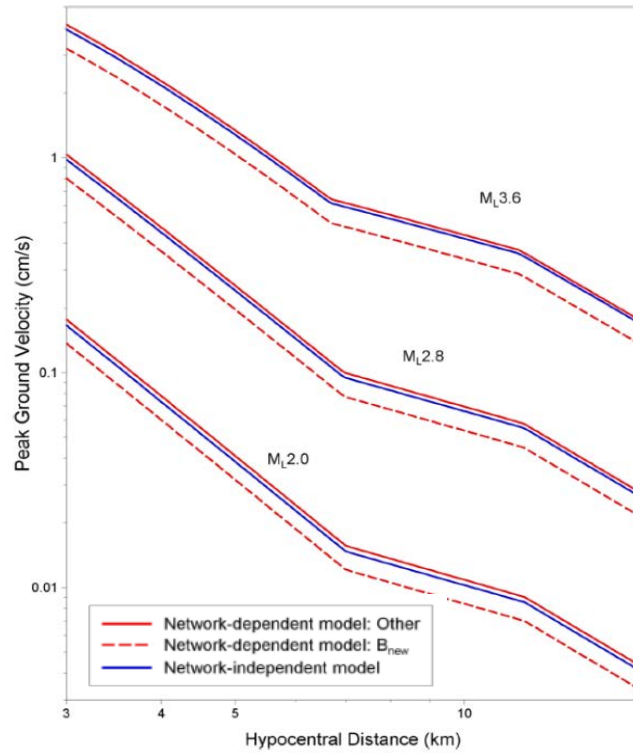


Figure 4-1 : Effect of the network on the PGV model (adapted from Bommer et al., 2022b).

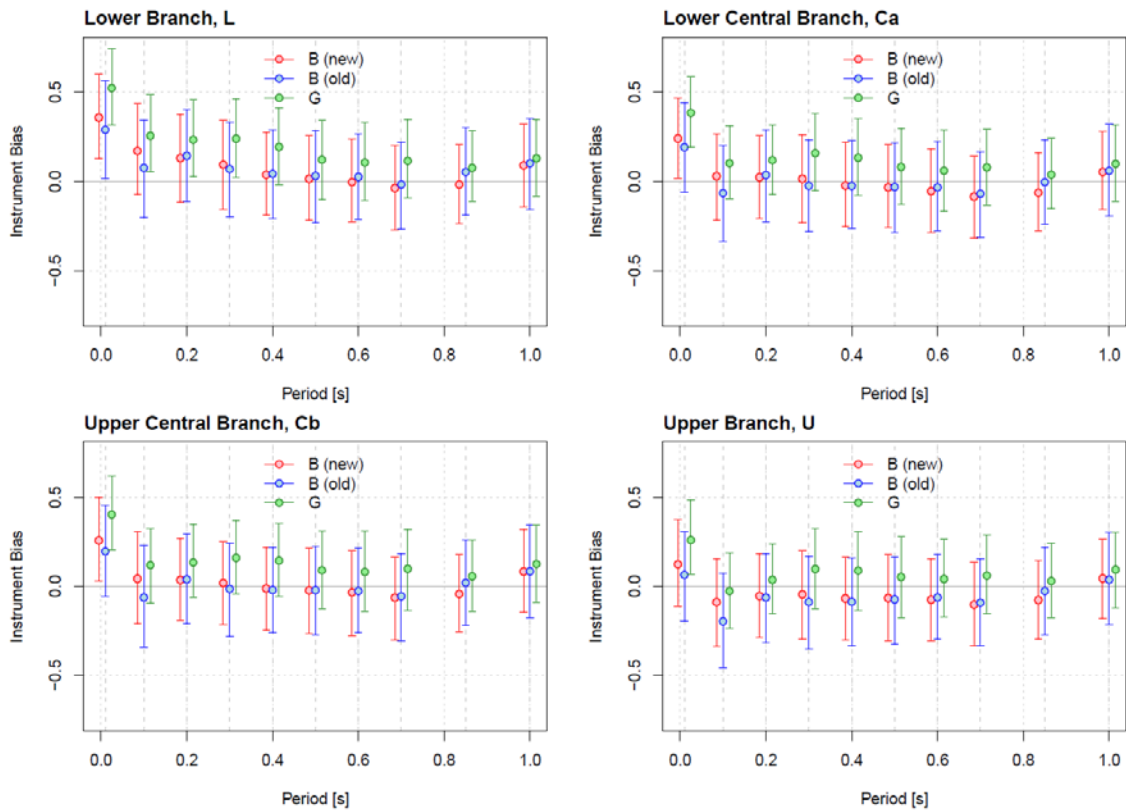


Figure 4-2 : Instrument bias as a function of spectral period determined from the NS_B regressions for the four stress-parameter branches (Figure 6.27 of Bommer et al., 2022a).

4.2 Revision of input parameters for ground motion simulations at NS_B horizon

As mentioned in Section 3.1, the input parameters for the EXSIM ground-motion simulations at NS_B horizon were revised in V7. Such revision is partly due to the fact that the soil model parameters for the deconvolution of surface recordings to NS_B have changed in V7 (e.g., the low-strain damping model) resulting in a new dataset at NS_B and new inversions and parameters for the EXSIM simulations.

We discuss herein two specific parameters that were pointed out in KEM04 concerning V5 and that have been revised in V7: (1) attenuation with distance (Section 4.2.1) and (2) stress parameters (Section 4.2.2).

4.2.1 Attenuation with distance

Figure 4-3 compares the predictions from V5 and V7 at NS_B horizon as a function of distance for two magnitudes ($M_L=4.0$ and $M_L=5.5$) and three spectral periods. In general, the short-period spectral accelerations at NS_B are lower in V7 except at very short distances and $M_L=4.0$. At long spectral periods V5 and V7 show higher consistency especially for $M_L=5.5$. A notable difference of particular interest for this study is the fact that the attenuation rate is significantly different in the two models between roughly 7 and 12 km (the decay-rate is lower in V5). This causes the predictions from V5 and V7 to be significantly different at about 10 km.

In KEM04 we performed a nonparametric spectral inversion (Ameri et al., 2020) in order to separate source, site and path effects from observed data. The resulting nonparametric attenuation functions were compared to the attenuation model used in V5 (i.e., geometrical spreading and quality factor) and significant differences were observed between roughly 7 and 12 km where V5 provided lower attenuation rate due mostly to the low decay-rate of geometrical spreading. The comparison between the nonparametric attenuation function by KEM04 and the attenuation in V5 is shown in Figure 4-4 for three frequencies of interest (in the Fourier domain). The figure also shows the new attenuation function based on geometrical spreading and quality factor adopted in V7. The geometrical decay rate between 7 km and 12 km is 0.23 in V5 and 0.67 in V7 resulting in attenuation functions much more in agreement with the nonparametric attenuation obtained in KEM04. The quality factor has also changed in V7 moving from a constant Q value in V5 to a depth- and frequency-dependent Q value in V7 which also contribute to a better agreement with the results of KEM04 at high frequencies.

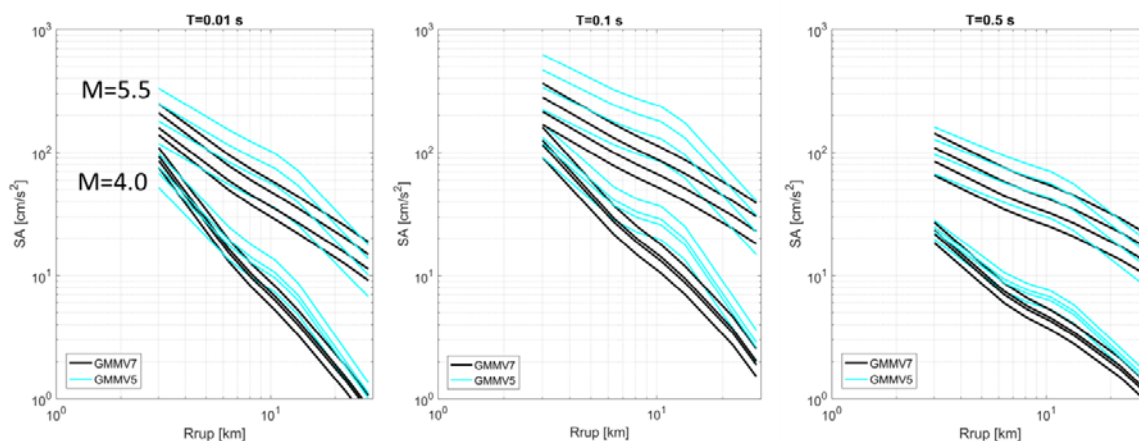


Figure 4-3 : Comparison of median spectral accelerations at NS_B from V5 and V7 for two magnitudes ($M_L=4.0$: lower curves; $M_L=5.5$: upper curves) and three spectral periods. For each case the median predictions from the 4 stress parameter branches are shown.

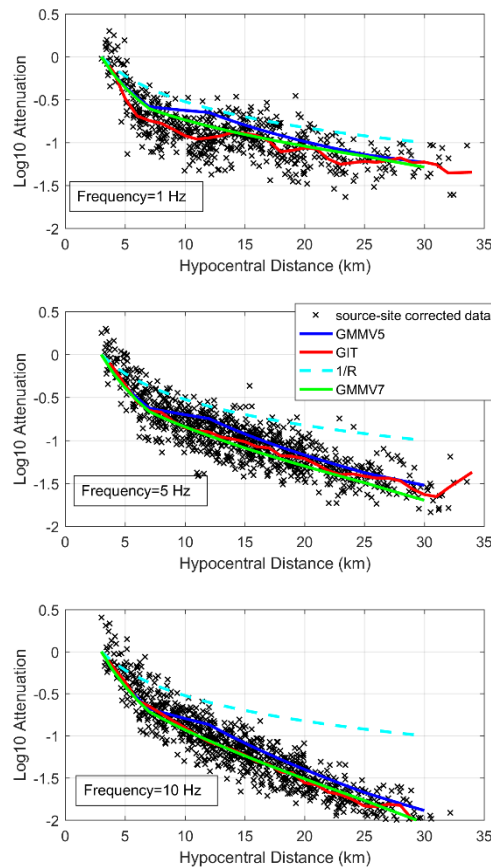


Figure 4-4 : Comparison of generalized spectral inversion technique (GIT)-based nonparametric attenuation function obtained in KEM04 (in red) and the attenuation model used in the Groningen V5 (Bommer et al., 2018; Edwards et al., 2018) and V7 (Bommer et al., 2022a) for three representative frequencies (top: 1 Hz; center: 5 Hz; bottom: 10 Hz). The source–site corrected spectral values are shown by black crosses. The 1/R decay is shown as reference. A $Q_0=60$ is considered for V7.

4.2.2 Stress parameter

The spectral inversion performed in KEM04 (Ameri et al., 2020) also allowed to estimate the values of stress parameter (sometime called stress drop) for the set of earthquakes investigated at the time ($M_L \geq 2.0$). We recall that the stress parameter is an important input parameter of the stochastic simulation approach (EXSIM) adopted in V5 and V7, controlling the level of short-period energy of the source spectra and thus of the simulated ground motion at NS_B.

The estimated stress parameters in KEM04 were between 5 and 20 bars for $M_L \geq 2.5$ that is significantly smaller than those adopted in V5 (between 40 to 100 bars, Figure 4-5, left). We suggested that low-strain damping model used in the deconvolution might have been overestimated in V5, providing NS_B spectra too rich in high frequencies leading to large stress parameter estimates.

In V7, the low-strain damping model has been revised and lower damping values are used. As a consequence, the stress parameter value used in V7 (Figure 4-5, right) are much more in agreement with KEM04 estimates. The fact that V7 simulations use lower stress parameters than V5 does not necessarily imply that the predicted spectral accelerations are lower in V7 for short spectral periods. Trade-off exists between stress parameter and other parameters also impacting the high-frequency part of spectrum. In any case, as shown in Figure 4-6, the response spectra predicted by V7 at NS_B are generally lower than those by V5 at short periods ($T=0.1$ s) and such difference is at least partially due to the new stress parameter branches.

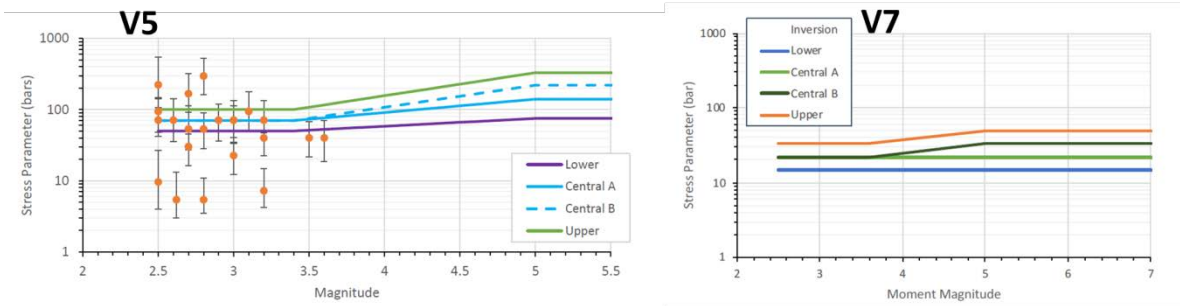


Figure 4-5 : Stress-parameter branches adopted in V5 (left, from Bommer et al., 2018) and in V7 (right, from Bommer et al., 2022a). The vertical bars on the left panel represent the stress parameter values estimated in the inversions performed in V5.

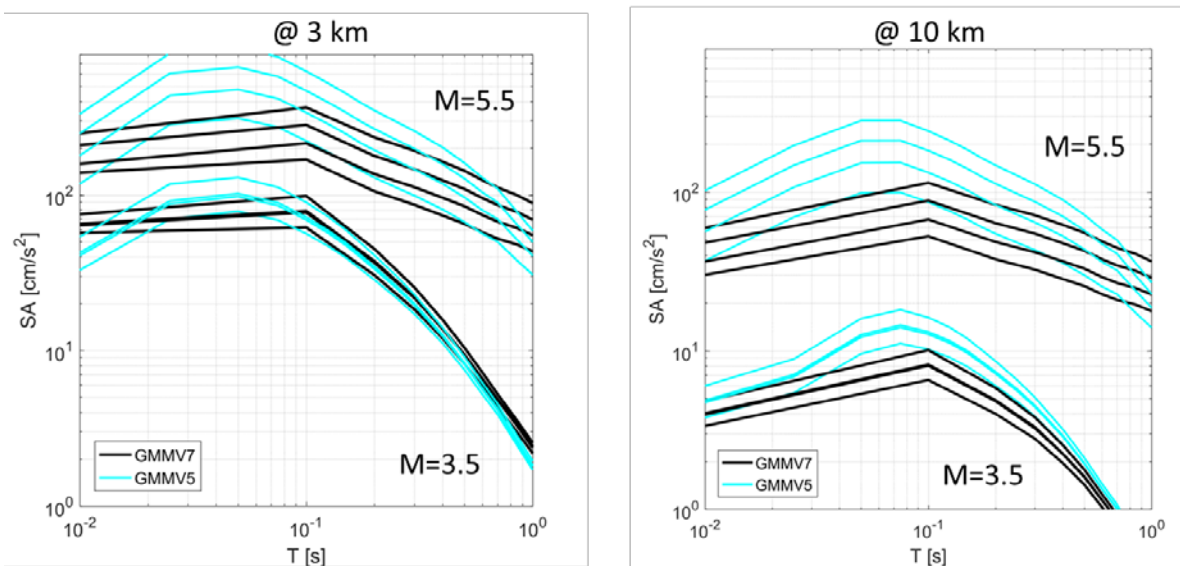


Figure 4-6 : Comparison of median spectral accelerations at NS_B from V5 and V7 for two magnitudes ($M_L=3.5$: lower spectra; $M_L=5.5$: upper spectra) and two distance (3 km: left; 9 km: right). For each case the median predictions from the 4 stress-parameter branches are shown.

4.3 Comparison of V7 with observed ground motions

In KEM04 a detailed residual analysis was performed between a set of observed spectral accelerations compiled in the project and the predicted values from V5. The objective was to highlight potential trends or bias in the residuals as a function of several explanatory variables such as magnitude, distance, V_{s30} and others. As already mentioned in Section 2, such analysis showed that the observed short-period spectral ordinates at short distances were underestimated by V5. A clear trend was also found when looking at the within-event residuals versus PGA showing that the strongest PGAs were underestimated by V5 and, conversely, lowest PGAs were overestimated.

The same residual analysis is conducted in KEM36 using V7 and two datasets of observations. The first is the same dataset used KEM04 containing data from events up to June 2019 and the second consists of recordings from 3 events occurred in 2022 that have not been used in the development of V7.

The total residuals for each record are calculated as the difference between the natural logarithms of the observed and predicted spectral accelerations (SA) at station j from event i at a specific spectral period.

$$Res_{i,j} = \ln(SA_{i,j}^{obs}) - \ln(SA_{i,j}^{GMMv7}) \quad \text{Eq.(1)}$$

Positive residuals thus indicate that the model underestimates an observation while negative residuals indicate the opposite. V7 (as it was the case for V5) provides median predictions for 4 different stress-parameter branches and thus residuals can be computed separately for each branch or combined according to the branches weights. In this study, consistently with the residual analysis presented in Bommer et al. (2022a), the central-lower (L2) branch is used. Note that for $M_L < 3.6$, which is the case of the considered events, the central branches (L2=central-lower and L3=central-upper) are equivalent.

As shown, among many others, by Al Atik et al. (2010) the total residuals can be further decomposed in between-event (δB_i) and within-event ($\delta W_{i,j}$) residuals:

$$Res_{i,j} = \delta B_i + \delta W_{i,j} \quad \text{Eq.(2)}$$

In particular, the between-event residual δB_i measures the average deviation of the observed ground motion of any individual earthquake, i , from the model median prediction. The within-event residual $\delta W_{i,j}$ quantifies the misfit between an individual observation at station j from the earthquake-specific median prediction, which is defined as the median model prediction corrected for δB_i .

Because of the issues in the B-stations recordings mentioned in the previous section, and because investigating the causes and addressing such issues was outside the scope of KEM04 and KEM36 projects, the residual analyses are presented only for surface G stations recordings (denoted in the following by G0).

Finally, we note that according to Ntinalexis et al. (2023) G050, G530 and G680 have permanent malfunctions and are excluded from the analyses (and have been also excluded in V7 development).

4.3.1 V7 residuals using the KEM04 dataset

The first considered dataset is the one already adopted for the residual analysis in KEM04. It consists of recordings at surface G stations from 9 events with $M_L \geq 2.5$ that occurred up to June 2019. The recordings have been processed following modern strong-motion data processing procedures in order to filter-out the noise and to define the usable frequency band for response spectra. Details on the processing procedure can be found in the KEM04 report. The considered events are reported for completeness in Table 4-1.

Table 4-1 : List of earthquakes with $M_L \geq 2.5$ considered in the KEM04 dataset.

Date (DD/MM/YYYY)	Time	ML
05/11/2014	01:12:34	2.9
30/12/2014	02:37:36	2.8
06/01/2015	06:55:28	2.7
06/01/2015	06:55:28	2.7
30/09/2015	18:05:37	3.1
27/05/2017	15:29:00	2.6
08/01/2018	14:00:52	3.4
13/04/2018	21:31:35	2.8
22/05/2019	03:49:00	3.4
09/06/2019	05:00:15	2.5

Figure 4-7 shows the total residuals as a function of hypocentral distance for several spectral periods (note that hypocentral and rupture distances are assumed equivalent here due to the small magnitude of the events). We observe that average positive residuals are observed for short spectral periods (mostly $T=0.01s$) at short distances (below 10 km) meaning that the V7 model on average underestimates such observations. At periods of 0.2s, 0.5s and 0.6s the average residuals are around zero and no trend with distance is observed. At the longest considered period ($T=1.0s$) a slight bias towards negative residuals (the model overestimates the observations) is observed. A comparable underestimation of short-period spectral ordinates at short distances was observed in KEM04 for V5.

Such results are consistent with the residual analysis and the similar plots presented by Bommer et al. (2022a), even though we used only G stations and thus our dataset contains less data. In particular, the underestimation by V7 of the observed PGAs is clearly acknowledged by Bommer et al. (2022a). The reasons for such underestimation are not detailed in the V7 report. However, the Authors point out that the V7 model is developed mostly to: 1) estimate ground motions for magnitude larger than the observed ones to date and 2) to predict the average spectral acceleration over the considered spectral periods (0.01s to 1s) which is the intensity measure adopted in the fragility functions for the risk assessment. With regards to this latter point, Figure 4-8 shows the residuals computed in terms of average spectral accelerations ($SA_{average}$) as reported by Bommer et al. (2022b) compared to those computed in this study. We can see that the underestimation of observed values at short distances is much reduced when considering $SA_{average}$. The differences between our residuals and those by Bommer et al. (2022b) can be mostly ascribed to the inclusion of B-stations data by the latter. Such recordings, characterized by lower short-periods spectral ordinates than those at G stations, mostly sample short source-site distances thus reducing the average residuals at short distances.

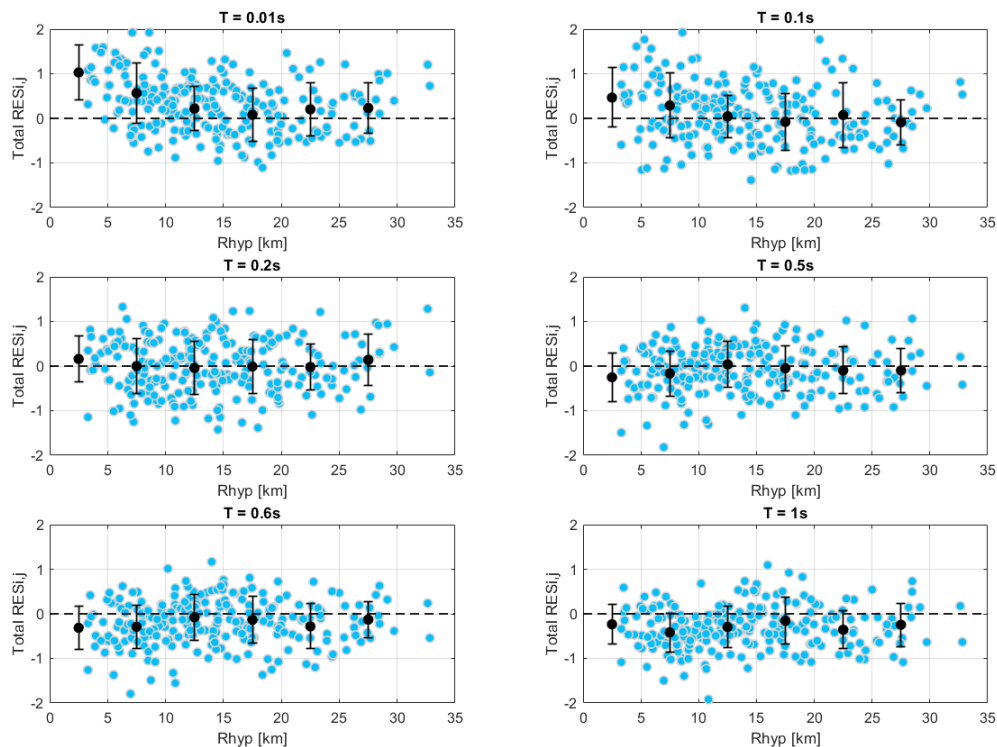


Figure 4-7 : Total residuals ($Res_{i,j}$) as a function of hypocentral distance calculated for spectral accelerations at six periods (blue dots) with respect to the central branch of the V7 model. The vertical bars show mean and standard deviation of the residuals over distance bins.

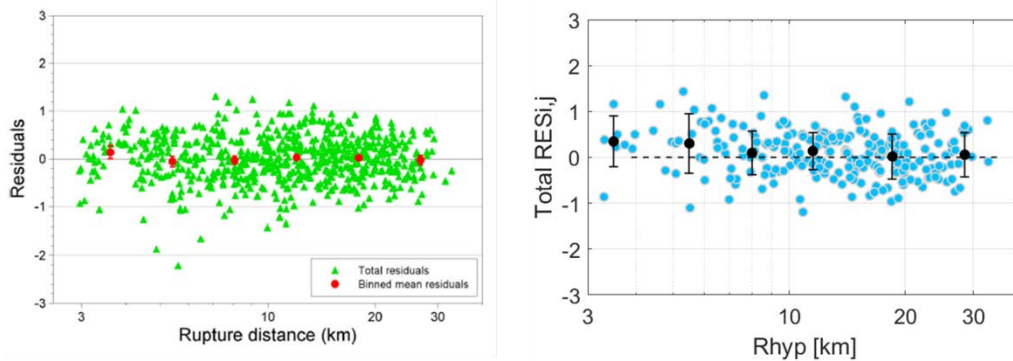


Figure 4-8 : Total residuals in terms of $SA_{average}$ over the considered periods (left: from Bommer et al. (2022b); right: this study considering the KEM04 dataset). The vertical bars in the plot on the right show mean and standard deviation of the residuals over distance bins.

Following the analyses presented in KEM04, we also computed the within-event residuals (see Eq. 2) as a function of PGA for V7 model and compared them with the ones for V5 (Figure 4-9). Similarly to what was observed for V5 in KEM04, the within-event residuals for short-period spectral accelerations for V7 also show a clear trend with PGA, showing that short-period ($T=0.01s$ and $0.1s$) ground motions are underestimated for recordings with large PGAs and overestimated for those with small PGAs. Such trend decreases with the increasing spectral period.

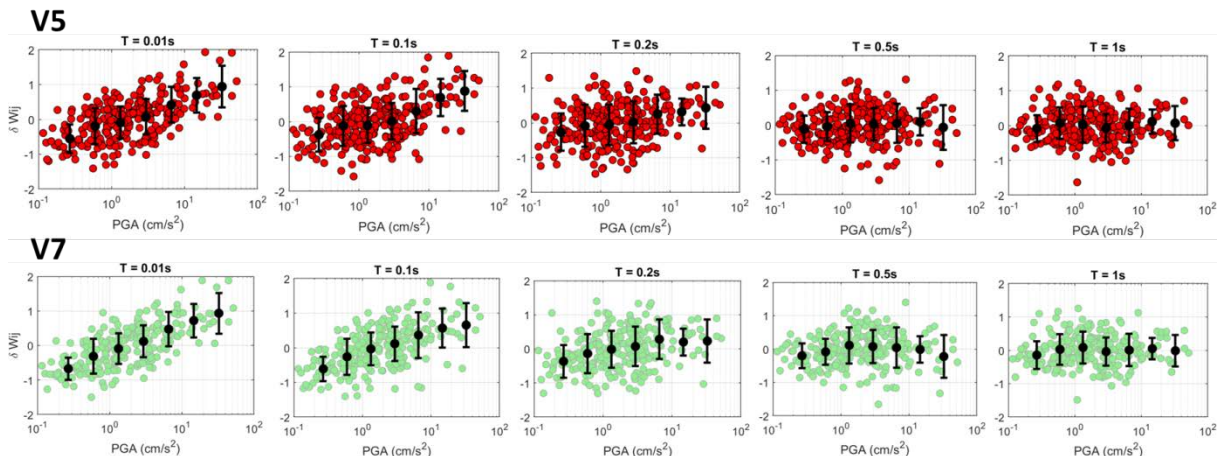


Figure 4-9 : Within-event residuals ($\delta W_{i,j}$) as a function of PGA calculated for spectral accelerations at five periods (from left to right) with respect to the central branches of V5 (upper plots) and of V7 (lower plots). The vertical bars show mean and standard deviation of the residuals over PGA bins.

4.3.2 V7 residuals using recent events in 2022

The second dataset considered for the residual analysis is composed of recordings from 3 events occurred in 2022 as shown in Table 4-2. Such recordings are not used neither in the development of V7 nor in KEM04 and so they represent a good opportunity to test V7 against recent independent data.

The recordings are processed in order to determine the usable frequency band using the same processing procedure applied in KEM04. These three events provide about 100 recordings at G0 stations.

Table 4-2 : List of earthquakes with $M_L \geq 2.5$ occurred in 2022 considered for the residual analysis.

Date	Time	Depth	ML
01/04/2022	17:11:08	3	2.7
24/09/2022	10:20:38	3	2.7
08/10/2022	21:07:17	3	3.1

Figure 4-10 shows the total residuals as a function of hypocentral distance for several spectral periods. Similarly to what was observed above using the KEM04 dataset, also in this case the residuals show positive values at the shortest spectral period and particularly at short distances meaning that V7 underestimates such observations. Compared to the KEM04 dataset, the 2022 data show average residuals that are slightly positive all over the considered periods (except at $T=1$ s). This is shown in Figure 4-11 (left) where the residuals for $SA_{average}$ are presented and depict a positive bias of up to 0.5 (a factor of about 1.6). The $SA_{average}$ estimated from the 2022 dataset is clearly underestimated by V7. In order to assess to what extent such underestimation is caused by the exclusion of B stations recordings (used in V7), the right-hand panel of Figure 4-11 shows the $SA_{average}$ residuals calculated including the recordings at B stations. The use of B stations reduces the residuals between 5 and 10 km but the bias still persists at other distances.

The between-event residuals for such events (not shown here for brevity) are positive in the short and mid-periods range suggesting that the 2022 events may be characterized by higher stress parameters, although this is purely speculative, and analyses should be performed to confirm this.

Figure 4-12 shows the within-event residuals versus PGA. The trend already observed using the KEM04 dataset is confirmed also using the 2022 dataset and it is clearly visible up to $T=0.2$ s. The short-periods spectral ordinates from recordings with the large PGAs are underestimated by V7 whereas the opposite is observed for recordings with small PGAs.

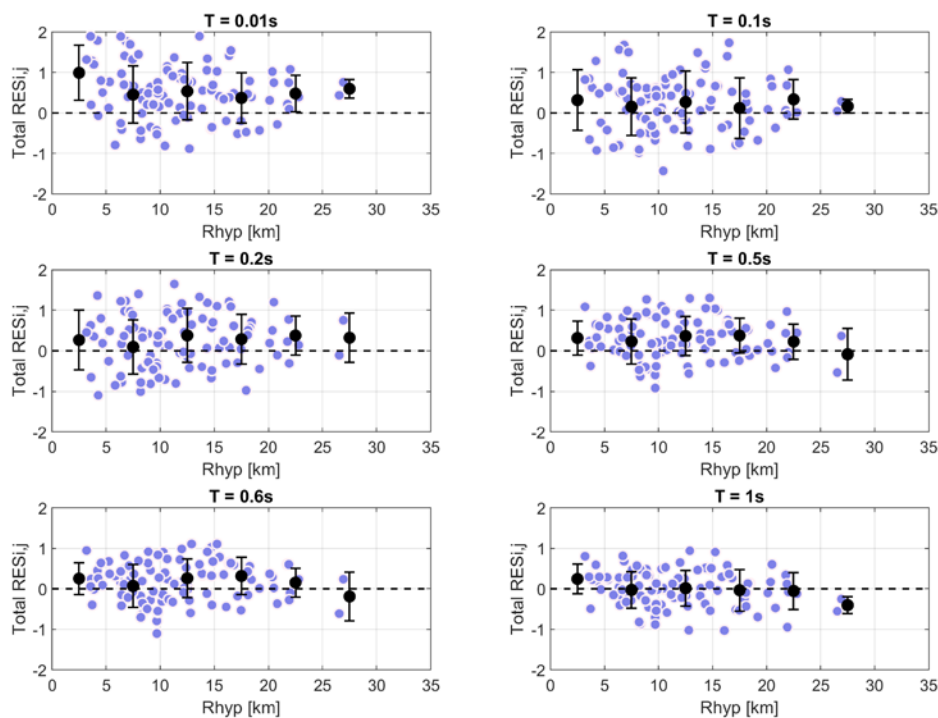


Figure 4-10 : Total residuals ($RES_{i,j}$) for the 2022 dataset as a function of hypocentral distance calculated for spectral accelerations at six periods (purple dots) with respect to the central branch of V7 model. The vertical bars show mean and standard deviation of the residuals over distance bins.

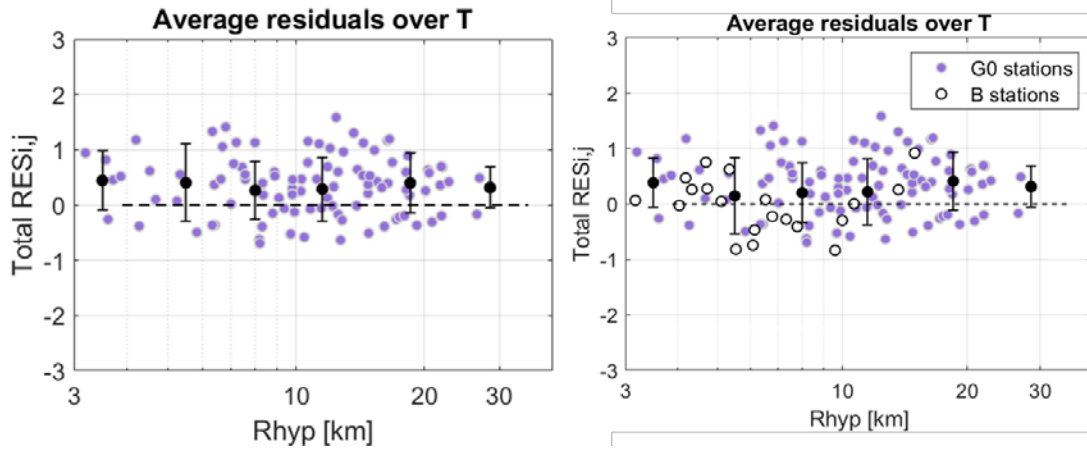


Figure 4-11 : Total residuals in terms of $SA_{average}$ for the 2022 dataset, considering only G0 stations (left) and G0 and B stations (right). The vertical bars show mean and standard deviation of the residuals over distance bins.

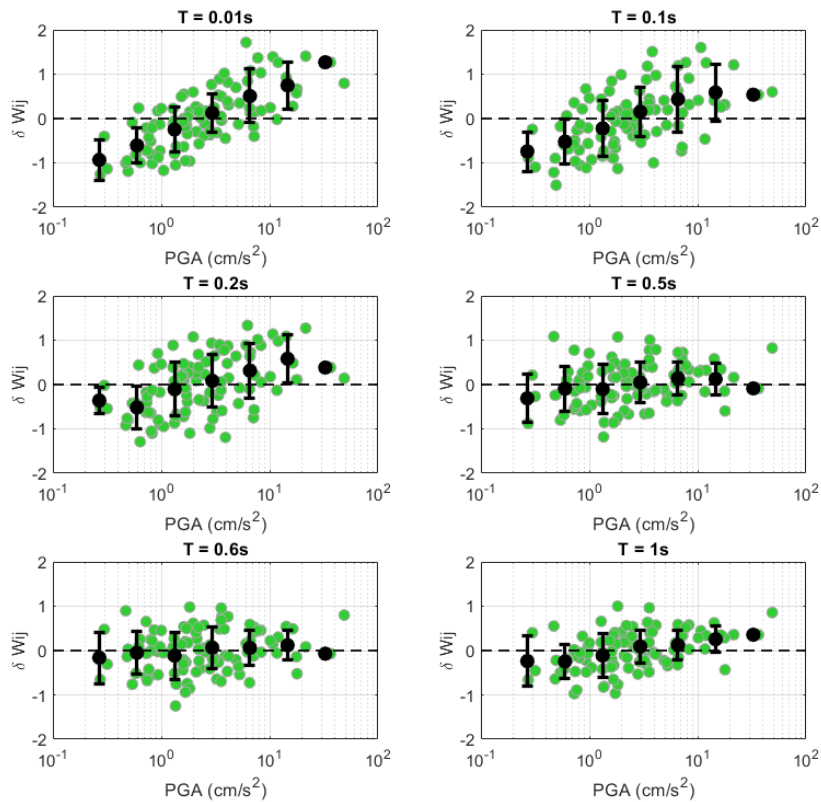


Figure 4-12 : Within-event residuals ($\delta W_{i,j}$) for the 2022 dataset as a function of PGA calculated for spectral accelerations at six periods with respect to the central branch of V7. The vertical bars show mean and standard deviation of the residuals over PGA bins.

4.4 Comparison with 3D physics-based simulations (SPEED)

This Section shows the comparisons of the ground motion estimates from the V7 model as well as from other empirical models for active tectonic environments (i.e. NGAW2, Ancheta et al. 2013) with the results of the 3D physics-based numerical simulations developed within the KEM04 project (Paolucci et al. 2021). We recall herein that the simulations were obtained using the high-performance computer code SPEED (<https://speed.mox.polimi.it>, Mazzieri et al. 2013) and a large-scale (20 km×20 km) heterogeneous 3D seismic wave propagation model for the Groningen field area capable of propagating frequencies up to 8 Hz. The 3D model was calibrated based on the vast existing geological and geophysical investigations and successfully validated on the ground motion recordings of the M_w 3.4 Zeerijp earthquake.

For comparison purposes, two different earthquake scenarios simulated with SPEED are considered herein: the M_w 3.4 Zeerijp event and a M_w 5.0 finite-fault scenario earthquake. For the M_w 3.4 Zeerijp event, the 1Ds-Qf model (i.e., 1D soil interfaces, visco-elastic linear soil model with frequency-proportional quality factor) is considered (see details in Paolucci et al. 2021). For the M_w 5.0 scenario, the soil behavior is modelled using a visco-elastic non-linear constitutive law and, therefore, is referred to as NL. For each scenario (M_w 3.4 and M_w 5.0), a pair of SPEED simulations is available: (1) a simulation with the actual soft soil model up to ground surface (minimum V_s of surface materials is 150 m/s), referred to as “SOIL” (1Ds-Qf model), and (2) a simulation with the same source as in (1) but where the soft ground material properties from ground surface to 800 m depth are replaced by those of the bedrock corresponding to $V_s=1500$ m/s (Chalk formation). Simulation (2) corresponds to the ideal situation of outcropping NS_B bedrock horizon and, therefore, referred as “OUTCROPPING BEDROCK” (1Ds-Qf-NS_B).

Figure 4-13 (left) shows the comparison between the records (black squares), the SPEED simulations (1Ds-Qf, pink squares) and the V7 predicted values in terms of PGA (geometric mean of horizontal components, HGM) for the M_w 3.4 Zeerijp event. For this comparison, SPEED and V7 values refer to surface soft soil conditions. The comparison is shown at the stations for which recordings are available. Note that the simulations have been low-pass filtered with a cut-off frequency at 10 Hz, in order to avoid spurious effects at frequencies higher than the resolution frequency of the numerical model. V7 predictions are reported considering both the lower (L1) and upper (L4) branches of the stress drop model with the corresponding $\pm\sigma$ bands (note that for V7 we used $\sigma^2 = \tau^2 + \phi_{SS}^2 + \phi_{S2S}^2$ for soil estimates and $\sigma^2 = \tau^2 + \phi_{SS}^2$ for NS_B). As for the plots shown in previous Sections, hypocentral and rupture distances are assumed to be equivalent. The comparison of PGA values at outcropping bedrock is shown in the same Figure 4-13, on the right, for the M_w 3.4 Zeerijp event, considering the SPEED simulations (1Ds-Qf-NS_B) and the V7 model.

For the soil case, both SPEED and V7 tend to underestimate the records at very short distances ($R_{hyp} < 5$ km), in particular, this underestimation is significantly strong for V7 predictions (up to a factor of 3). It should be highlighted that the frequency limit of SPEED simulations at about 8 Hz may affect the accuracy of PGA predictions. The attenuation with distance of recordings is better accounted for with SPEED simulations. Referring to the outcropping bedrock, at short distances, the comparison between SPEED and V7 improves significantly, suggesting the important influence of the local site response model of V7.

Figure 4-14 shows the same comparison as in Figure 4-13, for soil conditions, but for response spectral accelerations (SA, HGM) at 0.5 s (left) and 1 s (right). For both periods, the comparison between records, SPEED and V7 predictions is more satisfactory than for PGA.

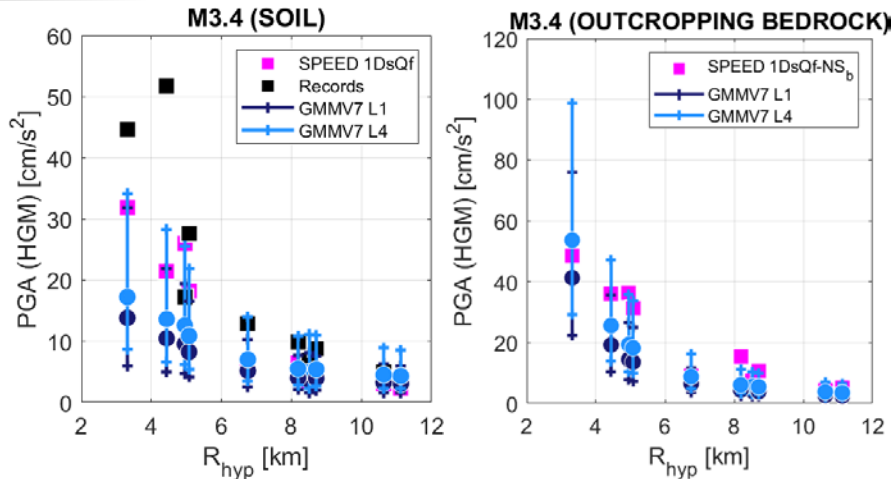


Figure 4-13: M_w 3.4 Zeerijp event: comparison between records, SPEED simulations and V7 GMM in terms of PGA (geometric mean of horizontal components, HGM). Left: comparison for soft soil conditions between SPEED (1Ds-Qf, pink squares), records (black squares) and V7 predicted values for the lower (L1=50 bar, dark blue) and upper branch of the stress model (L4=100 bar, light blue) within their corresponding percentiles of the distribution. Right: comparison at outcropping bedrock between SPEED (1Ds-Qf-NS_B, pink squares) and V7 predicted values for L1 and L4 branches.

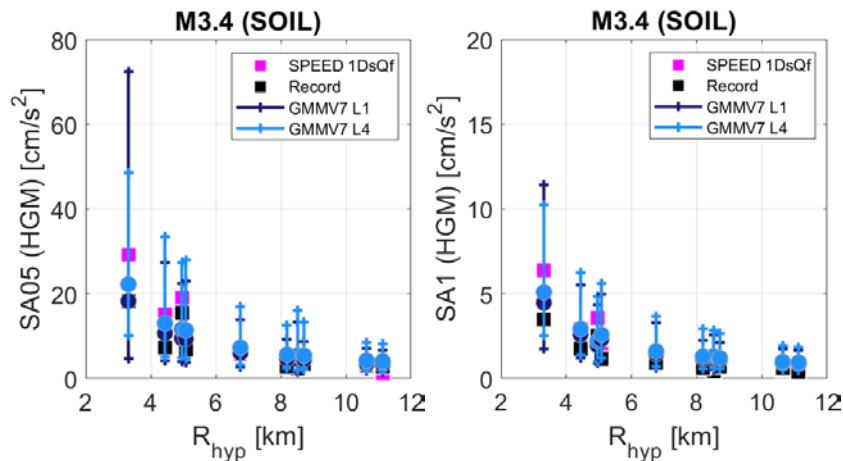


Figure 4-14 : M_w 3.4 Zeerijp event, soil conditions: comparison between records (black squares), SPEED simulations (1DsQf, pink squares) and V7 GMM (L1: dark blue; L4: light blue) in terms of SA (HGM) at 0.5 s (left) and 1 s (right).

The comparisons are then extended to the M_w 5.0 scenario by considering SPEED non linear simulations (M5-NL model), the V7 model (both L1 and L4 branches) and the predictions of the NGAW2 empirical models (namely, Boore et al., 2014; Chiou and Young, 2014; Campbell and Bozorgnia, 2014; Abrahamson et al., 2014). It should be remarked that, while the V7 model is specific for the Groningen area and for shallow induced events, the NGAW2 predictions are developed for seismic events of tectonic origin, having typically larger depths than the events at Groningen.

Figure 4-15 shows the comparison of horizontal (HGM) PGA (left), SA 0.5 s (center) and SA 1.0 s (right) as a function of hypocentral distance from SPEED simulations (M5-NL model, pink), V7 (blue), and NGAW2 models (grey).

Note that, referring to the SPEED values, the entire set of surface receivers of the numerical simulation has been grouped into bins of hypocentral distance to investigate the attenuation of ground motions with distance. Therefore, the pink triangles represent the average values within each distance bin, while the vertical lines denote the corresponding $\pm\sigma$. The variability of SPEED simulations is,

therefore, a measure of the intra-event variability for this particular scenario. Referring to the V7 model, the colored blue region represents, for each period, the range of the median values associated with L1 and L4 stress drop branches. For the NGAW2 models, the predictions on soft soil are computed for $V_{s,30} = 200$ m/s and the grey shaded region represents, for each period, the range of minimum and maximum median predictions of the four GMMs considered.

For PGA, V7 tends to be significantly lower than both SPEED simulations and NGAW2 predictions at all distances. On the other hand, considering longer periods (0.5 and 1 s), an increasing consistency is found between V7, NGAW2 models and SPEED simulated values.

To help understanding the low values of PGA predicted by V7 at ground surface, Figure 4-16 shows, for the same M_w 5.0 scenario, the comparison of PGA (HGM) from SPEED, V7 and NGAW2 at outcropping bedrock (1500 m/s). In this case, the agreement between V7, SPEED and NGAW2 is better than at ground surface, suggesting that the strong de-amplification of PGA in V7 is to be attributed to very relevant non-linear effects in the site response. Considering the relatively low magnitude values and the extent of linear response of peats in the Groningen area, up to shear strains of about 10^{-3} (Deltares, 2017), we believe that the V7 predictions at high frequencies may deserve further attention and further studies should be conducted to better constrain such model feature (as suggested for phase 2).

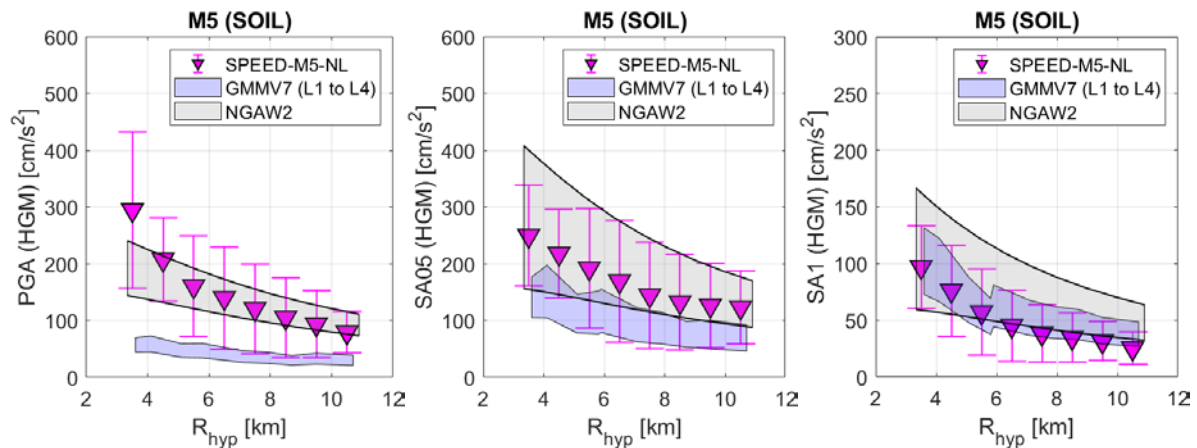


Figure 4-15: M_w 5 scenario, soil conditions: comparison of HGM PGA (left), SA0.5s (center) and SA1.0s (right) from SPEED simulations (SPEED-M5-NL, pink triangles, binned over distance ranges), V7 model with L1-L4 median predictions (blue band), and from the set of the NGAW2 models (grey band showing the range of median predictions). NGAW2 models have been calculated with $V_{s,30} = 200$ m/s.

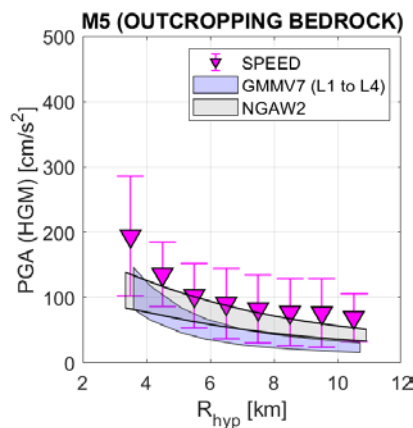


Figure 4-16: Same as Figure 4-15 for outcropping bedrock: comparison of HGM PGA from SPEED simulations (SPEED-M5-NL, pink triangles), V7 model (blue band), and from the set of NGAW2 models (grey band). NGAW2 models have been calculated with $V_{s,30} = 1500$ m/s.

5. Conclusions of KEM36 - Phase 1

In this Phase 1 of KEM36, the GMM V7 has been analyzed with respect to the results of KEM04 and the recommendations made in KEM04 for GMM V5. The objective was to assess whether the issues pointed out in KEM04 for V5 were improved in V7.

The main conclusions of Phase 1 are the following.

- A substantial amount of work has been done in order to investigate differences between B and G stations particularly with respect to the issues raised in KEM04. The impact of installation conditions of B stations on ground motion is clearly assessed in V7 and this certainly represents an improvement with respect to V5. Three B stations have been recognized as affected by SSI and corrected for such effects. It was also recognized that the other B stations provide ground motions that are different (lower) with respect to the free field ground motions, likely due to soil compaction at the construction of the building. This latter effect is not corrected or accounted for in V7 and, as a result, the model is biased with respect to ground motions at G stations (free field). This issue is clearly acknowledged in the V7 documentation.
- Several input parameters of the EXSIM simulations at NS_B were revised in V7, mainly relating to the different soil model adopted in the deconvolution of surface recordings to NS_B and the consequent new inversion results. In particular, the geometric attenuation model and the stress parameters used in V5 (questioned in KEM04) have been updated and are now much more in agreement with KEM04 results. We consider this to be an improvement of V7 and we like to think that such modifications were at least partly triggered by KEM04 study.
- The residual analysis of V7 with respect to the KEM04 dataset and a set of recordings from recent events in 2022 showed that V7 still underestimates observed short-period spectral ordinates at short distances (as it was for V5). This issue is clearly acknowledged by V7 but guidance on how to deal with it is missing. We also observed a clear trend of residuals with PGA where the short-periods spectral ordinates from recordings with the large PGAs are underestimated by V7 whereas the opposite is observed for recordings with small PGAs.
- The comparison of V7 with recordings for the M_w 3.4 Zeerijp event, that was used in KEM04 as a benchmark test with SPEED simulations, confirms the underestimation of V7 at short distances ($R_{hyp} < 5$ km) and short periods, especially for PGA, similarly to what was remarked in KEM04 referring to V5. Considering the Zeerijp event simulations at outcropping bedrock, the consistency of V7 with SPEED improves considerably, suggesting that the previously mentioned discrepancies observed at soil ground surface are probably related to different assumptions in the site response of the shallow layers.
- Similar considerations, as for the M_w 3.4 event, can be made for the M_w 5 scenario: while at soil ground surface V7 provides short-period values that are much smaller than SPEED, especially in terms of PGA, for outcropping bedrock there is a reasonable agreement between SPEED and V7 (considering that the comparison is made for a single scenario).
- Although based on data from tectonic earthquakes, the comparison of the M_w 5 scenario with the NGAW2 models provides additional interesting insights: while SPEED results are reasonably in agreement with NGAW2, V7 predictions at soil ground surface are significantly lower than NGAW2 in terms of PGA (by a factor of about 3 in terms of median values), while for increasing periods the agreement tends to improve. Instead, at outcropping bedrock, PGA predictions from V7 and NGAW2 are in reasonably good agreement.
- The previous remark for the M_w 5 scenario confirms what previously observed by the residual analysis as well as by comparison with records of the Zeerijp event: there is a tendency of V7 to overestimate the de-amplification of ground motion at short-periods, that is probably related to specific assumptions on soil damping and non-linear response of the shallow soil layers. While this tendency was already present in V5, the impact of the scenario-dependence of response spectral amplification functions, introduced in V7, may play a role in the previous results and deserves clarifications.

- Overall, several important improvements have been introduced in the GMM V7 with respect to V5. However, issues still exist mostly related to the underestimation of observed short-period spectral accelerations and to the nonlinear soil response model adopted. Further studies are proposed for the Phase 2 of the project in order to investigate more in details such issues particularly with respect to soil nonlinearity.

6. Planned activities for Phase 2

In the following we present the revised scope for Phase 2 of KEM36 with respect to the one of our initial offer “6423-228860.O01/OD” dated on 31 January 2023. Such revision is motivated mainly by feedback from the KEM panel and subpanel members and from Karin van Thienen – Visser (received on 04/09/2023) that allowed to refine the initial scope and suggested additional investigations on relevant issues.

In case of funding, the activity for Phase 2 of KEM36 will be divided into three interconnected topics:

- **Topic 1: Investigation of non-linear effects on ground motion in Groningen.** This topic will investigate the non-linear (NL) soil modelling approach adopted in GMM V7 and compare its results with other constitutive modelling assumptions and NL numerical approaches. The tasks are:
 - *Sensitivity to NL numerical approaches and to the Modulus Reduction and Damping (MRD) curves.* This will be done in 1D, using linear-equivalent, non-linear elastic and fully non-linear modelling approaches implemented in different computer codes. Different MRD curves will be considered: on one side, those implemented in the V7 and, on the other side, those available from in-field and laboratory tests for Groningen. Furthermore, few 3D simulations, within the scope of Topic 2, will be performed using both linear-elastic and non-linear elastic models implemented in the spectral element code SPEED, to check the impact of non-linear soil behavior in 3D seismic wave propagation with respect to 1D.
 - *Sensitivity of surface ground motion to the depth down to which NL behavior is considered.* As pointed out by the KEM subpanel members, in V7 such depth is of several hundred meters, which is a matter of debate and may be responsible for excessive short period ground motion attenuation.
 - *Sensitivity to damping values.* Consistency checks will be performed on damping values considered in the V7 and in the 3D numerical simulations of KEM04, where a calibration study was already carried out based on the fit with records.
 - *Involvement of Dr. Fabian Bonilla* (IPGP Paris) as external expert to discuss and review this part of the study.
- **Topic 2: update of 3D physics-based simulations (SPEED) considering elongated rupture models.** According to the most recent source model for Groningen, as highlighted in the 2022 Mmax workshop, the ruptures of induced events are confined in the reservoir. This implies elongated ruptures ($L/W > 10$) in order to accommodate magnitude larger than about 4.5. This is an important topic because it implies completely different rupture geometries with respect to the ones used in the past and in V7 simulations. The ground motions distribution may be significantly affected by such different source model assumptions. The tasks are:
 - *Improvement of the mesh resolution in the high-frequency range.* A new finer mesh will be constructed for SPEED simulations, suitable to enlarge the reliable frequency range, up to at least 10-12 Hz. This will imply an extensive use of High Performance Computing (HPC) resources and the execution of convergence tests to verify the high-frequency accuracy of the finer mesh. This point is important to strengthen the

reliability of simulations at the shortest spectral periods of interest (PGA, 0.1s), which are particularly affected by soil nonlinearity (See Topic 1 above). Moreover, this will allow a better assessment of period-to-period correlation from simulations (see Topic 3 below).

- *Construction of plausible kinematic source models for elongated ruptures for $M_w \approx 5$.* This point will require the involvement of an external expert (likely Jean-Paul Ampuero, if available, since he is already involved in this topic for Groningen) in order to assure the consistency of the assumed kinematic rupture models with the outcomes of the dynamic rupture simulations within the reservoir.
 - *Ground motion simulations for multiple elongated rupture realizations.* Several SPEED simulations for multiple rupture models, as defined at previous item, will be performed, in order to study the sensitivity of the ground motions for elongated ruptures with respect to “standard” rupture models used previously. The number of simulations will be decided based on the HPC resources required for the increased high-frequency accuracy of the numerical model.
 - *Analysis of results.* Results of ground motion simulations will be analyzed, for different intensity measures, mostly in relation to the following key aspects: (i) comparison with GMM V7; (ii) attenuation of ground motion with distance; (iii) directivity effects and azimuth dependence.
- **Topic 3: Assessment of the period-to-period (p2p) correlation.** There have been several discussions concerning the p2p correlation models adopted in V7 and the way they are used for the hazard and risk computations. This is demonstrated by the exchanges between TNO and NAM on this topic. The tasks are:
 - *Understanding of the V7 p2p correlation model.* This will be done based on the review of NAM and TNO corresponding documentation.
 - *Assessment of p2p correlations based on both SPEED simulations and records.* (i) Based on the new SPEED simulations developed within Topic 2, the p2p correlation will be evaluated at least up to 10 Hz (0.1 s) in order to cover the period range used in V7; (ii) the p2p correlations will be also evaluated using Groningen ground motion databases developed in KEM04 and in KEM36; (iii) Comparison of results from SPEED, records and from the models assumed in V7 GMM.
 - *Recommendations* for further detailed investigations of p2p correlation model based on outcomes of previous tasks.

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Replies to comments from K.van Thienen – Visser on KEM36 report (STR_FUG_23P07_01) received on 04/09/2023.

Page	Author	Comment	Reply
5	KVT	typo	Corrected
7	KVT	I will check with Ipo if the matlab code can be published on the KEM website as well.	Ok
8	KVT	mention also the black lines and the fact they coincide with the coloured lines	Done
9	KVT	mention black lines as well	Done
10	KVT	so, what does this exactly mean? Does it mean that GMM V7 also slightly exaggerates the ground motions at the buildings due to the fact the thin layer of building sand is not taken into account for the G stations?	Yes, correct.
15	KVT	Have these been used to derive GMM V7 of not?	No. Added in the text.
16	KVT	is the amplitude of the underestimation of V5 compared to the underestimation of V7 comparable/higher/lower?	Comparable. Added in the text.
17	KVT	you may introduce a bias because there are only 3 events. Therefore other effects may play a role in your analyses because of the small number of events.	Of course using only 3 events we could not comment much on the performance of V7. However, as detailed in the previous section, we are also using 9 events from the KEM04 dataset. The results (distribution of residuals) obtained using the 3 events recorded in 2022 are consistent with those obtained with the KEM04 dataset. Thus we do not think that our interpretations are biased by the use of these 3 events.
18	KVT	can you improve the resolution of the figure?	Done.
22	KVT	such has?	Explicated in the text.
23	KVT	1. can you give a general statement to the question whether V7 is better than V5 or not? Is it better to continue with V5 or go to V7? 2. In the conclusion I read mostly negative points while earlier points were mentioned that are solved in V7. Please check if you mention all here, including the positive points.	We updated Section 5 to more clearly highlight the improvements in V7. In general, there is no doubt that V7 has a number of improvements with respect to V5. Not all the improvements are mentioned in the report because we just focused on issues identified in KEM04. However, some of the issues of V5 are still present in V7. We added a final sentence in the report to underline this and the fact that further studies are needed to assess some modeling choices in V7, particularly concerning soil nonlinearity.
23	KVT	Is it a bias? You want to know the effect on buildings. If the GMM V7 correctly prognoses movement on buildings but not on free field. Is this truly an issue? In the end the results are not meant for the free field but for the building stock	We believe that there are two issues. 1. the V7 mixes data from free-field and within-buildings instruments so that the model is in principle biased with respect to both; 2. The effects of the building or of the soil layers below B stations are not homogeneous (variable on a case-by-case basis) and are difficult to quantify (this is the reason why no correction is attempted in V7). Thus it is difficult to assess if all the building stock in Groningen is subjected to the same effects.