Probabilistic Seismic Hazard Analysis for Induced Earthquakes in Groningen, Update June 2016

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Introduction

This report presents the results of a new Probabilistic Seismic Hazard Assessment (PSHA) for induced seismicity in Groningen, which is an update of the Dost and Spetzler (2015) report. The need for the current update comes mainly from the further development of the Ground Motion Prediction Equation (GMPE) for Groningen, v2, and the publication of the production plan (winningsplan) 2016 by the NAM. Both the current NAM model and the new KNMI model are using the same GMPE v2 model, but differ in the applied methodology and source model. Results from the two models will be compared.

The main feature of the GMPE v2 model is the introduction of a laterally varying site response model using non-linear site amplification functions (Bommer et al., 2015). A reference horizon was chosen at about 350 m depth and a lateral varying shear-wave velocity model for the upper 350 m was developed. Based on shallow (0-50m) subsurface information and site response characteristics, the upper layer was divided into 167 zones. Within each zone similar site response characteristics apply. Also important to note is the expansion of the observation network in Groningen which has resulted in the extension of the dataset used in the construction of the GMPE from 85 to 146 records.

The introduction of a laterally varying upper layer in the model required a modification of the PSHA method used (Cornell, 1968). The hazard at the surface is obtained by a convolution of the site-specific hazard curve at the reference horizon with the probability distribution of the amplification function (Bazzurro and Cornell, 2004). In order to compare our model to the NAM model, we have decided to follow the suggestion by the regulator (State Supervision of the Mines (SSM)) to put more emphasis on induced earthquakes characterized by a higher stress-drop and disregard the effect of the low stress-drop events. This was done by modification of the weights in the logic-tree that was developed in the v2 version of the GMPE. In addition to a map of predicted ground motions at the surface for a 475 year return period, spectra will be shown at a few selected locations. Insight will be given in the contribution of events to the PSHA map through disaggregation.

We will present a short overview of the observed seismicity in Groningen and discuss the parameters derived from it and used as input in the PSHA method. Next, the concept behind the v2 hazard model is explained and modifications needed to implement the amplification factor are discussed. Finally, the results of the hazard study are presented. For the v2 hazard model, a new hazard map and a site-specific analysis of a location in Groningen city and

Loppersum are shown. The return period for all hazard results is 475 y (equivalent to a 10 % chance of exceedance in 50 years) according to the Eurocode 8.

Characteristics of seismicity in Groningen
The PSHA calculations require a characterization of the seismic activity in the area of interest, usually in terms of spatial variation assuming a stationary process, and leads to a proposed seismic zonation for the region. Each zone is characterized by two parameters: 1] activity rate and 2] b-value. Since seismicity in the region is non-stationary, an estimate of both parameters will be based on a chosen time frame in which the activity is assumed to be approximately stationary. For all zones the same value for the maximum magnitude, M_{max} = 5.0, was assumed. The best value for M_{max} for Groningen is still debated and an international panel of experts met earlier on this topic. It is foreseen that in future updates a distribution of M_{max} values will be used and implemented in the logic tree.

Temporal distribution
Figure 1 shows the temporal development of seismic activity until June 29, 2016. Over the last two full years, 2014 and 2015, activity rate of the total Groningen field shows a relatively stable number between 20 and 25 events per year of M> 1.5. Since variation in the number of events per year over the last 3-5 years is high and the event rates used in the previous report are in line with the simulated rate by NAM (e.g., based on a production scenario of 27 Bcm per year), it was decided to use the same activity rate for the Groningen field as in the previous report.
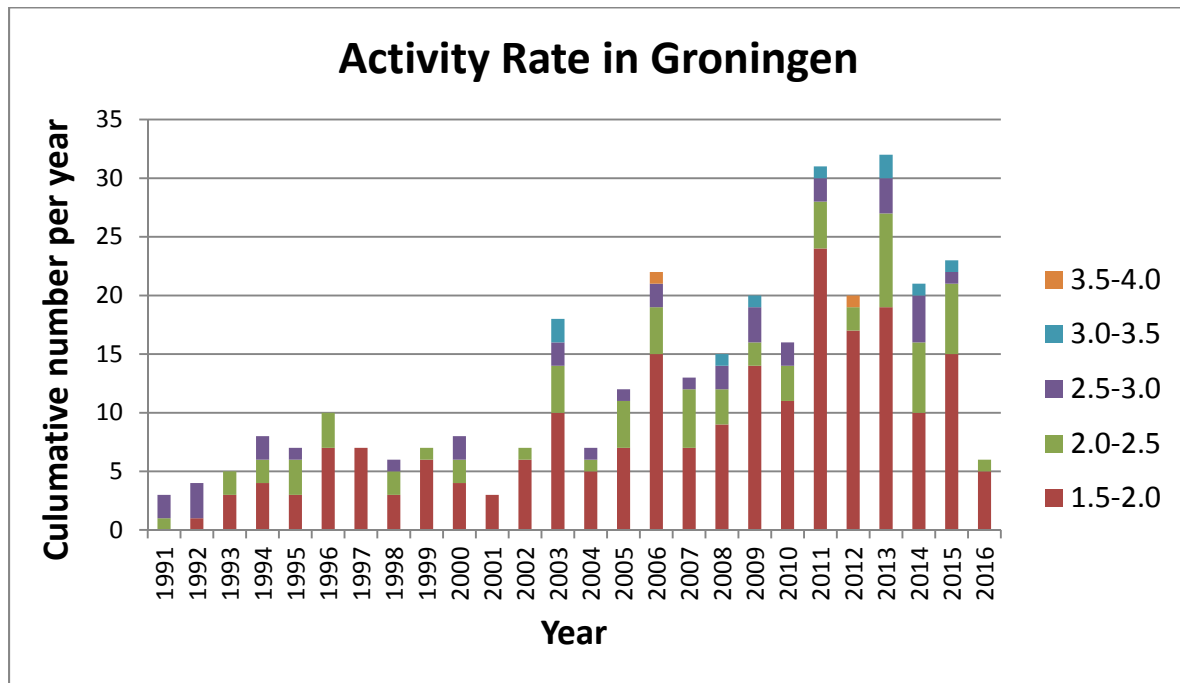

Figure 1: Activity of observed induced earthquakes in Groningen over the years. Only events with a magnitude greater than 1.5 are used in the KNMI earthquake catalog. The graph is valid for recordings before June 29, 2016.

Spatial distribution
The spatial distribution of induced earthquakes in Groningen is shown in Figure 2. The figure on the left shows earthquake density in the region for the period 2011-2016 and on the right the proposed zonation, as used in the 2015 update.

In the last five years there is a concentration of induced earthquakes in the Loppersum area and in another area further south close to Hoogezand. The four zones with specific characteristics of seismicity as previously used in the KNMI v1 hazard map (Dost and Spetzler, 2015) are the *Central north*, *Central south*, *Active area* and *background*; see right-hand plot in Figure 2. The Central north and Central south zone are the two areas with most seismicity. There is a smaller number of recorded events in the Active area and Background zone.

There are indications for a possible shift in seismicity from the Central north zone towards the south in the last one to two years. However, the number of events in recent years is still too limited to be used in a statistical spatial analysis. A comparison of the spatial distribution of seismicity in Groningen in the last 3 or 5 years shows no significant changes for the entire gas field.
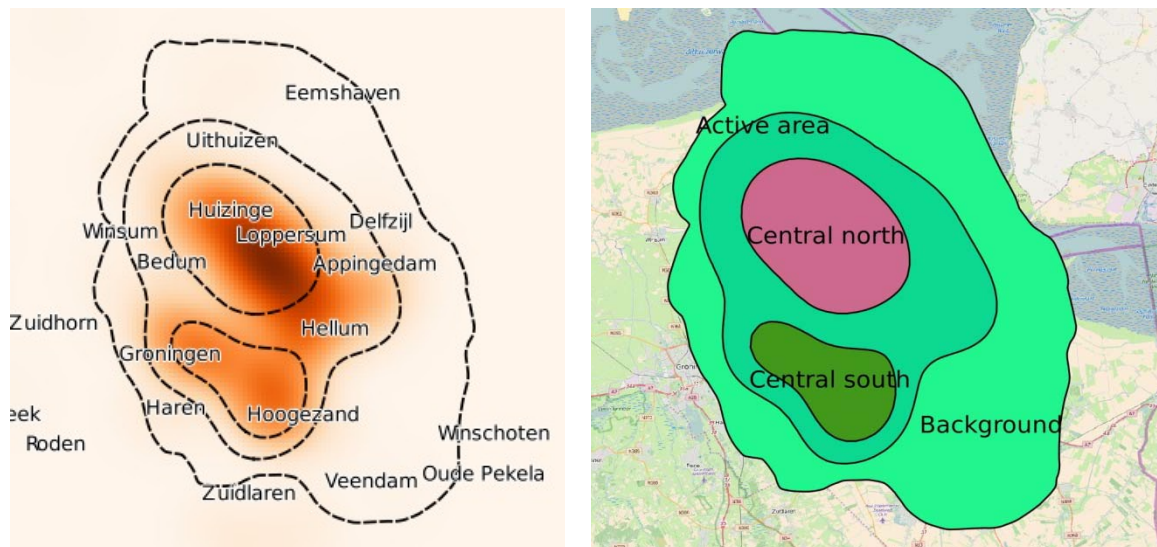

Figure 2: Distribution of induced earthquakes in Groningen between 2011 and 2016 and the corresponding zonation.

Frequency-magnitude relation
The Gutenberg-Richter (GR) law describes the relationship between the event-frequency and magnitude. An analysis of the induced earthquakes between 2011 and 2016 in Groningen has shown that the b-value (i.e., the slope of the GR curve) is equal to 1.0 for the zones Central south, Active area and Background. However, the Central north zone with the highest density of events is best characterized with a b-value equal to 0.8.

The seismological hazard parameters for the zonation are summarized in Table 1. Summing the activity rates for the four zones gives 22.8 events per year, just as it was the case in the KNMI v1 hazard map (Dost and Spetzler, 2015).

Zone	Central north	Central south	Active area	Background
B-value	0.8	1	1	1
Activity rate	10.4	4.2	6.4	1.8
Magnitude range	1.5-5.0	1.5-5.0	1.5-5.0	1.5-5.0
Surface area [km^2]	167	90	363	716

Table 1: Seismological hazard parameters for the four zones in the zonation.

Hazard model

Similar to the results presented in the previous report (Dost and Spetzler, 2015), the method by Cornell (1968) was used to calculate the PSHA. However, since the latest version of the GMPE (v2) introduced an upper layer with laterally varying characteristics, the method required modification. We followed the approach by Bazzurro and Cornell (2004) to include an amplification factor. The methodology is illustrated in Figure 3 and consists of a two-step approach. First, the hazard curve at a selected reference level, which is for Groningen the bottom of the upper North Sea group at ~350 m depth, is calculated by summing up the contribution of induced earthquakes over the zonations and the magnitude range. Second, the hazard curve at the surface is obtained by convolving the probability density function of the spectral acceleration at the reference level with the probability distribution of the amplification factor. The convolution method permits each reference ground-motion level to contribute to the hazard for each surface ground-motion level. The result of this two-step PSHA method is the seismic hazard assessment at the surface in terms of spectral acceleration including the site-specific non-linear amplification factor. The PSHA results presented in this report are calculated for a return period of 475 years or its equivalent a 10% chance of exceedance in 50 years. An example of a similar approach applied in a site analysis for a nuclear power plant site in South Africa is explained in Rodriguez-Marek et. al. (2014).
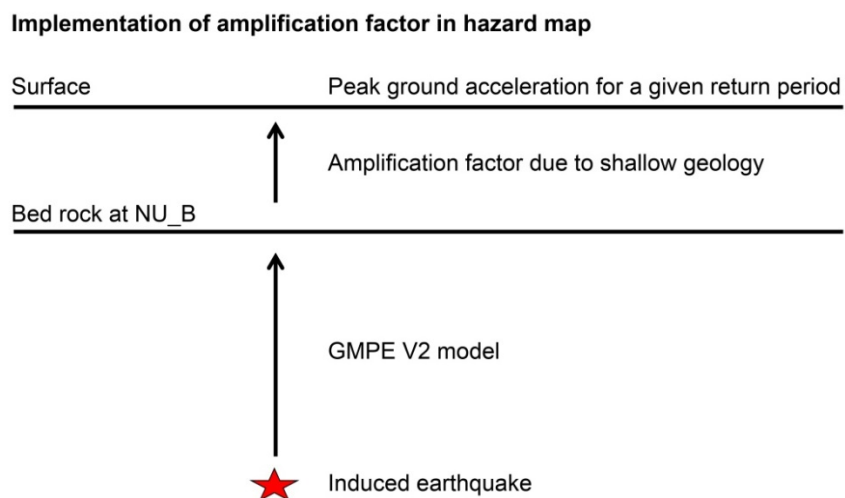

Implementation of amplification factor in hazard map

Surface — Peak ground acceleration for a given return period

Amplification factor due to shallow geology

Bed rock at NU_B

GMPE V2 model

Induced earthquake

Figure 3: Illustration of methodology in the hazard V2 model. Vertical scaling is exaggerated.

Ground Motion Prediction Equation
The most important new feature in the v2 version of the GMPE is the introduction of non-linear site amplification functions. In addition, predictive equations are given for spectral accelerations at 16 periods, from 0.01 s to 5 s. Similar to the v1 model, the v2 model includes three logic-tree branches based on a lower, central and upper estimate of stress-drop (10, 30 and up to 100 bar). Weights are assigned to these branches, 0.2, 0.5 and 0.3 respectively. In a discussion between NAM and the regulator (State Supervision of the Mines), it was suggested to put more weight on the higher stress-drop branches and weights 0.0, 0.5 and 0.5 were suggested. Since the NAM results are calculated with the latter weights, we decided to follow this suggestion in our calculations in order to compare results. It should be noted that the GMPE is calibrated for M=2.5 and above, while in the KNMI hazard calculations also lower magnitudes are included (1.5<M<2.5). Although events in this category will only have a minor effect on the hazard, the GMPE is most probably conservative.

Amplification factor due to shallow geology
Seismic waves propagating towards the surface start to slow down especially in the shallow part of the subsurface below Groningen. The impedance contrast of the shallow layers results in an amplification of these waves at the surface. Typical soil types are sand, clay and peat. Kruiver et al. (2015, 2016) developed an integrated shear-wave velocity model for the first 350 m for Groningen. The first 50 m is based on a combination of measurements and models, followed by a reinterpretation of ground-role data from data from seismic reflection surveys down to 120 m and from 120-350 m shear velocities are added from an improved time-to-depth model from seismic imaging of the reservoir.
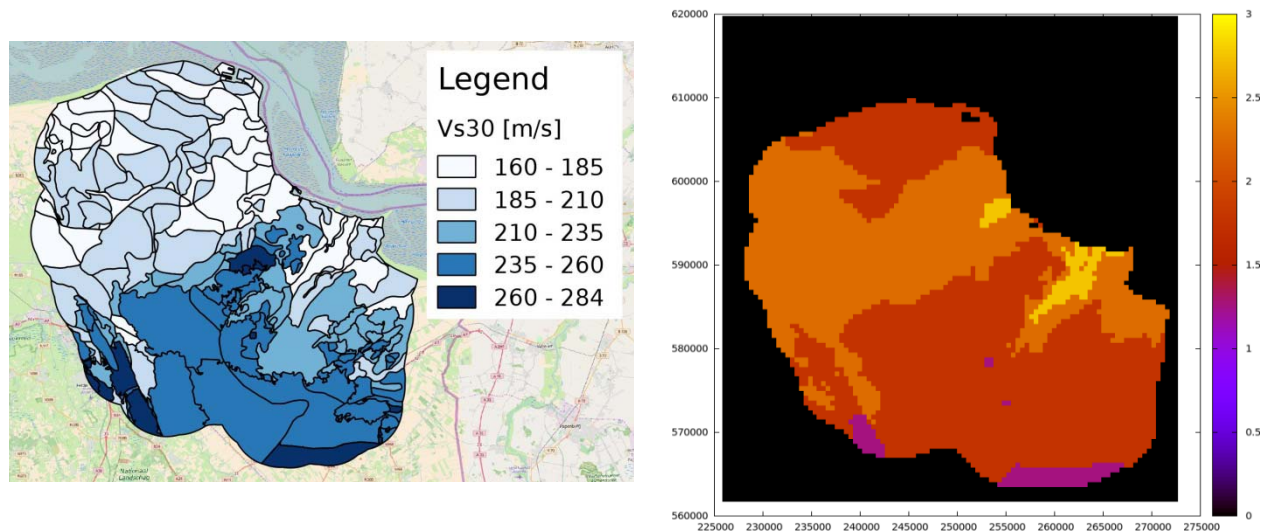

Figure 4: Illustration of the amplification factor due to shallow geology. Left: Geological zones and shear wave velocities in the shallow subsurface. Right: Example of the amplification factor due the shallow geology for the period T = 0.01 s.

Figure 4 shows the map of the shear wave velocity model in the first 30 m in Groningen (left figure), which dominates the amplification factor. The largest shear-wave velocities are

generally found in the southern part of the province of Groningen, and lower values are in the north. In the right panel of Figure 4, an example of the amplification factor for the period T = 0.01 s (PGA) is presented. Generally, seismic waves are amplified less in the south compared to the north for this period.

Since the measured accelerations at the surface are still small (< 1 m/s^2), non-linear behavior of the upper layers is not yet observed. However, this effect should be taken into account in the hazard analysis because much larger magnitude earthquakes are considered. Bommer et al. (2015) used an Equivalent Linear (EQL) approach based on Random Vibration Theory (RVT) to model the non-linear behavior and discussed at length (chapter 8) the difference with the fully non-linear approach. Based on a literature review it was concluded that RVT based EQL can be regarded a conservative estimate.

Results

Figure 5 shows the new seismic hazard map for Peak Ground Acceleration (PGA). The main differences with the previous update (Dost and Spetzler, 2015) is the reduction of the highest PGA level near Loppersum from 0.36 g to 0.22 g and a more irregular pattern. This is due to the effects of the non-linear site amplification functions and the selection of alternative weights in the logic tree. Please note that the 2015 map was calculated using the original proposed weights. Due to the effect of laterally varying amplification functions, the PGA values in the hazard map are plotted on a grid this time, instead of using contour lines as it was done in the earlier KNMI hazard maps. Table 2 gives a summary of the most important parameters used in the PSHA calculations.

Hazard model	Return period	GMPE weights	Activity rate model
V2	475 y	(0, 0.5, 0.5)	KNMI zonation based on observed induced earthquakes, 22.8 events/year

Table 2: Hazard parameters applied in this study.

The highest PGA values are concentrated around the area between Loppersum, Ten Boer, Appingdam and Spijk. A few other areas, standing out with a slightly higher hazard than neighboring locations, are found north-west of Huizinge and south from Groningen city. The southern part of the province of Groningen shows small PGA values (< 0.1 g). For comparison, the hazard map for the v0 and v1 model are included in the Appendix. The hazard in Groningen has been reduced from a maximum of 0.42 g for the v0 model, through 0.36 g for the v1 model to 0.22 g for the latest v2 model. The main reason for the reduction of hazard comes from a better understanding of the subsurface structure and an extension of the dataset from the new station network in Groningen, as well as the refinements of the GMPE to both reflect local conditions (and the associated uncertainty) and incorporate non-linear response of the soft soil deposits.
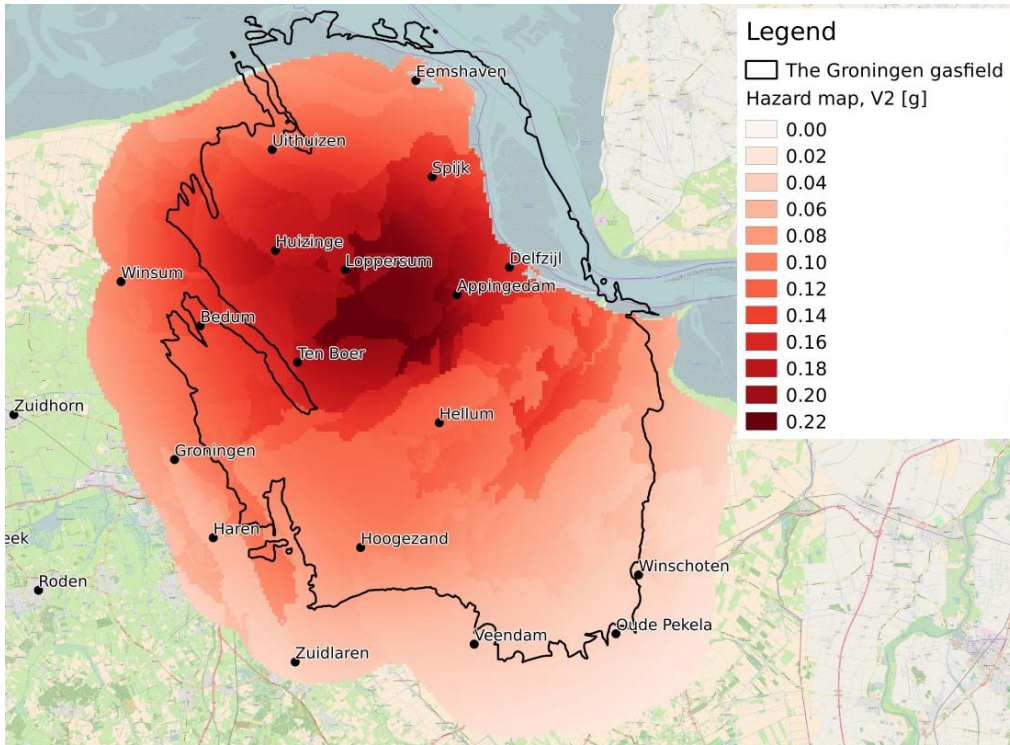
Figure 5: Probabilistic seismic hazard map for Groningen for the period T = 0.01 s. The return period is 475 y according to Eurocode 8, max PGA = 0.22 g. The black solid line indicates the contours of the Groningen gas field.

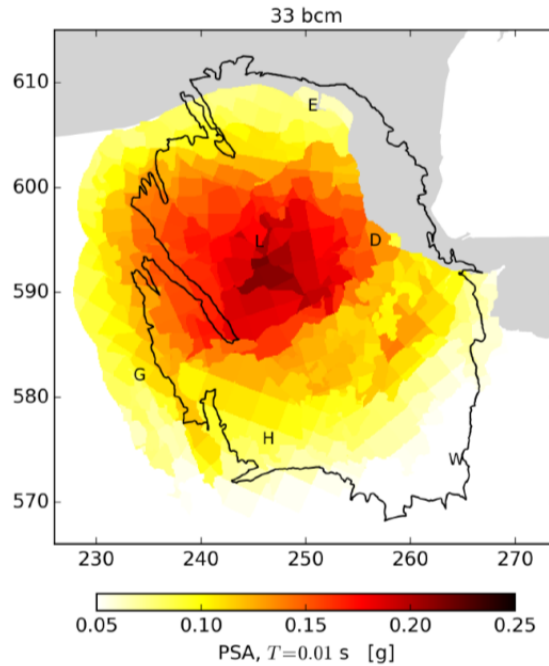*Comparison with NAM results*

Figure 6: NAM PGA hazard map (fig 7.13 from Technical addendum to the winningsplan Groningen, 2016), max PGA = 0.21 g.

A qualitative comparison between results from NAM (Figure 6) and KNMI (Figure 5) shows a good correspondence. The maximum PGA value is comparable, while also the irregular shape of the hazard levels are similar. This is caused by the site response functions, but also shows that the application of different source models and methods of calculating the hazard do not have a large effect. At larger distances, the south-eastern part of the gas field shows values at or below 0.05g in both maps and near the north-western boundary of the field values around 0.15g are found on both maps. Only a quantitative comparison between both digital maps, which is planned, would reveal detailed differences.

In addition to the PGA map, which is equivalent to the Spectral Acceleration (SA) at a period of 0.01s (100 Hz frequency), also maps of SA at the other 15 periods may be presented. However, a total suite of 16 plots does not provide a clear insight in the variation over frequency and therefore spectra will be presented and discussed on selected locations in the field. The spectra show SA values for periods between 0.01 s and 5 s which are most relevant for the evaluation of hazard and risk in Groningen.

A site analysis is presented for two locations: one in the city of Groningen (coordinates: X: 234.120; Y: 582.057) and another in Loppersum (X: 245.598; Y: 594.788). At these locations, spectral accelerations are shown as a function of period (1/frequency). In addition, results from disaggregation show which events contribute most as a function of distance and/or magnitude.

The spectra for the locations in Groningen Stad and in Loppersum are presented in Figure 7 for the return period of 475 years. In both cases, spectra do have a maximum value around 0.3 s. The two spectra in Figure 7 show similar characteristics as the spectra in chapter 11 of Bommer et. al. (2015). In both reports, the spectra show a maximum peak around 0.3 s. Disaggregation results in Figure 8 for the period T = 0.01 s and in Figure 9 for the period T = 0.3 s show that the main contribution to the hazard in the city of Groningen comes from events at 12 km distance and magnitude 5, while at Loppersum the distance is reduced to 2.5 km. However, it should be noticed that disaggregation indicates a magnitude 4.5 rather than 5 for Loppersum at the period T = 0.3 s. Both spectra compare very well with the spectra calculated by NAM for the same locations for periods up to 1 s. For longer periods the spectra start to show small differences at low levels of spectral acceleration. The cause of this difference will be investigated. NAM data were made available for the 27 bcm (Nov-2015 HRA version) scenario.
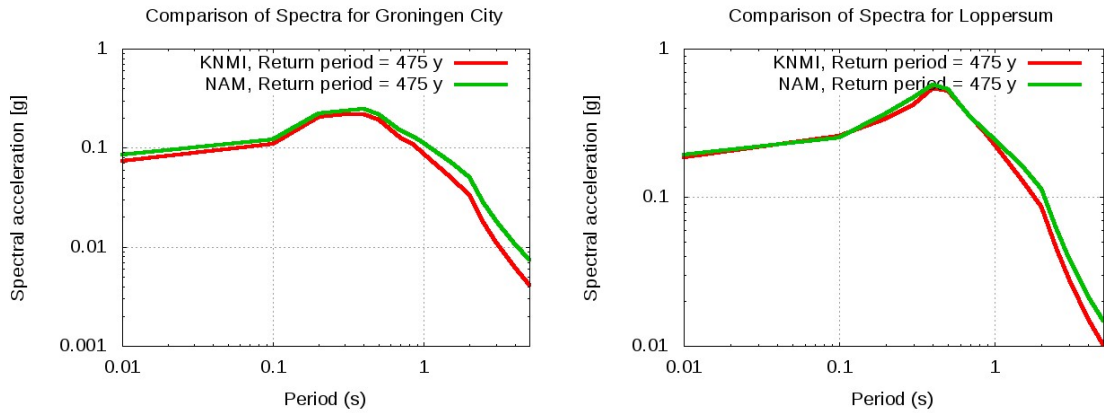
Figure 7: Spectral acceleration for a location in Groningen city and Loppersum. KNMI results in red, NAM results in green.
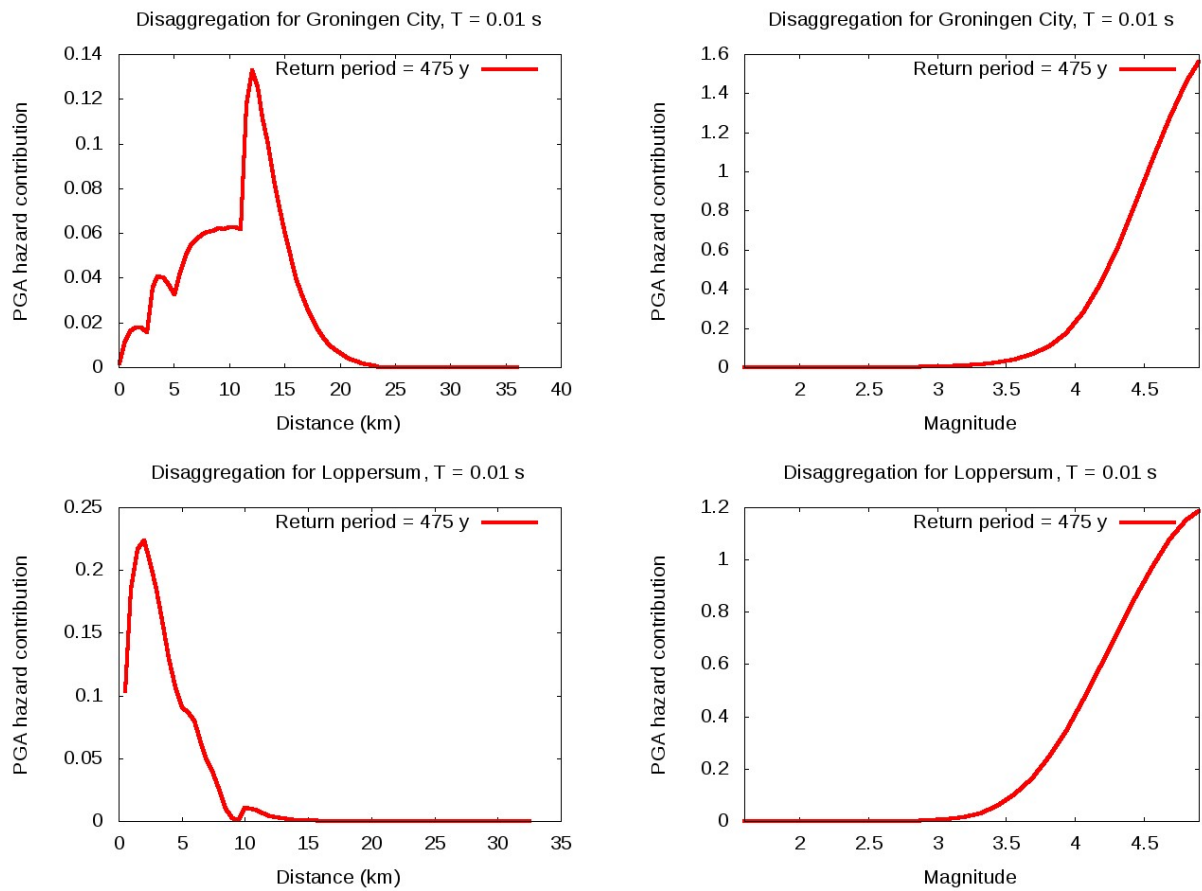

Figure 8: Disaggregation results for period T = 0.01 s for the distance and magnitude for a location in Groningen city and Loppersum.
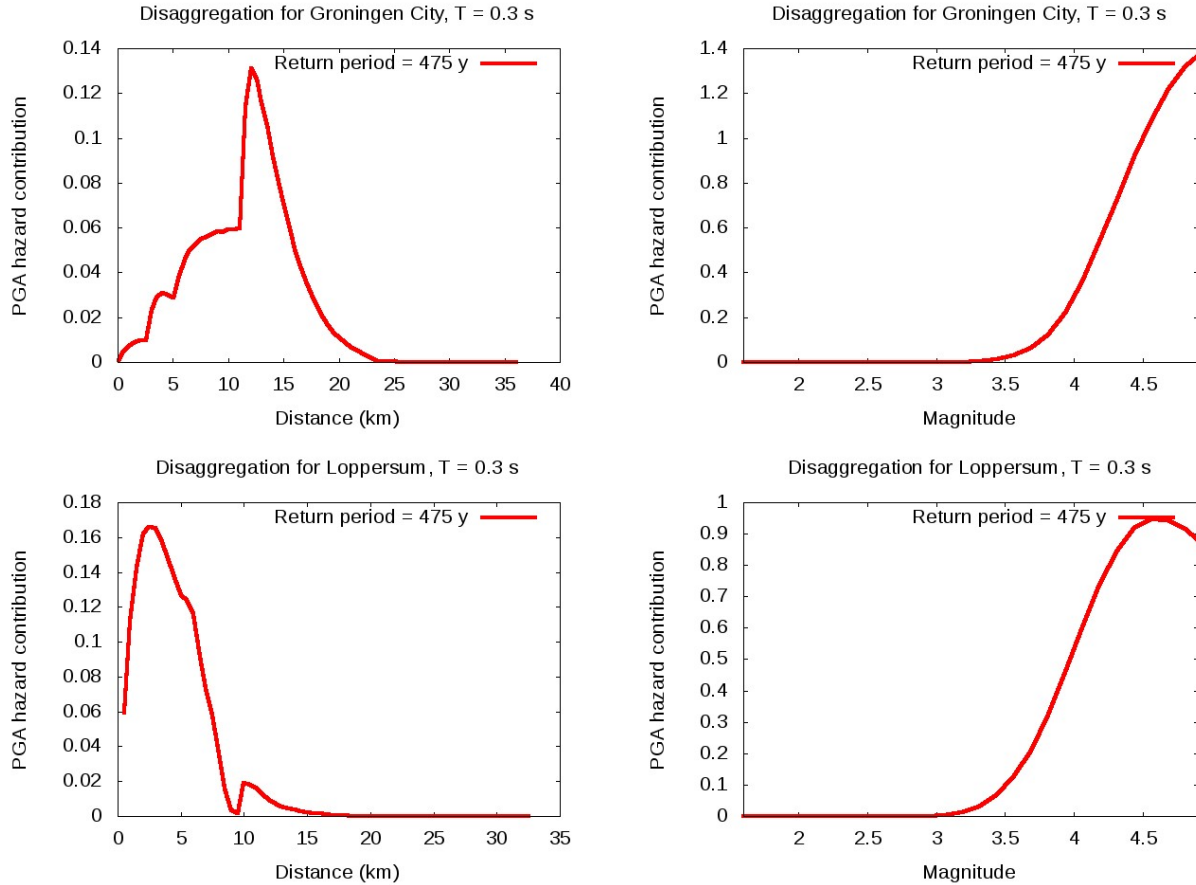
Figure 9: Disaggregation results for period T = 0.3 s for the distance and magnitude for a location in Groningen city and Loppersum.

Discussion and conclusions

A new version of the hazard map for Groningen is presented, motivated by an important update of the GMPE model (v2) for induced seismicity in the region. The main feature of the update is the introduction of a laterally varying site response model, which also implied a modification of the method to calculate hazard. Due to the introduction of non-linearity in the site response model, the maximum PGA value in the hazard map is reduced from 0.36 g to 0.22 g. The extension of the period range at with Spectral Acceleration is evaluated, allowed the presentation of spectra at different locations in the field. As an example two locations were presented. These calculations can be carried out on request for selected locations in the field. Disaggregation gives insight in the seismic sources that contribute to the spectral accelerations.

A qualitative comparison with the model published by NAM in their winningsplan 2016 (33 bcm, NAM report (2016)) shows a similar pattern and level of PGA over the Groningen gas field. This finding gives a confirmation that the PSHA results for Groningen are robust, since hazard calculations of KNMI and NAM differ in their source model, the assumed maximum magnitude and the method to calculate the hazard.

The GMPE will be further developed keeping the same structure as v2. The new monitoring network will provide new data that can be used to improve our understanding of the processes at depth. Outstanding questions are e.g. what is the best estimate for M_{max} in the region and how accurately can we model the movement along existing faults for potentially larger magnitude events (M>4) that have not been recorded.

The KNMI hazard model based on the v1 version of the GMPE was used by the NPR committee of the NEN in their national guideline (NPR-9998:2015), but was limited to the PGA map. An adjustment was made to include non-linear site response. The current model includes both the spectral acceleration at relevant periods and non-linear site effects and is a potential candidate to be used in the upgrade of the NPR.

Acknowledgements

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Appendix

The hazard maps for the v0 and v1 model developed by the KNMI in the past years are shown in this appendix. For details about the hazard analysis previously carried out, we refer to Dost and Spetzler (2015). The hazard parameters for each respective map are repeated in a table before the hazard map is presented. The results of the hazard maps can be understood without an additional explanation.

Hazard model	Return period	Gmpe weights	Activity rate model
V0	475 y	Only one gmpe	KNMI zonation based on observed induced earthquakes, 40 events/year

Table A1: Hazard parameters applied in the v0 hazard model.

Figure A1: V0 Hazard model. The hazard map for Groningen for the period T = 0.01 s. The maximum PGA is 42 % of g.

Hazard model	Return period	Gmpe weights	Activity rate model
V1	475 y	(0.3, 0.5, 0.2)	KNMI zonation based on observed induced earthquakes, 22.8 events/year

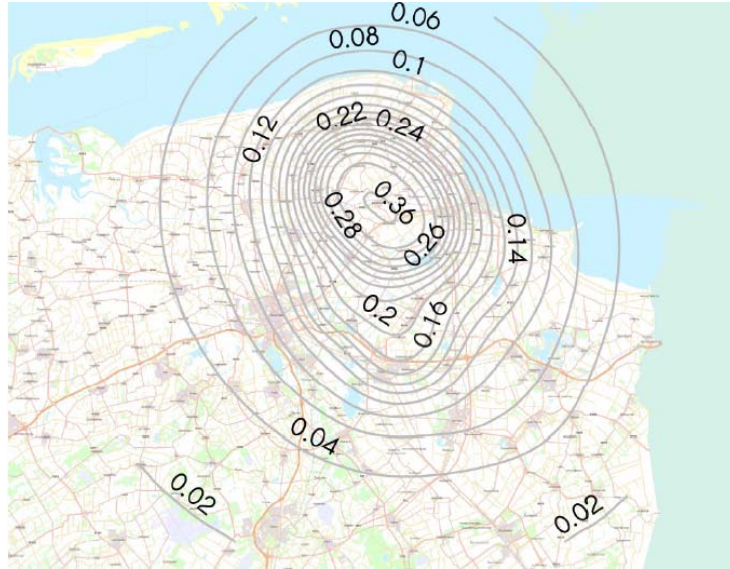*Table 2: Hazard parameters applied in the v1 hazard model.*

Figure A2: V1 Hazard model. The hazard map for Groningen for the period T = 0.01 s. The maximum PGA is 36 % of g.