Probabilistic Seismic Hazard Analysis for Induced Earthquakes in Groningen; Update 2015

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Introduction

In this report an update of the Probabilistic Seismic Hazard Assessment (PSHA) for induced seismicity in Groningen is presented. The original map, see Appendix A.1, has been published in a slightly different form in Dost et al. (2013) and was published in the context of the NPR-9998:2015v1.1 ("Netherlands Guideline for the assessment of buildings in case of erection, reconstruction and disapproval - Basic rules for seismic actions; Induced earthquakes"). The map shows the probabilities of exceedance of ground motions in the area for a return period of 475 years.

The hazard analysis was carried out using a probabilistic method, developed by Cornell (1968). Usually this method is applied to natural events of magnitudes (M>4) under assumption of a stationary process. For shallow induced events, magnitudes of damaging events are in general smaller and the process non-stationary and this requires an adaptation of the method (e.g. Eck et al., 2006; Kraaijpoel et al., 2014). A PSHA analysis consists of different components. Most important are a spatial and statistical description of the seismicity in the area and a Ground Motion Prediction model, relating event magnitudes to peak ground acceleration (PGA) at the surface.

The need for an update of the original map is twofold. Since the end of 2013, which is the end of the time period taken into account in the previous version of the hazard map, the real-time availability of data from the continuously recording accelerometer monitoring network in Groningen is rapidly improving. As a result the Groningen dataset more than doubled, from 40 to 85 accelerograms (Bourne et al., 2015; Bommer et al., 2016). The current analysis includes seismicity until June 1, 2015. In the last 18 months production measures have been taken, that are expected to influence seismicity. In addition an important update of the Ground Motion Prediction Equation (GMPE) was realized, moving from an equation based on shallow tectonic seismicity in the region covering the Mediterranean and the Middle-east and extrapolating to lower magnitudes for Groningen (V0), towards an equation that was purely based on Groningen data and extrapolated by stochastic simulation to higher magnitudes using seismological theory (V1). This updated GMPE shows a significantly reduced variability with respect to V0 (smaller sigmas), but whereas V0 was a single conservative model, we now have three branches capturing the range of epistemic uncertainty (Bommer et al., 2016).

The current analysis method uses a source model based on recorded seismicity. An alternative source model, based on a reservoir compaction model, has been developed by Bourne et al. (2014). Although the methods in both approaches are different, the same GMPE for Groningen is used and the outcome can be compared.

In the next chapters the model and their input parameters are discussed.

Source zonation

Similar to other seismically active areas, the earthquake spatial density varies over the Groningen gas field. In the PSHA method it is common practice to divide a seismic area into zones, where the distribution of events and their characteristics is assumed to be uniform. Figure 1 and 2 show the proposed zonation (Z2) and a comparison with the ones used in earlier studies (Z1) for the same region (Dost et al., 2013). The Z1 distribution was obtained manually by visual inspection.

The new version (Z2) is now based on an event density map, sometimes also referred to as a "heat map", and shows a smooth pattern. The exact form or smoothness of these zones is of minor importance to the final result. More important is to assign events to specific zones, since this effects the statistical parameters in each zone. Zonation Z2 has been enlarged with respect to Z1 up to 2 km outside the Groningen gas field, capturing events that are most likely related to the gas field.

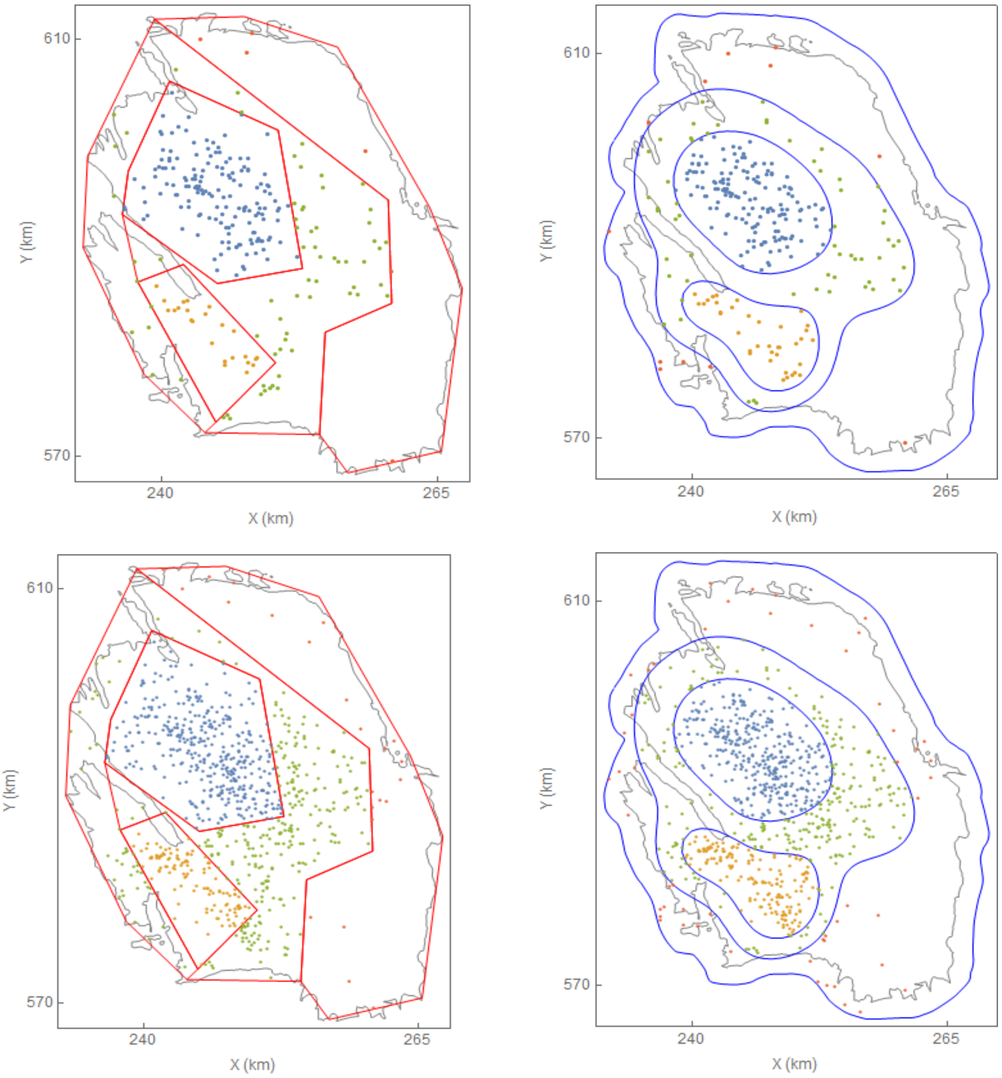


Figure 1. Zonations Z1 (left), used for the NPR, and Z2 (right) used in the present study. Earthquakes in the different zones are indicated by colored dots, each zone a different color. Upper figures show events with M > 1.5, level of completeness, and are used in the analysis; lower figures show all data.

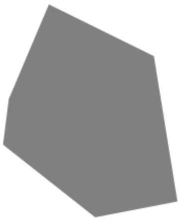
	Central–North (CN)	Central–South (CS)	Active Area (AA)	Background (BG)
Zonation Z1	 Area: 212 km^2	 Area: 83 km^2	 Area: 427 km^2	 Area: 369 km^2
Zonation Z2	 Area: 167 km^2	 Area: 90 km^2	 Area: 363 km^2	 Area: 716 km^2

Figure 2. Naming and characteristics of zones in Figure 1

Temporal distribution

In the previous hazard map an exponential trend-model was used to describe the temporal distribution of seismicity in Groningen. Such a model requires some continuity in the system parameters (e.g. the production rate) and was based on seismicity in a situation of increased production. Over the last two years several production control measures have been taken in the Groningen gas field in order to reduce seismicity, especially in the Loppersum area (Central North zone). The implications of these changes are that the exponential trend-model is no longer applicable in this study.

Instead, we have decided to use a recent calibration period for N years before June 1, 2015, the end of the catalogue. In this calibration period, we determine the annual average number of induced earthquakes per zone. The only degree of freedom in this model is the choice of N. For higher values of N, more data are available which is an added value in the calculation of averages. However, a lower value for N results in an improved sensitivity to trends, which is advantageous for the effects of production changes, but has as disadvantage that it may also include random changes unrelated to the production changes.

We tested calibration periods of N = 1, 2, 3, 4, 5, 10 and 20 year. For this report we selected N=5 years as a compromise between short and long duration. This period is expected to show the effects of changes in production and contains enough data to calculate statistical parameters for each zone.

Magnitude distribution

The classical Gutenberg-Richter (GR) relation is used to describe the statistical distribution of magnitudes. This model describes the relative frequency of stronger events with respect to smaller ones, the b-value, being the slope of the curve relating the logarithm of the cumulative annual frequency of events to magnitude. In addition the activity rate parameter a can be derived. A b-value equal to 1 indicates that events with a magnitude greater than M is about 10 times more frequent compared to events with a (stronger) magnitude M + 1.

In the previous hazard map, the b-value was calculated for the complete earthquake catalog for Groningen (b= 1.0 ± 0.2) and assumed b=1 in the analysis. In the meantime spatial and temporal variations have been observed, see Harris and Bourne (2015) for a detailed explanation. Based on this observation, we have decided to estimate the b-value for each zone separately for the given calibration period. However, if the number of events in a zone is too small, annual rate < 5, an average value of b= 1.0 is selected. In this study, the range of b-value is limited to values between 0.8 and 1.0 to reduce the effect of random errors.

In practice, the Gutenberg-Richter distribution is almost always cut-off at a certain maximum magnitude, known as M_{max}. The M_{max} parameter takes into account that every seismic system is limited to a maximum possible magnitude. It is not an easy task to estimate M_{max}. For Groningen statistical- and geomechanical studies have been carried out, but this did not yet led to a satisfactory estimate of M_{max}. We know that the maximum magnitude must be larger than the maximum observed magnitude of 3.6, the Huizinge event on August 16th, 2012. For an upper bound, we assume that M_{max} is not larger than 5.0 based on literature studies of gas fields around the world. For a more detailed discussion see Dost et al. (2013).

In this study, we decided to use M_{max} = 5.0. If in future new information becomes available on this parameter, we will modify this parameter.

Ground motion prediction equation

A preliminary Ground Motion Prediction Equation (GMPE) was derived for the Groningen gas field (Bourne et al., 2015). This model (V0) was based on the model from Akkar et al. (2014), who used data of M>4 tectonic earthquakes from Europe and the Middle-East, and extended to lower magnitudes using recorded events in Groningen (2.7 < M_L < 3.6). The combination of different datasets results in a significant uncertainty in the GMPE, but at that time the limited Groningen database did not allow a more sophisticated model development.

In the meantime an update of the V0 model has been developed, based on an extended dataset for Groningen only. Instead of relying on data from other regions and extrapolating to lower magnitudes, the new version (V1) is developed directly from Groningen field data and extrapolated to larger magnitudes using stochastic simulations. Input for the stochastic simulations are damping parameters, Q and κ, and stress-drop, geometrical spreading and an average site amplification derived from the acceleration spectra of Groningen records. The V1 model consists of a weighted sum of three equations for the region based on different assumed values of the stress drop: a lower, central and higher model. Details on the construction of the V1 model can be found in Bommer et al. (2016).

In both the V0 and the V1 model only a network averaged site amplification function was taken into account. In the next update of the Groningen GMPE model (V2), regional variations in site effects will be included.

The extension of the dataset for the V1 model is significant for larger epicentral distances (10-20 km), which is not well covered in the V0 model. This results in a different attenuation at these distances. While the V0 model only provides relations for PGA and PGV, the V1 model includes spectral accelerations at 5 periods (0.01, 0.2, 0.5, 1.0 and 2.0s; note that spectral acceleration at 0.01 s is equivalent to PGA).

Results

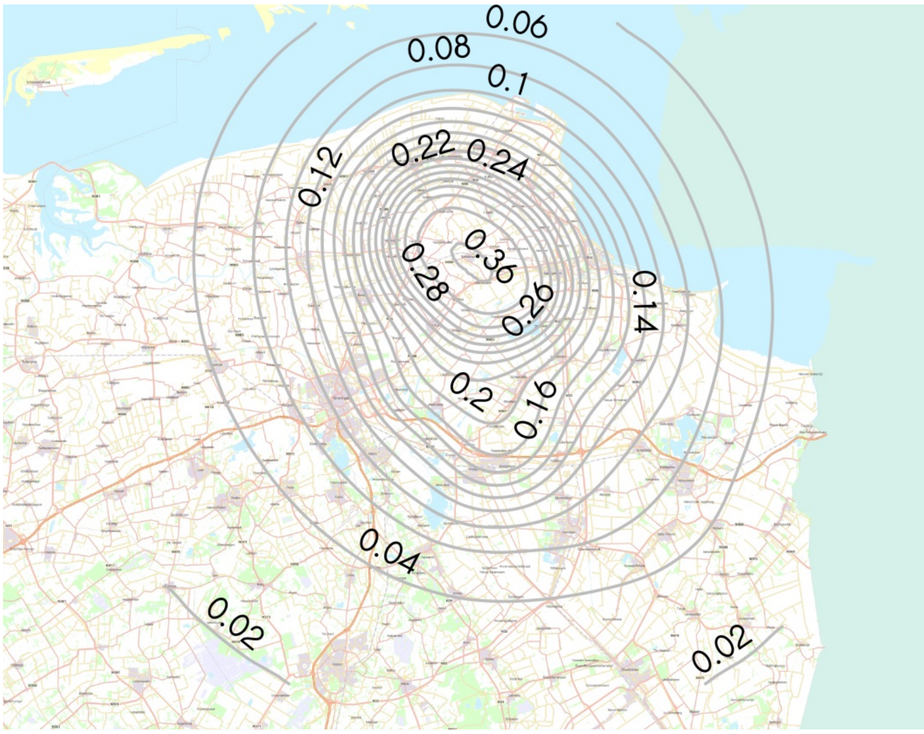


Figure 3. Predicted ground motions with a 10% chance of exceedance in 50 years (475 year return rate), using the GMPE V1 model and M_{max}=5.0. Maximum PGA values near Loppersum of 0,36g.

Figure 3 shows the new seismic hazard map. The main features of this map with reference to the original map are a reduction of the highest PGA level near Loppersum by 14% and a reduction of up to 50% in the outer regions. In Appendix A.2.1 details are shown on the parameters used and a comparison with the previous model (NPR case). In addition the effect of different assumptions on the calibration period are shown in Appendix A.2.2 (N=3 years) and A.2.3 (N=10 years), where differences with respect to the map in A.2.1 (base case) are shown in percentages. For the 3 year period the difference is limited (within 5%), while for the 10 year period the differences in the outer most regions to the south-east could even reach nearly 20% lower hazard values.

In all models shown a M_{max}= 5.0 has been used and there is presently no convincing evidence for a different assumption on this parameter. However, in order to show the sensitivity of the model to a different choice of this parameter, a model is presented in Appendix A.2.4 based on M_{max}=4.5, while keeping the other parameters similar to the base-case. Over the entire field this model shows a 20% reduction of the hazard.

Discussion and conclusion

An update of the hazard map for Groningen is presented, based on an extended dataset for accelerations recorded in Groningen and the development of a new GMPE model (V1) for induced seismicity in the region. The map shows, as a consequence of the new functional form, reduced variability in the GMPE and the calibration to local conditions, a significant reduction in the expected PGA values. Another new feature in the modelling is the introduction of a differentiation of b-values in the different zones. The central-north zone is characterized by a smaller b-value compared to the other zones and this causes an increase in the hazard.

Further development of the GMPE will concentrate on the introduction of a laterally varying site effect, due to variations in the shallow geology. Due to the extension of the observation network in the region, the level of completeness of events in the Groningen region is expected to go down from M=1.5 to approximately M= 0.5. The implication of this change is the availability of a larger dataset that can be used for the estimation of seismicity parameters.

We propose the NPR-committee of the NEN to consider the use of this map in their national guideline. Also, it can be used by other parties as a reference for risk assessment, strengthening measures and designs for other infrastructure, not covered by the NPR.

Acknowledgements

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References

Akkar, S., M.A. Sandikkaya, J.J. Bommer (2014). Empirical ground-motion models for point- and extended-source crustal earthquake scenarios in Europe and the Middle East, *Bull. Earthq. Eng.*, Vol **12** (1), 341-358, doi:10.1007/s10518-013-9461-4.

Bommer, J. J., B. Dost, B. Edwards, P.J. Stafford, J. van Elk, D. Doornhof and M. Ntinalexis (2016). Developing an Application-Specific Ground-Motion Model for Induced Seismicity, *Bull. Seismol. Soc. Am.*, **106**(1), *in press*.

Bourne, S.J., S.J. Oates, J. Van Elk and D. Doornhof (2014). A seismological model for earthquakes induced by fluid extraction from a subsurface reservoir, *J. Geophys. Res.* **119**, 8991-9015, doi: 10.1002/2014JB011663.

Bourne, S.J., S.J. Oates, J.J. Bommer, B. Dost, J. van Elk and D. Doornhof (2015). A Monte Carlo method for probabilistic hazard assessment of induced seismicity due to conventional natural gas production. *Bull. Seismol. Soc. Am.* **105**(3), 1721-1738.

Cornell, C.A. (1968) Engineering seismic risk analysis. *Bull. Seismol. Soc. Am.*, **58**, 1503-1606.

Dost, B., M. Caccavale, T. Van Eck and D. Kraaijpoel (2013). Report on the expected PGV and PGA values for induced earthquakes in the Groningen area, KNMI report, 26pp. (http://bibliotheek.knmi.nl/knmipubDIV/Report_on_the_expected_PGV_and_PGA_values_for_induced_earthquakes.pdf)

Eck, T. van, F. Goutbeek, H. Haak and B. Dost (2006). Seismic hazard due to small-magnitude, shallow source, induced earthquakes in the Netherlands, *Eng. Geol.* **87**, 105-121.

Harris, C.K. and S.J. Bourne (2015). Maximum Likelihood Estimates of b-value for Induced Seismicity in the Groningen Field, NAM report (http://www.tweedekamer.nl/kamerstukken/moties/detail?id=2015D24980)

Appendix A.

A.1

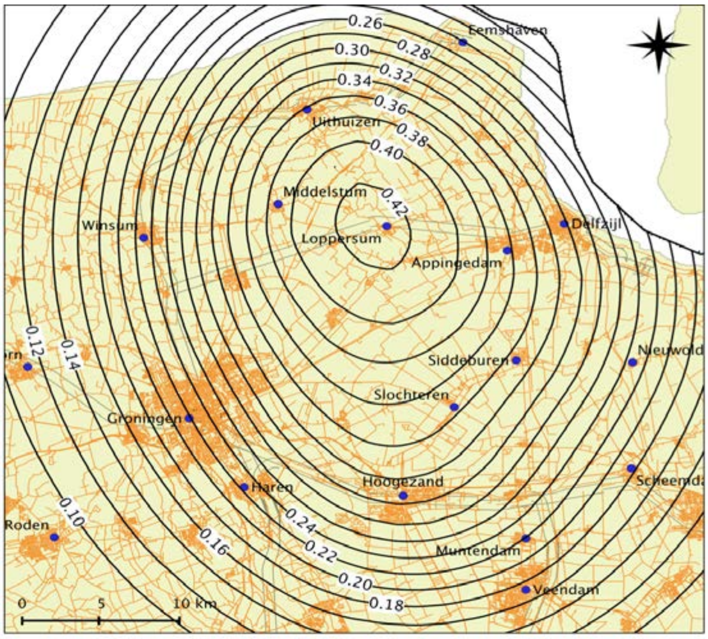
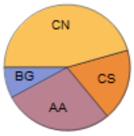
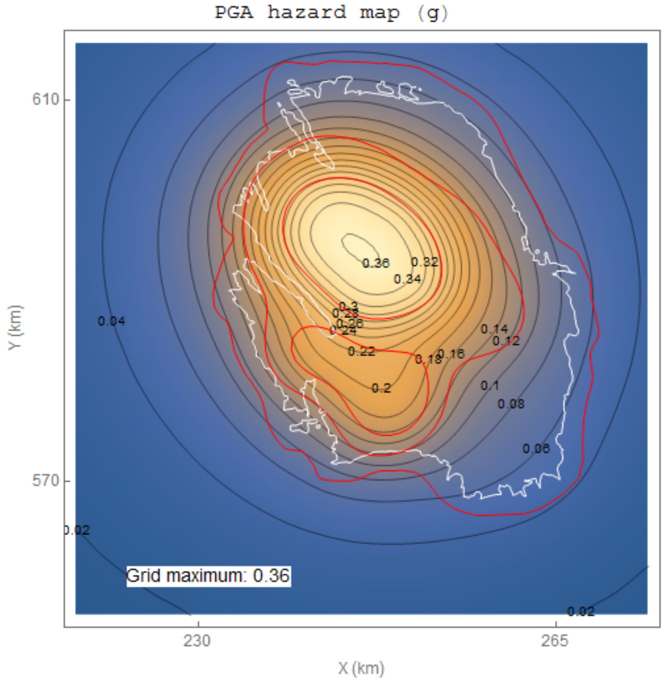
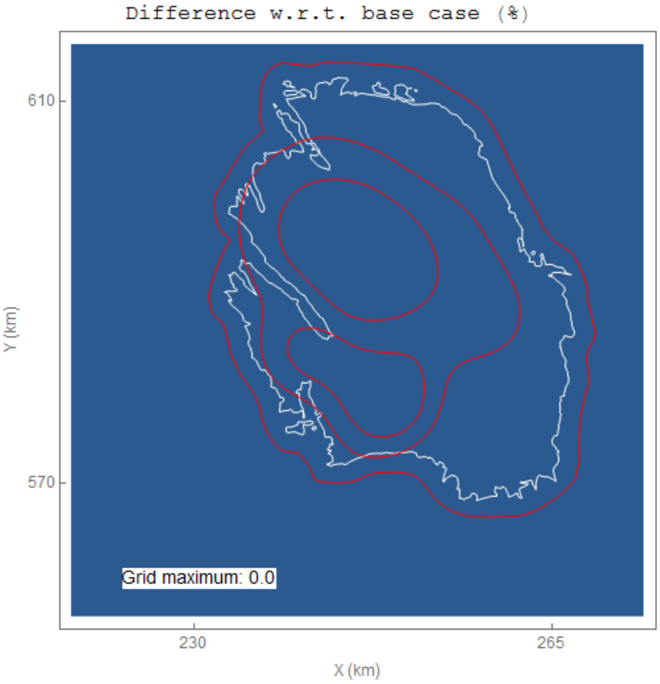


Figure A.1. Predicted ground motions with a 10% chance of exceedance in 50 years (475 year return rate), using the GMPE V0 model, b=1 and M_{max}=5.0. Maximum PGA values near Loppersum of 0,42g. This figure is referred to as the NPR-case.

Appendix A.2.1

zonation	Z2
calibration time frame (years before 2015-06-01)	5
maximum magnitude model	5.0
ground motion prediction model	V1
return period (years)	475.
annual number of events	22.8
b-values per zone	CN: 0.8 CS: 1.0 AA: 1.0 BG: 1.0
average distribution of events per zone (relative)	CN: 0.46 CS: 0.18 AA: 0.28 BG: 0.08 
average distribution of events per zone (annual)	CN: 10.4 CS: 4.2 AA: 6.4 BG: 1.8





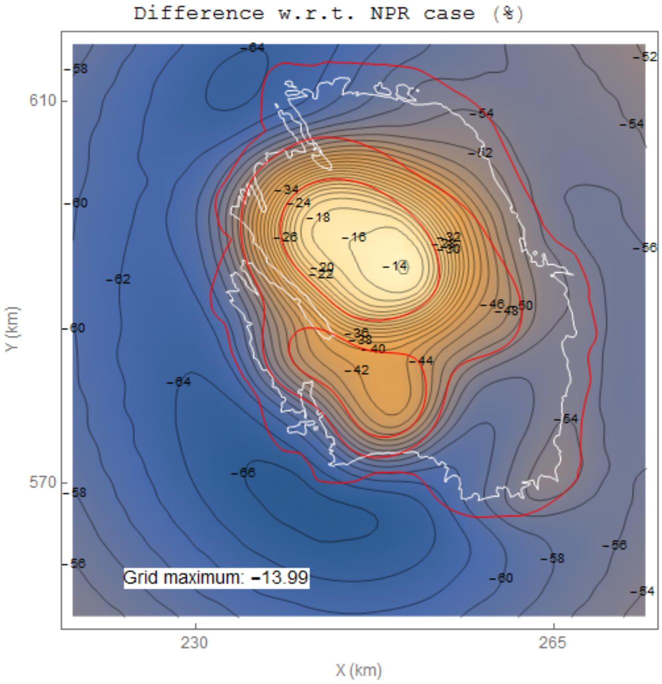
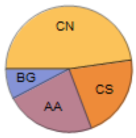
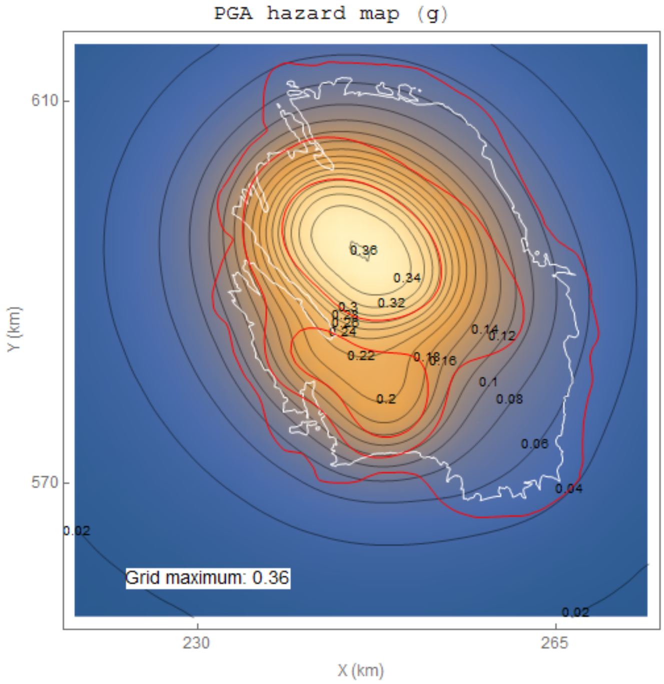
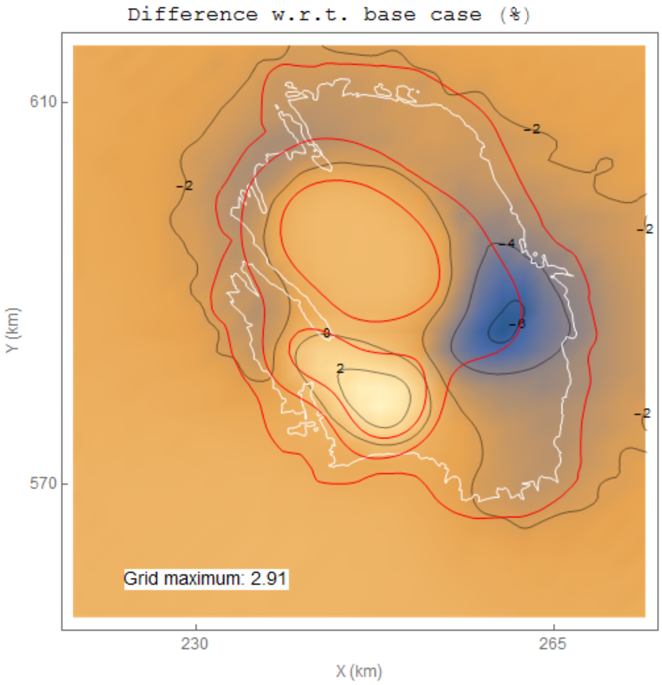


Figure A.2.1. Detailed information on the parameters used to calculate the hazard map (upper panel, left), the corresponding hazard map (upper right), comparison with the base case (lower left) and comparison with the previous model (lower right)

Appendix A.2.2

zonation	Z2
calibration time frame (years before 2015-06-01)	3
maximum magnitude model	5.0
ground motion prediction model	V1
return period (years)	475.
annual number of events	21.6667
b-values per zone	CN: 0.8 CS: 1.0 AA: 1.0 BG: 1.0
average distribution of events per zone (relative)	CN: 0.48 CS: 0.22 AA: 0.23 BG: 0.08 
average distribution of events per zone (annual)	CN: 10.3 CS: 4.7 AA: 5.0 BG: 1.7





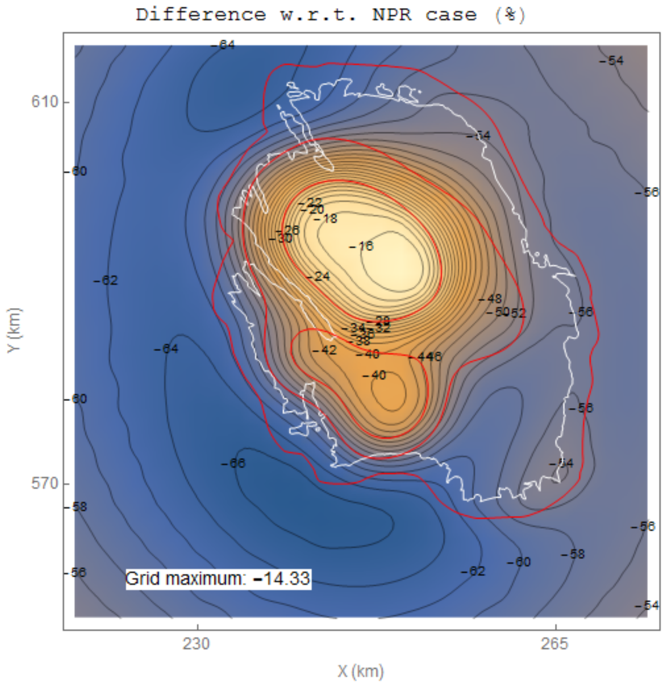
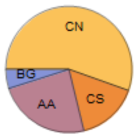
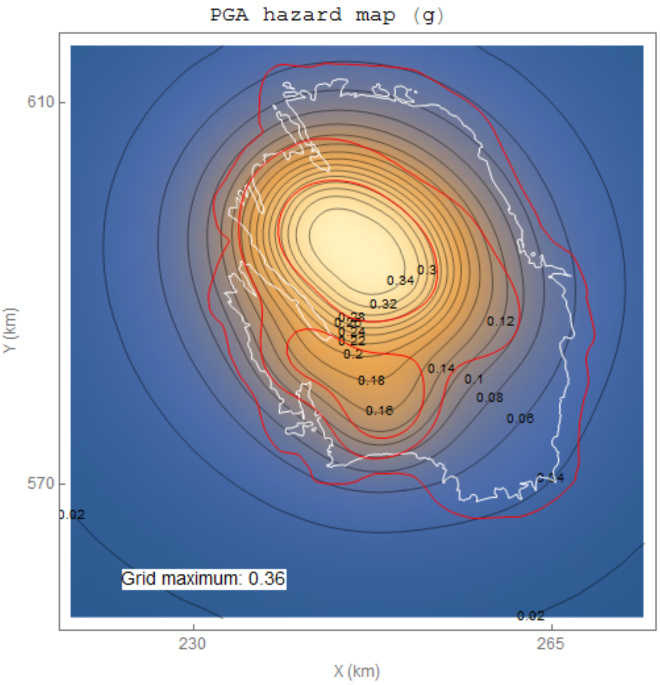
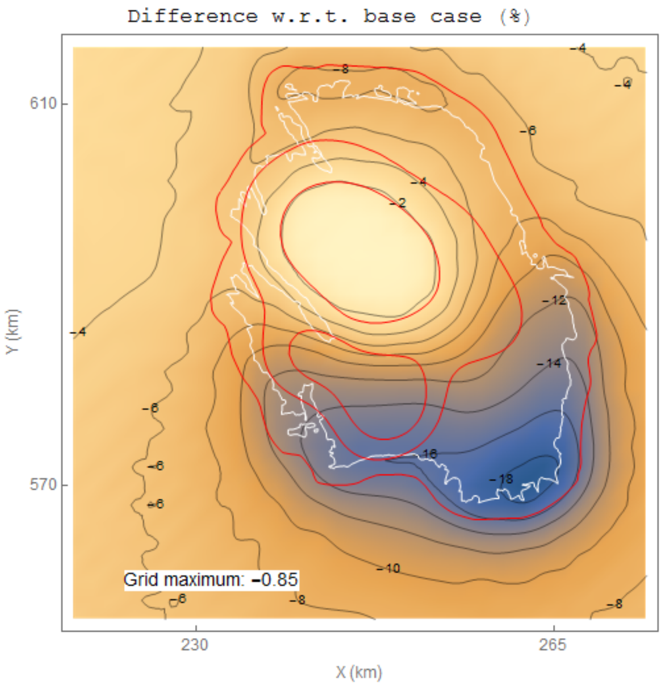


Figure A.2.2 Detailed information on the parameters used to calculate the hazard map (upper panel, left), the corresponding hazard map (upper right), comparison with the base case (lower left) and comparison with the previous model (lower right)

Appendix A.2.3

zonation	Z2
calibration time frame (years before 2015-06-01)	10
maximum magnitude model	5.0
ground motion prediction model	V1
return period (years)	475.
annual number of events	18.4
b-values per zone	CN: 0.8 CS: 1.0 AA: 1.0 BG: 1.0
average distribution of events per zone (relative)	CN: 0.55 CS: 0.16 AA: 0.24 BG: 0.05 
average distribution of events per zone (annual)	CN: 10.2 CS: 2.9 AA: 4.4 BG: 0.9





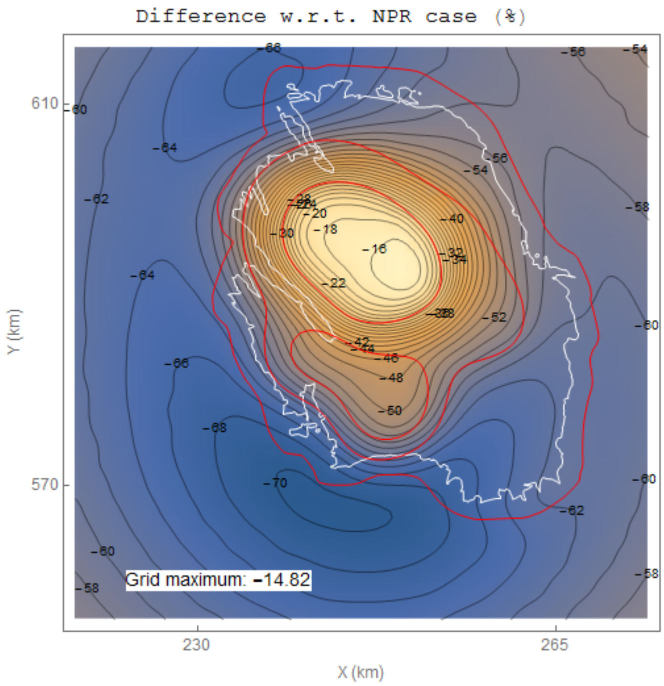
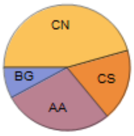
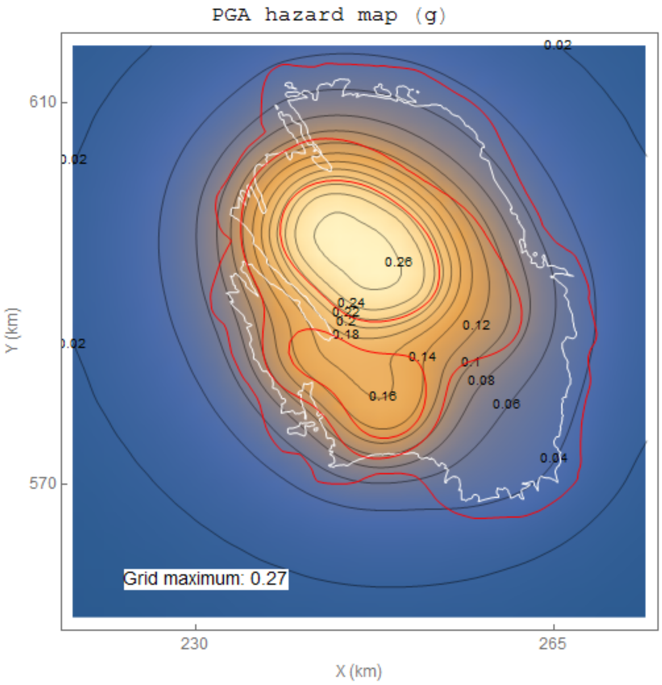
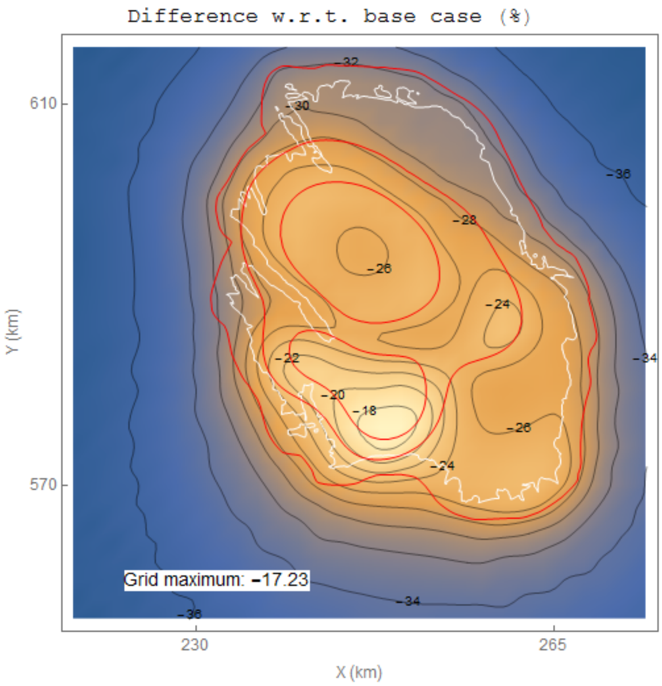


Figure A.2.3 Detailed information on the parameters used to calculate the hazard map (upper panel, left), the corresponding hazard map (upper right), comparison with the base case (lower left) and comparison with the previous model (lower right)

Appendix A.2.4

zonation	Z2
calibration time frame (years before 2015-06-01)	5
maximum magnitude model	4.5
ground motion prediction model	V1
return period (years)	475.
annual number of events	22.8
b-values per zone	CN: 0.8 CS: 1.0 AA: 1.0 BG: 1.0
average distribution of events per zone (relative)	CN: 0.46 CS: 0.18 AA: 0.28 BG: 0.08 
average distribution of events per zone (annual)	CN: 10.4 CS: 4.2 AA: 6.4 BG: 1.8





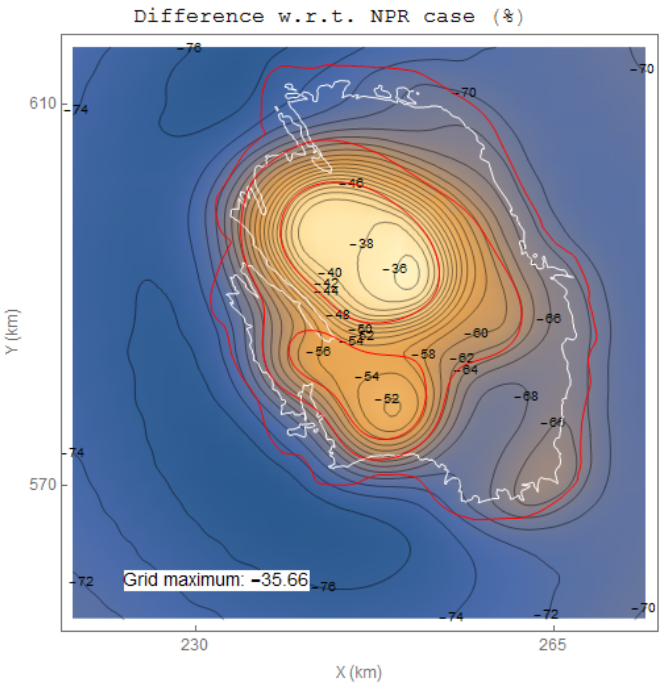


Figure A.2.2 Detailed information on the parameters used to calculate the hazard map (upper panel, left), the corresponding hazard map (upper right), comparison with the base case (lower left) and comparison with the previous model (lower right)