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TNO report

TNO2020 R11659

TNO Model Chain Groningen: Update and quick scan comparison of 2020 HRA model

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Contents

1 Context

Production from the Groningen gas field induces earthquakes and ground motion at the earth's surface. The TNO Model Chain is a Probabilistic Seismic Hazard and Risk Analysis (PSHRA) tool, specifically developed for the Groningen area to predict personal risk from future induced earthquakes. The tool is based on the NAM Hazard and Risk Assessment (HRA), but implemented independently in the public domain using a different numerical methodology. Barring acceptable numerical differences, the tool is able to reproduce the NAM HRA results exactly (TNO, 2019; 2020a).

Since the publication of the in-depth reports describing the comparison between NAM and TNO results (TNO, 2019) and describing the technical implementation of the TNO Model Chain (TNO, 2020a), the individual model components in the NAM tool have been updated. TNO has been asked to also include these updates in the TNO Model Chain. This report aims to:

1) Summarize the model updates and their implications for technical implementation in the TNO Model Chain
2) Compare the results of the new implementations in the TNO Model Chain with the results obtained by NAM in the HRA 2020.

The content and scientific merit of the model updates themselves are not discussed in this report. In addition, TNO has had no access to detailed, specific output from NAM, nor has had access to their computations or codes. Hence, the current report is a *quick scan* to compare TNO and NAM output and the analysis is therefore described in a *qualitative* sense.

2 Introduction

The in-depth report describing the comparison between the NAM and TNO results (TNO, 2019) is based on the status of the TNO Model Chain and the NAM HRA as they existed in 2019, when the HRA for gas year 2019/2020 was submitted by NAM (2019). Since then, the Seismological Source Model was updated from V5 to V6 (Bourne and Oates, 2019), the Ground Motion Model was updated from V5 to V6 (Bommer et al., 2019) and the Fragility and Consequence Model (together formerly called Damage Model) was updated from V5 to V6 to V7 (Crowley et al., 2019; Crowley and Pinho., 2020).[1]

In the update described here, TNO has implemented these model updates in the TNO Model Chain. Doing so, the TNO Model Chain is up-to-date with the NAM efforts and is therefore equipped to execute the public SHRA Groningen 2021.

[1] These version indicators are proposed by NAM and represent 'major' updates to the model logic and/or calibration. They do not refer to a given state of the software. Where the HRA 2019/2020 was based on a V5-V5-V5 setup (NAM, 2019), the HRA 2020/2021 was based on a V6-V6-V7 setup (NAM, 2020).

3 Updates

3.1 Seismological Source Model

In Bourne and Oates (2019), a detailed description is given of the model updates applied to the Seismological Source Model (SSM), to get from V5 to V6. Here, we summarize the changes:

Frequency-magnitude model
In V5, the Frequency Magnitude Distribution (FMD) is given by:

$$P(m \geq M) = \begin{cases} 1 & M \leq M_{min} \\ \left(1 - \dfrac{1 - 10^{b(\Delta C)(M - M_{min})}}{1 - 10^{b(\Delta C)(M_{max} - M_{min})}}\right) & M_{min} \leq M \leq M_{max} \\ 0 & M > M_{max} \end{cases}$$

where at any given point in the field (both in space and time) $b(\Delta C)$ is given by:

$$b(\Delta C) = \min\left(3, b_{min} + \left(\frac{\Delta C - s_0}{s_1}\right)^{-s_2}\right)$$

where $b_{min}, \Delta C, s_0, s_1$ and s_2 are model parameters. Please note that this does not correspond to the description document of V5 (Bourne et al., 2018), but rather to the NAM HRA code.

In V6, the FMD is given by:

$$P(m \geq M) = \begin{cases} 1 & M \leq M_{min} \\ \left(\dfrac{10^{-b(M - M_{min})} \times e^{-\zeta\left(10^{1.5(M - M_{min})} - 1\right)} - 10^{-b(M_{max} - M_{min})} \times e^{-\zeta\left(10^{1.5(M_{max} - M_{min})} - 1\right)}}{1 - 10^{-b(M_{max} - M_{min})} \times e^{-\zeta\left(10^{1.5(M_{max} - M_{min})} - 1\right)}}\right) & M_{min} \leq M \leq M_{max} \\ 0 & M > M_{max} \end{cases}$$

where both b and ζ are potentially dependent on ΔC.

Two models are an additional factor in the logic tree. One model (upper branch) describes a relation between the b-value of the Gutenberg-Richter relation and incremental Coulomb Stress (ΔC); the other model (lower branch) describes an exponential taper on the Gutenberg-Richter relation which depends on incremental Coulomb Stress (ΔC):

$$\text{Upper branch: } \begin{cases} b = \theta_0 + \theta_1(1 - \tanh(\theta_2 \Delta C)) \\ \zeta = 0 \end{cases}$$

$$\text{Lower branch: } \begin{cases} b = \theta_0 \\ \zeta = \theta_1 e^{-\theta_2 \Delta C} \end{cases}$$

Incremental Coulomb Stress fields
In V5, a single Incremental Coulomb Stress field is used as input for both the activity rate model and the FMD model. In V6, the activity rate model and the FMD model use two independent Incremental Coulomb Stress fields.

3.2 Ground Motion Model

In Bommer et al. (2019), a detailed description is given of the model updates applied to the Ground Motion Model (GMM), to get from V5 to V6. In terms of implementation differences, the update only consists of updated input tables.

3.3 Fragility and Consequence Model

In Crowley et al. (2019), a detailed description is given of the model updates applied to the Fragility and Consequence Model (FCM; formerly called Damage Model (DM)), to get from V5 to V6. The update consists of updated input tables and a change in calculation of the Intensity Measure. In FCM V5, each building type (structural system) has an intensity measure that depends on either one spectral period, two spectral periods, or one spectral period and duration. The spectral period(s) of interest vary between different structural systems.

In FCM V6, the intensity measure is the geometric mean of the same 10 spectral periods (0.01, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.85 and 1.0) for all structural systems. Duration is no longer used in the calculation of the Intensity Measure.

In Crowley and Pinho (2020), a detailed description is given of the model updates applied to the Fragility and Consequence Model (FCM), to get from V6 to V7. In terms of implementation differences, the update only consists of updated input tables.

4 Implementation

4.1 Seismological Source Model

The SSM V5 is implemented in a number of ways:

- An implementation based solely on the documentation provided by NAM.
- An implementation specifically built to mimic the forward model as implemented by NAM as closely as possible.
- An implementation specifically built to mimic the forward model as implemented by NAM as closely as possible, and able to accept MCMC-derived posterior parameter distributions, which can be provided by NAM. This implementation is developed to be able to compare full PSHRA results between TNO and NAM.

The update to SSM V6 therefore also required adaptations in all these implementations. All updates are implemented such that the V5 versions remain available and unchanged.

Implementation based solely on the documentation provided by NAM
The updates to this implementation are relatively minor. They involve adding the two new frequency-magnitude model definitions to the array of available frequency-magnitude models. All previously existing frequency-magnitude models (previously known as b-value models) simply return $\zeta = 0$, leaving their numerical results identical.

Since the TNO implementation of the source model allows for integration over a full distribution of Incremental Coulomb Stress fields, the update to the Incremental Coulomb Stress fields is implemented slightly differently from NAM. Both the activity rate model and the frequency magnitude model are calibrated on the full distribution of Incremental Coulomb Stress fields. Similarly in the forecast, the full distribution of Incremental Coulomb Stress fields is used, but never using different Incremental Coulomb Stress fields for activity rate and frequency magnitude model.

Implementation specifically built to mimic the forward model as implemented by NAM
This implementation was updated to produce two Incremental Coulomb Stress fields, one to be used for activity rate modelling, and an independent one to be used for modelling of the frequency magnitude distribution.

This approach was only implemented to accept MCMC-derived posterior parameter distributions, which can be provided by NAM. The third option – which was implemented for V5 – allowed TNO to derive a posterior distribution, based on the NAM-mimicking forward model. This implementation was not yet upgraded to V6.

4.2 Ground Motion Model

Since the update to GMM V6 only consists of input table updates, the changes to the code base are minimal:

- The new input tables were added to the code base
- A switch was built in, such that the correct input tables are read, depending on whether the user selects V5 or V6.

4.3 Fragility and Consequence Model

The update to FCM V6 requires changes at several points in the code.

- A switch was built in, such that the correct input tables are read, depending on whether the user selects V5 or V6.
- The code was updated to ensure that both models with and without duration modelling can be run, maintaining appropriate correlations where needed.
- The updated intensity measure calculation was implemented, and a switch was added to ensure the correct intensity measure calculation is used, depending on whether the user selects V5, V6 or V7.

Since the update from FCM V6 to FCM V7 only consists of input table updates, the changes to the code base are minimal:

- The new input tables were added to the code base.
- A switch was built in, such that the correct input tables are read, depending on whether the user selects V5, V6 or V7.

5 Verification

To verify consistent model implementation between TNO and NAM, a comparison is performed. The extensive verification performed earlier on the ‘full V5’ chain and individual V5 model components provides a solid foundation for this (TNO, 2019). NAM provided (at the request of EZK) four risk model outputs based on SSM V6, GMM V6, and FCM V7. Supplementary comparisons had earlier been made to the NAM HRA 2020 (TNO 2020c). The four risk model-output files of NAM, however, do not contain hazard results, or mean logic tree risk results, but only risk results for specific logic-tree choices.

The NAM output files are based on the following configurations:

	File 1	**File 2**	**File 3**	**File 4**
Forecast period	GY ‘20/’21	GY ‘20/’21	GY ‘20/’21	GY ‘20/’21
Strategy	OS1	OS1	OS2	OS2
Frequency-Magnitude model	Upper	Lower	Upper	Lower
Mmax	5.0	5.0	5.0	5.0
Ground motion τ_{median}	Upper	Upper	Upper	Upper
Ground motion Φ_{ss}	Upper	Upper	Upper	Upper
Fragility	Central	Central	Central	Central
Fatality	Central	Central	Central	Central

For the comparison, TNO employs the SSM V6 specifically built to mimic the forward model as implemented by NAM as closely as possible, and using MCMC-derived posterior parameter distributions, which were provided by NAM. This is done in order to be able to compare hazard and risk results, based on essentially identical source distributions.

In the comparison below, a summary of the results obtained is shown. For additional figures and tables, the reader is referred to Appendix A.

5.1 Seismological Source Model

The NAM output contains 750,000 synthetic earthquake catalogues with quasi-infinite location resolution. In order to compare the discrete source distribution from the TNO Model Chain to these catalogues, a spatial histogram is applied to the synthetic catalogues. For all four NAM output files, the results compare very well to the TNO Model Chain output as shown below.

Figure 1 compares both the spatial distributions and the frequency-magnitude distributions of TNO and NAM. The NAM HRA forecasts 7.96 events of M1.5 and above, the TNO Model Chain forecasts 7.86 events. This is also seen in the field-wide FMD subplot in Figure 1, where the TNO curve is consistently lower than the NAM curve. This is a difference of 1.3% in number of events. This difference is explained by sampling and discretization artifacts and deemed acceptable given the different implementations.

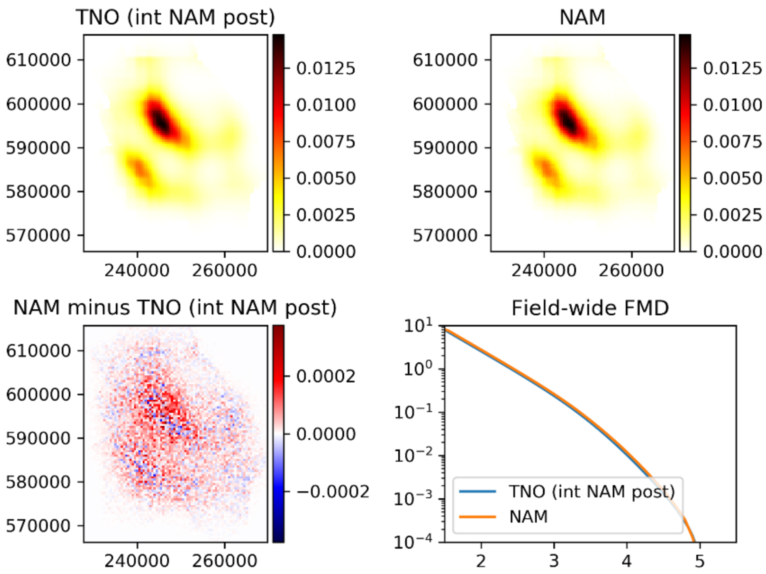

Figure 1: Comparison of the seismological source model forecast for GY2020/2021, for 1 branch of the logic tree (corresponding to NAM file 2). The TNO forecast is based on integration of a posterior parameter distribution provided by NAM (indicated by 'int NAM post').

We use the report by NAM (2020) to compare the mean source distribution. This report contains a table with exceedance probabilities for larger magnitude events, based on the mean logic tree (see Table 1). Here, we compare this table with the one obtained by TNO (Table 2), using the same logic tree weightings. Table 3 demonstrates that the maximum difference (TNO minus NAM) of the annual exceedance probabilities is less than 0.2 percentage point for relatively low magnitudes (M>=3.6). The difference in probabilities converges to zero for higher (M>=5.0) magnitude events. The differences in probabilities generally decrease with time for all magnitudes.

As also shown below for hazard and risk, the observed differences between TNO and NAM results in annual exceedance probabilities are generally on the same order of magnitude as we have reported earlier at individual logic tree branch level in the 'V5 chain' comparative analysis (TNO, 2019). These individual differences arise from finite sampling and grid resolution and average out over the full logic tree chain comparison. Therefore the mean logic tree results of TNO and NAM are in better agreement than the two individual branches for the two Operational Strategies compared here.

GAS-YEAR	P(M>=3.6) NAM	P(M>=4.0) NAM	P(M>=4.5) NAM	P(M>=5.0) NAM
2020/2021	4.73%	1.29%	0.16%	0.02%
2021/2022	3.64%	0.97%	0.12%	0.02%
2022/2023	3.09%	0.83%	0.11%	0.02%
2023/2024	2.78%	0.74%	0.09%	0.01%
2024/2025	2.43%	0.64%	0.08%	0.01%
2025/2026	2.20%	0.57%	0.08%	0.01%
2026/2027	2.10%	0.55%	0.07%	0.01%
2027/2028	1.93%	0.50%	0.07%	0.01%
2028/2029	1.80%	0.46%	0.06%	0.01%
2029/2030	1.67%	0.43%	0.06%	0.01%

Table 1 Annual exceedance probabilities for larger magnitude events of the NAM HRA 2020, average temperature gas-year and operational strategy 1 (OS1).

GAS-YEAR	P(M>=3.6) TNO	P(M>=4.0) TNO	P(M>=4.5) TNO	P(M>=5.0) TNO
2020/2021	4.55%	1.23%	0.17%	0.02%
2021/2022	3.53%	0.96%	0.14%	0.02%
2022/2023	2.90%	0.79%	0.11%	0.02%
2023/2024	2.59%	0.70%	0.10%	0.01%
2024/2025	2.34%	0.63%	0.09%	0.01%
2025/2026	2.14%	0.58%	0.08%	0.01%
2026/2027	1.97%	0.53%	0.07%	0.01%
2027/2028	1.83%	0.49%	0.07%	0.01%
2028/2029	1.69%	0.45%	0.06%	0.01%
2029/2030	1.59%	0.42%	0.06%	0.01%

Table 2 Annual exceedance probabilities for larger magnitude events of the TNO Model Chain, average temperature gas-year and operational strategy 1 (OS1).

GAS-YEAR	P(M>=3.6) DIFF	P(M>=4.0) DIFF	P(M>=4.5) DIFF	P(M>=5.0) DIFF
2020/2021	-0.18%	-0.06%	0.01%	0.00%
2021/2022	-0.11%	-0.01%	0.02%	0.00%
2022/2023	-0.19%	-0.04%	0.00%	0.00%
2023/2024	-0.19%	-0.04%	0.01%	0.00%
2024/2025	-0.09%	-0.01%	0.01%	0.00%
2025/2026	-0.06%	0.01%	0.00%	0.00%
2026/2027	-0.13%	-0.02%	0.00%	0.00%
2027/2028	-0.10%	-0.01%	0.00%	0.00%
2028/2029	-0.11%	-0.01%	0.00%	0.00%
2029/2030	-0.08%	-0.01%	0.00%	0.00%

Table 3 Difference in annual exceedance probabilities of TNO Model Chain and NAM HRA 2020, OS1.

5.2 Hazard

The hazard calculations for the mean logic tree compare very well. Both the spatial distribution (Figure 2), the maximum acceleration and the temporal evolution of the hazard (Table 4) are virtually identical. The difference in the maximum PGA (TNO minus NAM) increases negatively with time from zero (at GY 2020/2021) to -0.003g (at GY 2029/2030). As discussed above, individual differences of the two compared branches for the two Operational Strategies arise from finite sampling and grid resolution and average out over the full logic tree comparison.

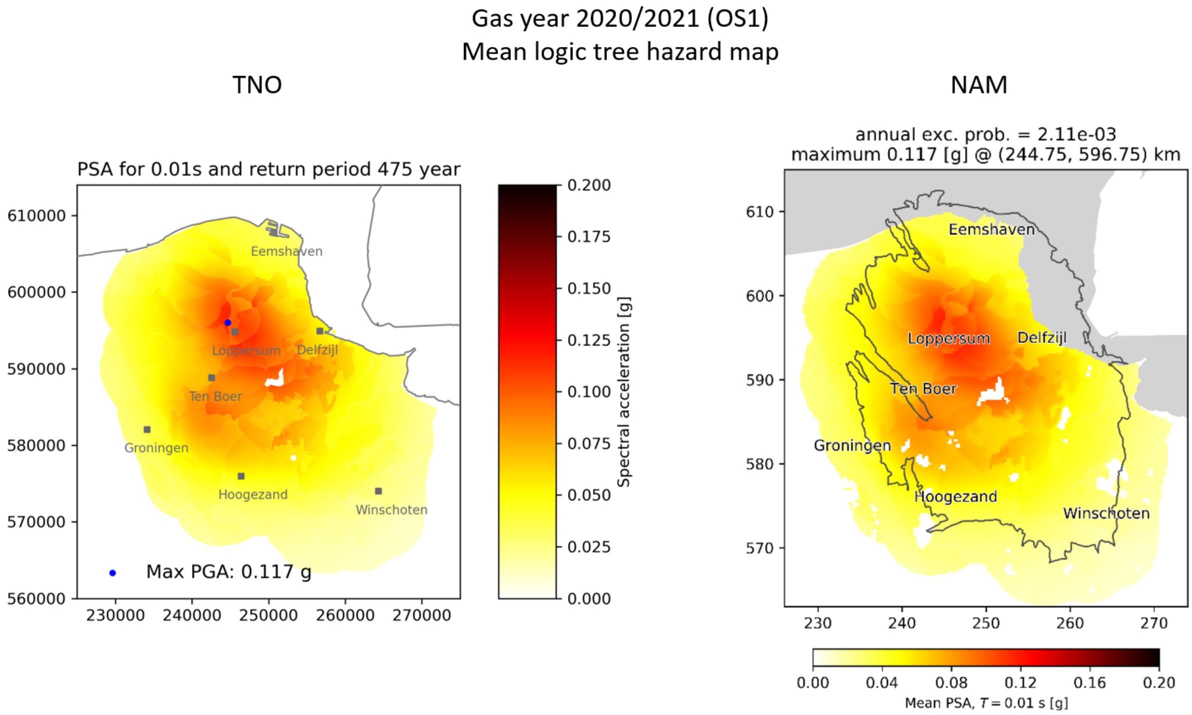

Figure 2 Comparison of ground motions between TNO Model Chain and NAM HRA 2020. Gas year 2020/2021, average-temperature and OS1.

GAS-YEAR	MAX PGA (TNO)	MAX PGA (NAM)	MAX PGA DIFF
2020/2021	0.117g	0.117g	0.000g
2021/2022	0.112g	0.111g	-0.001g
2022/2023	0.106g	0.105g	-0.001g
2023/2024	0.102g	0.101g	-0.001g
2024/2025	0.098g	0.097g	-0.001g
2025/2026	0.094g	0.092g	-0.002g
2026/2027	0.090g	0.088g	-0.002g
2027/2028	0.087g	0.084g	-0.003g
2028/2029	0.083g	0.080g	-0.003g
2029/2030	0.079g	0.076g	-0.003g

Table 4 Max PGA comparison for average-temperature and OS1 of the TNO Model Chain and NAM HRA 2020.

5.3 Risk

The risk calculations for the mean logic tree compare very well for the buildings with a relatively high risk (10^{-5} < LPR < 10^{-6}). For buildings with a very low risk (LPR < 10^{-6}) there are minor differences between the curves. From Figure 3 we also infer that for the specific logic-tree choices compared here, all buildings in the Groningen area meet the life safety risk of LPR < 10^{-5}/year (the Meijdam-norm).

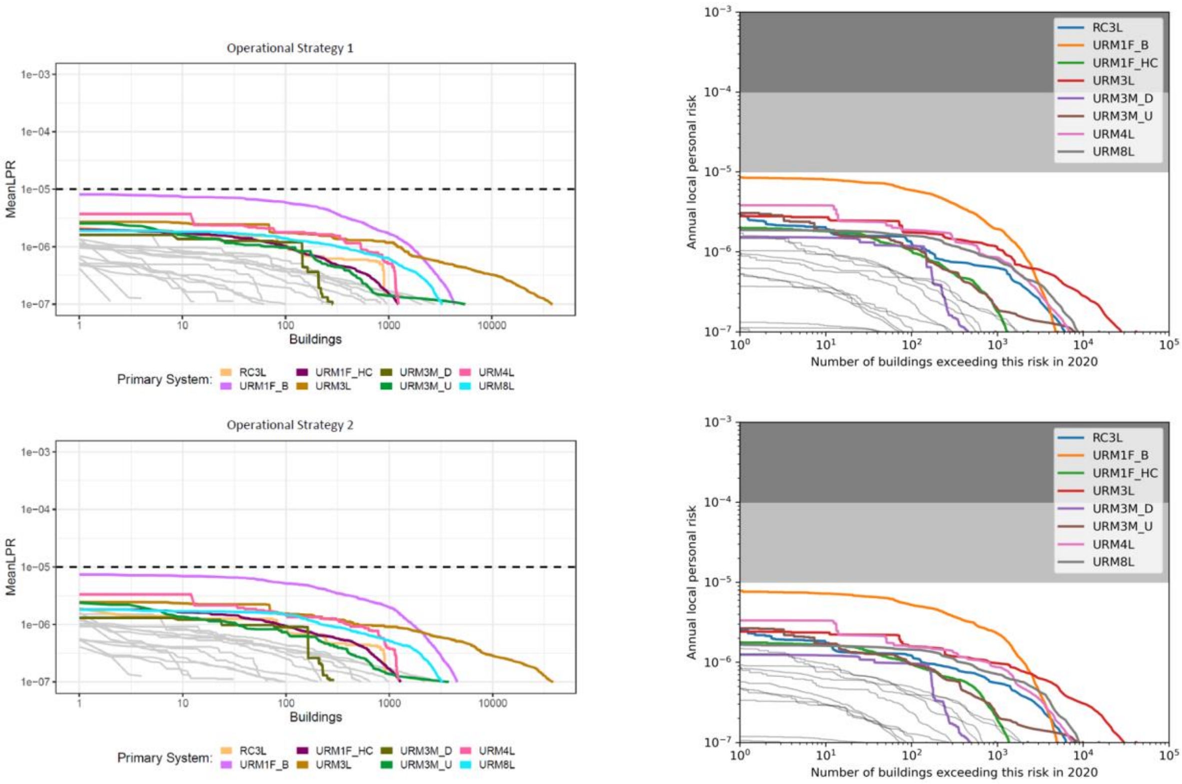

Figure 3 Comparison of LPR between NAM HRA 2020 (left) and TNO Model Chain (right) for Operational strategy 1 (top) and 2 (bottom) for the gas year 2020/2021 for an average temperature scenario.

6 Conclusion

In 2020, all models involved in the hazard and risk calculation HRA 2020 have been updated with respect to the version of the models used in the HRA 2019. These model updates have been incorporated in the TNO Model Chain Groningen. A *quick scan* comparison to the HRA 2020 results shows that the TNO Model Chain Groningen and the NAM HRA tool produce *qualitatively* very similar results for both hazard and risk, when the same input files are used.

The report describes the updates to the models, and shows a comparison of two independent implementations of the models. The scientific merit of the models and their updates is not discussed in this report. We conclude that the TNO Model Chain is up-to-date to execute the public SHRA Groningen 2021.

7 References

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8 Signature

Utrecht, 6 November 2020 TNO

Drs. J.A.J. Zegwaard
Head Advisory Group for Economic Affairs

Appendix A

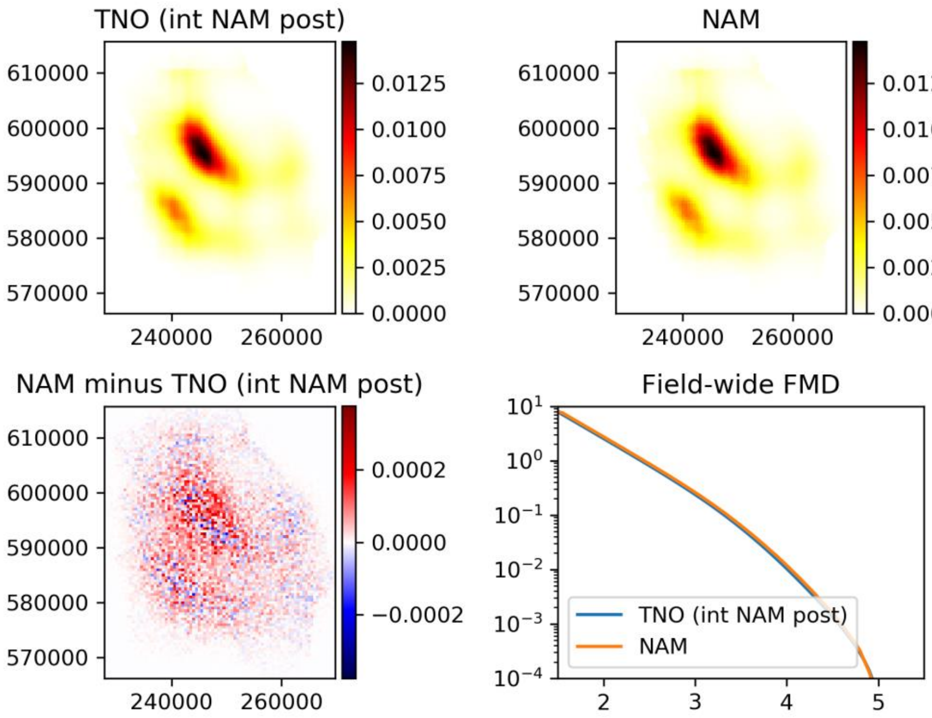

Figure A1: OS1, stress-dependent taper (Upper branch in the Frequency-Magnitude factor of the logic tree).

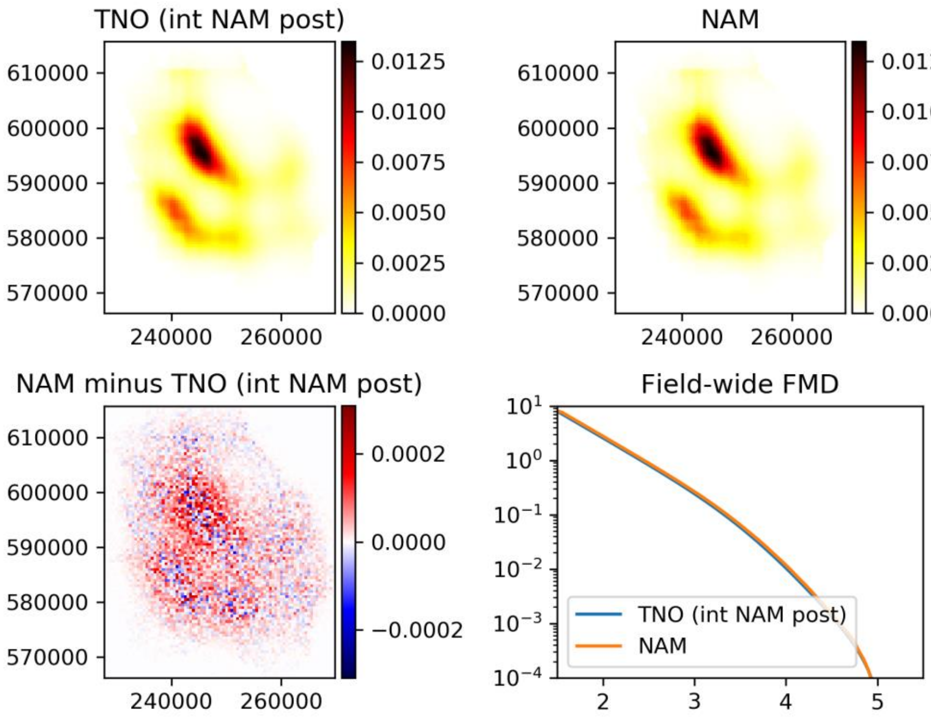

Figure A2: OS2, stress-dependent taper (Upper Frequency-Magnitude branch).

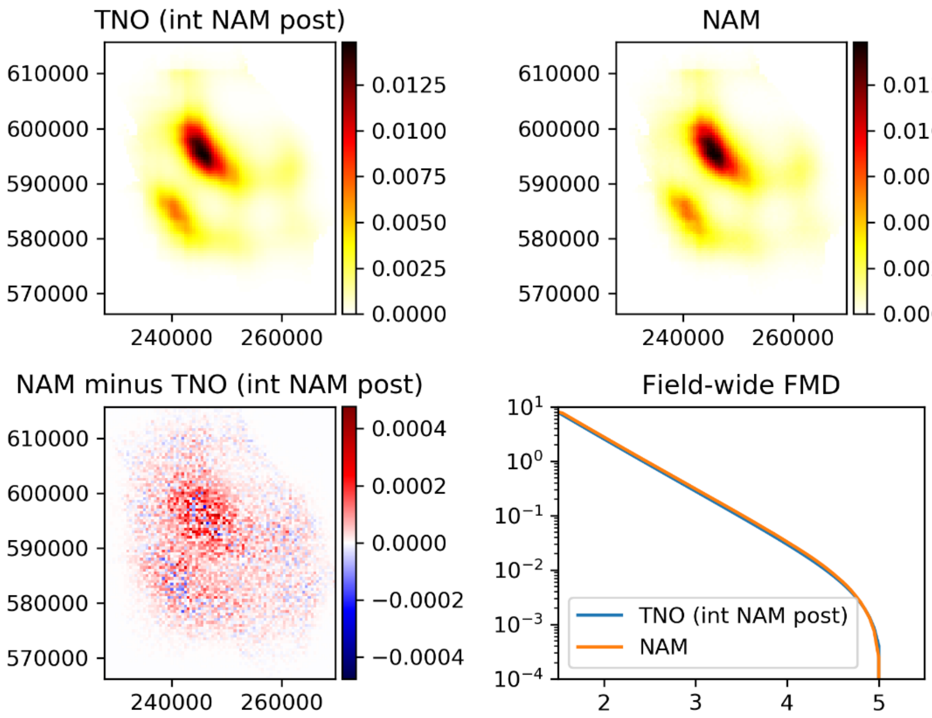

Figure A3: OS1, stress-dependent b-value (Lower Frequency-Magnitude branch).

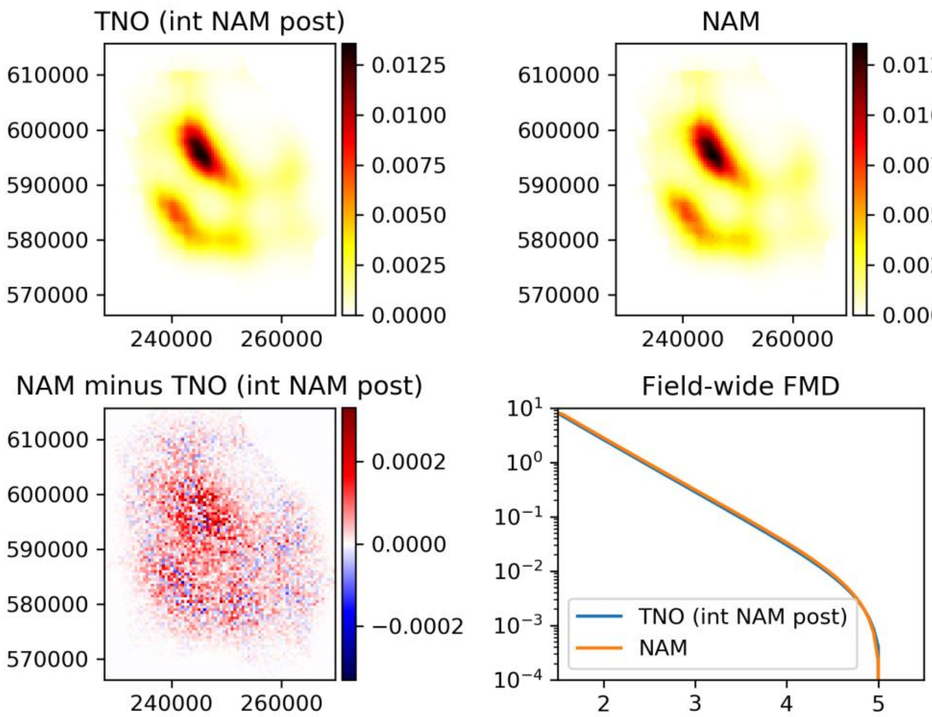

Figure A4: OS2, stress-dependent b-value (Lower Frequency-Magnitude branch).

GAS-YEAR	P(M>=3.6) NAM	P(M>=4.0) NAM	P(M>=4.5) NAM	P(M>=5.0) NAM
2020/2021	4.88%	1.30%	0.17%	0.02%
2021/2022	3.58%	0.94%	0.12%	0.02%
2022/2023	3.03%	0.84%	0.10%	0.01%
2023/2024	2.74%	0.74%	0.09%	0.02%
2024/2025	2.47%	0.68%	0.09%	0.01%
2025/2026	2.31%	0.60%	0.08%	0.01%
2026/2027	2.09%	0.56%	0.07%	0.01%
2027/2028	1.91%	0.52%	0.07%	0.01%
2028/2029	1.84%	0.48%	0.06%	0.01%
2029/2030	1.67%	0.45%	0.06%	0.01%

Table A1 Annual exceedance probabilities for larger magnitude events of the NAM HRA 2020, average temperature gas-year and operational strategy 2 (OS2).

GAS-YEAR	P(M>=3.6) TNO	P(M>=4.0) TNO	P(M>=4.5) TNO	P(M>=5.0) TNO
2020/2021	4.63%	1.25%	0.18%	0.02%
2021/2022	3.42%	0.93%	0.13%	0.02%
2022/2023	2.90%	0.79%	0.11%	0.02%
2023/2024	2.61%	0.71%	0.10%	0.01%
2024/2025	2.37%	0.64%	0.09%	0.01%
2025/2026	2.17%	0.58%	0.08%	0.01%
2026/2027	1.99%	0.54%	0.08%	0.01%
2027/2028	1.85%	0.50%	0.07%	0.01%
2028/2029	1.71%	0.46%	0.06%	0.01%
2029/2030	1.60%	0.43%	0.06%	0.01%

Table A2 Annual exceedance probabilities for larger magnitude events of the TNO Model Chain, average temperature gas-year and operational strategy 2 (OS2).

GAS-YEAR	P(M>=3.6) DIFF	P(M>=4.0) DIFF	P(M>=4.5) DIFF	P(M>=5.0) DIFF
2020/2021	-0.25%	-0.05%	0.01%	0.00%
2021/2022	-0.16%	-0.01%	0.01%	0.00%
2022/2023	-0.13%	-0.05%	0.01%	0.01%
2023/2024	-0.13%	-0.03%	0.01%	-0.01%
2024/2025	-0.10%	-0.04%	0.00%	0.00%
2025/2026	-0.14%	-0.02%	0.00%	0.00%
2026/2027	-0.10%	-0.02%	0.01%	0.00%
2027/2028	-0.06%	-0.02%	0.00%	0.00%
2028/2029	-0.13%	-0.02%	0.00%	0.00%
2029/2030	-0.07%	-0.02%	0.00%	0.00%

Table A3 Difference in annual exceedance probabilities of TNO Model Chain and NAM HRA 2020 (TNO-NAM), OS2.

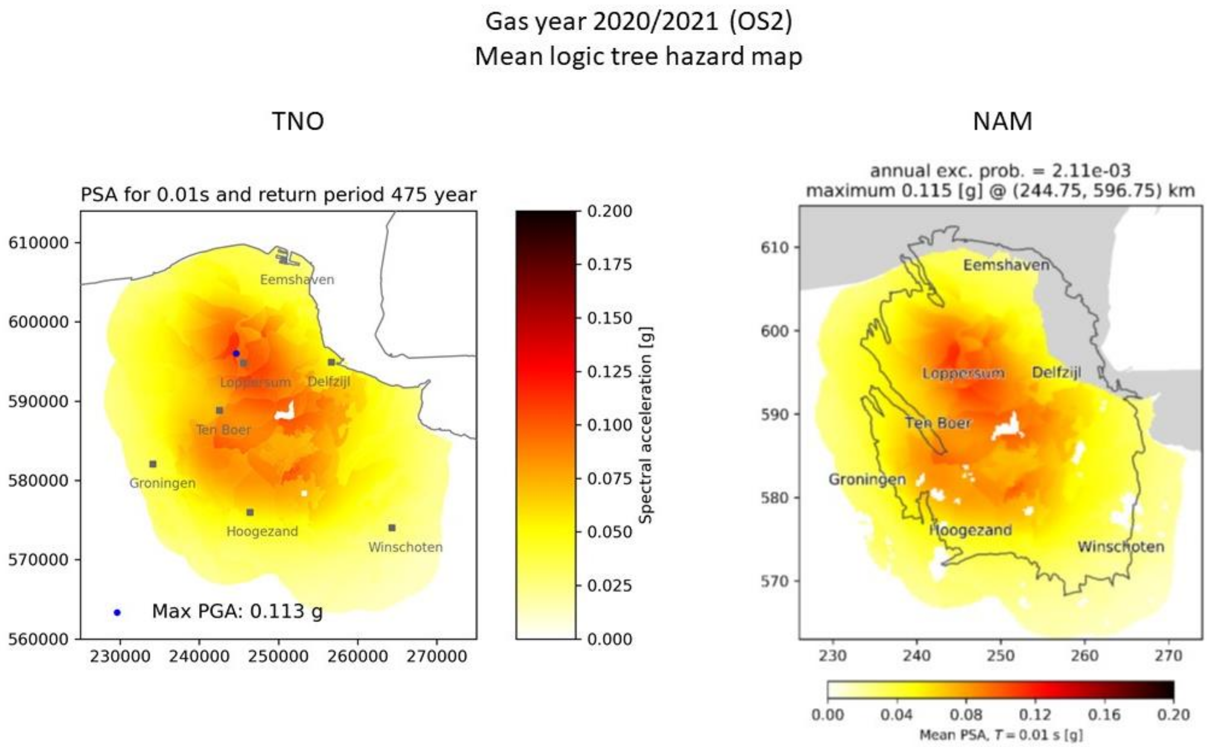

Figure A5 Comparison of ground motions between TNO Model Chain and NAM HRA 2020. Gas year 2020/2021, average-temperature and OS2.

GAS-YEAR	MAX PGA (TNO)	MAX PGA (NAM)	MAX PGA DIFF
2020/2021	0.113g	0.115g	-0.002
2021/2022	0.110g	0.109g	0.001
2022/2023	0.106g	0.106g	0.000
2023/2024	0.102g	0.101g	0.001
2024/2025	0.098g	0.098g	0.000
2025/2026	0.094g	0.092g	0.002
2026/2027	0.090g	0.088g	0.002
2027/2028	0.087g	0.086g	0.001
2028/2029	0.083g	0.081g	0.002
2029/2030	0.079g	0.076g	0.003

Table A4 Max PGA comparison for average-temperature and OS2 of the TNO Model Chain and NAM HRA 2020.