Project phase 1, WP2

Review of the public KNMI induced earthquake catalogue from the Groningen gas field

June 2018

NORSAR

Contents

Executive summary

This report covers Work Package 2 (WP2) of the NORSAR project to review the public KNMI induced seismicity catalogue from the Groningen gas field. The objective of the report is to investigate the significance of different seismological parameters related to the induced seismicity catalogue and how they relate to understanding the causes of the seismicity as well as the hazard and risk assessment for the Groningen field, and what further work is needed to improve how these parameters are determined. Understanding the causes of seismicity in this context implies understanding the physical processes involved in the nucleation of seismic events, and their relationship with the production parameters, for example, to assess whether a change in production rate (such as the reduction implemented in 2014) would result in a change in seismicity rates and magnitudes, and if so, over which time scale. Ultimately, the knowledge gained could be used to adjust the production parameters such that the induced seismicity remains as low as possible.

Causes of seismicity: The causes of seismicity are best understood via event detection, magnitude determination and accurate and precise event locations. Moreover, parameters derived from the event magnitude including b-value, seismic moment/released seismic energy, and magnitude of completeness are all important for accurately modelling the seismicity or understanding the seismicity rate without introducing bias from network changes. Improvements to these parameters would aid the establishment of an integrated seismo-geomechanical model, which would better demonstrate how production and induced seismicity are linked.

Earthquake hazard: We consider the maximum magnitude to be the most significant parameter for estimating the hazard of large earthquakes. However, for small to intermediate sized earthquakes, and in the case of Groningen, we consider the κ parameter, the stress parameter $\Delta\sigma$, source mechanisms, and earthquake depth to be more significant. Each of these parameters are not straightforward to determine and require high quality data and detailed analysis. Furthermore, it should be noted that KNMI continue to use a point source approach in the current hazard model, rather than incorporating the fault rupture area - for larger earthquakes this can result in underestimating the seismic hazard. Determination of the source parameters would provide constraints on the fault rupture area, to improve the current hazard models.

Earthquake risk: The building stock for the Groningen region is particularly sensitive to the high frequencies of ground motion from regional and local events, due to the predominant natural resonant frequencies of the buildings. It is therefore required that data are of high quality and recorded with sufficient sampling rate to measure the high frequency ground motion to better understand the seismic risk. Similarly, high quality and good spatial coverage of Peak Ground Acceleration (PGA) measurements are required. Additional parameters that effect the sensitivity of any risk analysis include focal mechanism solutions, location precision (epicentral and depth), maximum magnitude, horizontal-to-vertical shaking amplitudes, stress drop, and the κ parameter. Analysis of these parameters would add value to the seismic risk analysis for Groningen.

Relative importance of seismological parameters: Ranking the relative importance of seismological parameters is strongly dependent on the objectives of a study. When considering the causes of seismicity, and both hazard and risk assessments together, earthquake location, focal depth, stress drop, and source mechanism are all regarded as significant parameters that influence all three study areas. The parameters: maximum magnitude Mmax; the stress drop or stress parameter $\Delta\sigma$; κ; and the ratio of horizontal to vertical shaking and their phase shift all influence both hazard and risk assessments; while the placement of faults, event magnitudes, and seismicity rates prove to be influential for both understanding the causes of seismicity as well as the seismic hazard assessment.

Assessment of earthquake-related core parameters: In terms of the three areas of interest for this report - causes of seismicity, seismic hazard assessment, and seismic risk assessment - we have highlighted the main parameters that are either used as input or add to the understanding of these topic areas. From these parameters we have identified tasks that we deem high priority and those tasks that we recommend in addition. The high priority tasks include the estimation of earthquake depth, source mechanism determination, moment magnitude estimates, and temporal changes of the magnitude of completeness. The additional tasks comprise of improved determination of epicentral locations, estimation of stress drop, and estimation of the ratio of the horizontal to vertical components of motion and their potential phase shifts. These tasks partially follow the recommendations given by the SSHAC expert panel with the aim to reduce uncertainties in the estimation of the maximum magnitude (Coppersmith et al., 2016).

Overall, taking into account that the KNMI induced seismicity catalogue covers the complete time period of seismicity occurring within the Groningen field, in which both the instrumentation of the field as well as methodologies for data processing changed considerably, we consider the catalogue as extensive and of high quality and as such, a sound basis for the tasks of seismic hazard and risk assessment as well as any studies aimed at resolving the underlying causes of seismicity.

1 Introduction

The report is subdivided into six chapters. The first three chapters identify the earthquake catalogue-related core parameters that are essential to (a) better understand the causes of seismicity (chapter 2), (b) perform a seismic hazard assessment (chapter 3), and (c) perform a seismic risk assessment (chapter 4). Simultaneously, they summarise the work that has been performed so far in these three areas of research.

Chapter 5 merges all seismological parameters described so far and proposes two ways to weigh their relative importance. In chapter 6, these parameters are assessed with regard to the effort that has been put in their estimation until now and determines research topics with need for action.

Finally, we collected the references to these three areas of interest that we consulted during the course of this work package in the appendix, for the modelling of seismicity in appendix A, for seismic hazard assessment in appendix B, and for seismic risk assessment in appendix C. Note that these lists cannot be complete, but we hope they may be useful for others engaged in research on the Groningen field. Further, references that are cited within the text are collected at the end of each section separately.

2 Earthquake catalogue-related core parameters important for the understanding of the causes of seismicity

2.1 Context

Production at the Groningen gas field started in 1963. The first felt earthquakes occurred after more than 20 years of production. These were recorded by stations in the Northern Netherlands and could be associated with the gas production. Until 2012, new seismic instruments were installed and different studies were made in order to assess the maximum possible event magnitude. Various estimates ranged from less than 3.0 to 3.9 (de Waal et al., 2015). In August 2012, the Huizinge earthquake (M_L=3.6) happened. Although within the range of predicted size, it caused damages and increased awareness about induced seismicity at Groningen. Measures were taken to reduce the production of the field in January 2014 and efforts were made towards a more thorough analysis of the induced seismicity at Groningen, most notably via the installation of a very dense seismic network as in 2015.

In this part of the report NORSAR discuss the core parameters that are relevant for the understanding of the causes of seismicity in the Groningen field. Understanding the causes of seismicity in this context implies understanding the physical processes involved in the nucleation of seismic events, and their relationship with the production parameters. For example, to assess whether a change in production (such as the reduction implemented in 2014) would result in a change in seismicity rates and magnitudes, and if so, over which time scale? Ultimately, the knowledge gained could be used to adjust the production parameters so that the induced seismicity remains as low as possible.

For this purpose, we have analysed a number of peer-reviewed scientific publications, listed in the reference section, and summarize the main findings and communalities in terms of relevant parameters. Remaining controversies or unsolved questions are mentioned to the extent possible. The goal is to assess the feasibility of building a seismo-geomechanical model which allows to predict the seismicity in terms of number of events, magnitude and location as a function of production parameters.

In the following sections, we first describe briefly the different types of models discussed in the literature and then list the seismological parameters which are either used as input to build the models, or are used for comparison with the models' output.

2.2 Brief overview of the models

We can basically distinguish between three families of models with increasing degrees of complexity (figure 2.1):

- empirical models (Hettema et al., 2017) exploit the empirically derived relation between the seismic activity rate and the production rate as a function of the produced volume. In another study, Bourne et al., 2014 assumes that compaction is the main mechanism behind induced seismicity and therefore generates earthquake probability density maps from compaction maps by using an empirical relation linking compaction strain and total seismic moment.

- statistical/probabilistic models analyse the statistical properties of observations (seismicity, reservoir properties) in order to estimate the probability of generating or exceeding an earthquake of a specific size or a specific ground motion limit for a specific production setting. For example, Sijacic et al. (2017) uses both Bayesian and classical statistics to find that the time delay between production changes and seismicity is on the order of 6 months. Under the assumption that pressure change is the driving physical parameter, the delay can be explained by the characteristic time needed by the pressure diffusion process to reach the hypocentral area (Nepveu et al., 2016; van Thienen-Visser et al., 2016; de Waal et al., 2015). By comparing a large number of reservoir properties with the cumulative released seismic energy, van Eijs et al. (2006) found three key parameters to correlate well to seismicity: (1) pressure drop, (2) fault density and (3) stiffness contrast between reservoir and surrounding rocks. This can be formulated in terms of a decision tree returning the probability of occurrence of earthquakes.
- physical/geomechanical models are forward-calculating the subsurface stresses and deformations and fluid pressure evolution to investigate when and where seismicity-generating failure can occur, either on reactivating faults or elsewhere (Wassing, 2015). For example van Wees et al. (2017) started with a generic model containing a single fault and limited parameter variations, and concluded that a production decrease should immediately restrain the seismic moment increase.

The first two types of models are explicitly using the observed seismicity as input for the predictions. They mainly aim at finding out how induced seismicity relates to gas production.

> Three types of models are developed: (1) empirical, (2) stochastic, and (3) geomechanical.

Geomechanical models, on the other hand, mainly aim to understand the physical processes and conditions that lead to a rupture and generate a seismic event. They can be more computationally demanding, especially when partial differential equations are solved to compute deformations, fluid flow, and sometimes even seismic wave propagation.

> Only geomechanical models could provide a physical understanding of the causes of induced seismicity. The other models provide probabilistic prediction of the seismicity trend.

The output of such models may give information on the number, the size, the location (which fault is more likely to fail?), the source mechanism and the stress drop of the seismic events. As such, they do not use seismicity parameters as input. They do however require a detailed model of the elastic and hydraulic properties of the reservoir and overburden. Building such a detailed model with sufficient accuracy giving observational uncertainties of in-situ properties is a challenge of its own, and hence the result of such modeling should be used in a more general way to develop an understanding and derive the physical context of observed correlations. Some studies are trying to calibrate the physical modeling results with the actual seismicity observations in a form of history matching.

It is noteworthy that ideally, seismological parameters should be used in geomechanical models both as input and as output in an iterative way. The models' output should be compared with the seismological observations in order to validate the models' veracity and then fine-tune the models by adjusting the input.

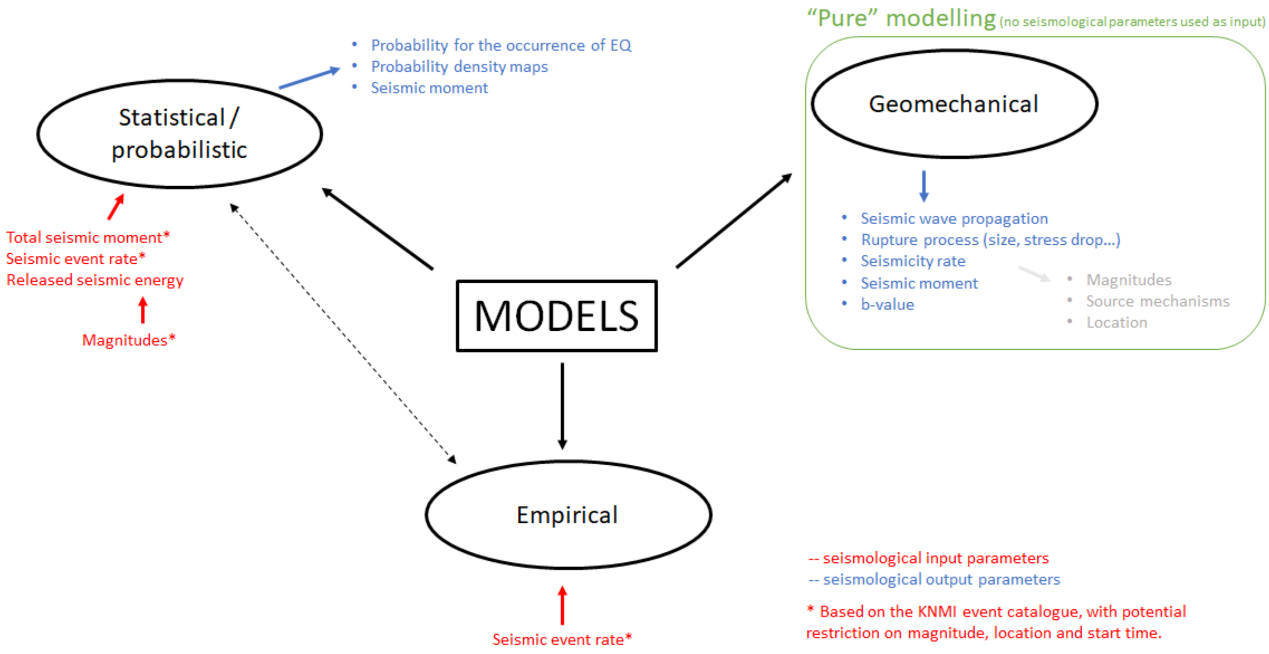

Fig. 2.1: *Simplified scheme representing the three types of models that can be defined. For each of them, we give a non-exhaustive list of the seismological parameters used either as input or output.*

2.3 General observations in the Groningen field

The following general observations are used in various ways by the mentioned model classes. The seismicity can be generally characterized by the following attributes (Nepveu et al., 2016; van Wees et al., 2017; Bourne et al., 2014):

- constant event rate up to 2003;
- increasing event rate from 2003 to 2014;
- decreasing event rate since 2014.
- delay in the onset of induced seismicity compared to production start.

- non-linear increase of the seismic moment.
- preferred location of the seismicity in the central part of the field.

These seismicity attributes are compared to the following production characteristics (Nepveu et al., 2016; Hettema et al., 2017):

- seasonality depending on the demand (high in winter, low in summer).
- measures taken in January 2014 to reduce the production at least in the central part of the field.

2.4 Outcome

It is commonly agreed that the occurrence of seismicity in the Northern Netherlands is related to reservoir depletion resulting from gas production in the Groningen field. Differential reservoir compaction (measurable in terms of surface subsidence) and resulting differential stress development are the main mechanisms which are believed to lead to fault reactivation. A correlation of production parameters to seismicity rate is well established, and reduced production has led to a decrease in seismicity rate.

> Recurrent seismological parameters include (1) seismic event detection, (2) magnitude determination and (3) location.

Many analyses that were performed in the Groningen field so far rely on the KNMI catalogue itself (Hettema et al., 2017; Sijacic et al., 2017; Pijpers, 2017; Bourne et al., 2014)... This means the catalogue should be complete in terms of detection, but also (inherently) in terms of magnitude determination. Especially when using the seismicity rate as input to a model, it is important to ensure that the catalogue used in the model is complete such as to exclude apparent rate increases which may be due to sensitivity increases after network upgrades. Cut-off magnitude values of the studies considered lie generally between 1 and 2 and consider the events which occurred after 1995, i.e. when the seismic network consisted of a sufficient number of stations. This is consistent with the determined completeness magnitudes and hence should prevent network-upgrade artifacts from entering the models. Moreover, seismological parameters that are derived from the event magnitude are often used, such as b-value, seismic moment or released seismic energy.

Event locations are important when trying to correlate modelled (or observed) deformations and pressure perturbations of particular reservoir areas or compartments to seismicity. However, the uncertainties in event location are oftentimes still significant compared to the detail of a reservoir model (fault compartments, vertical reservoir stratification) and these need to be honored in an adequate way. As underlined by Kortekaas and Jaarsma (2017), faults play an important role both in the generation of seismic events and in the production of gas; therefore, they need to be taken into account in the different models. A detailed fault mapping of the Groningen field has been made by

Kortekaas and Jaarsma (2017) and could help identifying the faults more prone to fail (if any), providing that accurate seismic event location and source mechanisms are available. This knowledge could in turn help improving the models.

References

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". In: *Journal of Geophysical Research: Solid Earth* 119.12, pp. 8991–9015.

de Waal, J.A., A.G. Muntendam-Bos, and J.P.A. Roest (2015). "Production induced subsidence and seismicity in the Groningen gas field-can it be managed?" In: *Proceedings of the International Association of Hydrological Sciences* 372, p. 129.

Hettema, M.H.H., B. Jaarsma, B.M. Schroot, and G.C.N. van Yperen (2017). "An empirical relationship for the seismic activity rate of the Groningen gas field". In: *Netherlands Journal of Geosciences* 96.5, s149–s161.

Kortekaas, M. and B. Jaarsma (2017). "Improved definition of faults in the Groningen field using seismic attributes". In: *Netherlands Journal of Geosciences* 96.5, s71–s85.

Nepveu, M., K. van Thienen-Visser, and D. Sijacic (2016). "Statistics of seismic events at the Groningen field". In: *Bulletin of Earthquake Engineering* 14.12, pp. 3343–3362.

Pijpers, F.P. (2017). *Interim report: correlations between reservoir pressure and earthquake rate*. Tech. rep. Statistics Netherlands.

Sijacic, D., F. Pijpers, M. Nepveu, and K. van Thienen-Visser (2017). "Statistical evidence on the effect of production changes on induced seismicity". In: *Netherlands Journal of Geosciences* 96.5, s27–s38.

van Eijs, R.M.H.E., F.M.M. Mulders, M. Nepveu, C.J. Kenter, and B.C. Scheffers (2006). "Correlation between hydrocarbon reservoir properties and induced seismicity in the Netherlands". In: *Engineering Geology* 84.3-4, pp. 99–111.

van Thienen-Visser, K., D. Sijacic, J.D. van Wees, D. Kraaijpoel, and J. Roholl (2016). *Groningen field 2013 to present: gas production and induced seismicity*. Tech. rep. TNO.

van Wees, J.-D., P.A. Fokker, K. van Thienen-Visser, B.B.T. Wassing, S. Osinga, B. Orlic, S.A. Ghouri, L. Buijze, and M. Pluymaekers (2017). "Geomechanical models for induced seismicity in the Netherlands: inferences from simplified analytical, finite element and rupture model approaches". In: *Netherlands Journal of Geosciences* 96.5, s183–s202.

Wassing, B.B.T. (2015). "Modeling of fault reactivation and fault slip in producing gas fields". In: *2nd EAGE Workshop on Geomechanics and Energy: The Ground as Energy Source and Storage*.

3 Earthquake catalogue-related core parameters for seismic hazard assessment

3.1 Probabilistic seismic hazard assessment

The investigation of the earthquake wave propagation effects to the surface, which represents the hazard assessment part of the conducted risk study, was based on the traditional probabilistic seismic hazard and risk framework introduced by Cornell (1968), an internationally recognized and standard method that has been widely used in different parts of the world for earthquake risk assessment studies in the past 50 years.

The implementation of the probabilistic seismic hazard assessment (PSHA) involves four main steps (figure 3.1):

1. the definition of the earthquake sources,
2. the definition of a recurrence model (expressed by frequency of occurrence vs. magnitude) for each source,
3. the definition of ground motion attenuation as a function of distance and spectral frequency, and
4. the computation of ground shaking intensity vs. probability of exceedance (seismic hazard curves).

3.2 Short summary of work conducted on PSHA for the Groningen field at KNMI

The work on seismic hazard assessment for the Groningen field started by the attempt to develop new Ground Motion Prediction Equations (denoted as GMPEs in the following) for the Netherlands based on the attenuation relation that was determined with the aim of calculating location magnitudes for induced events by Dost et al. (2004). The first computation of seismic hazard due to induced seismicity applied basic methodology for PSHA was performed by van Eck et al. (2004) and van Eck et al. (2006), who developed hazard maps for return periods of 10 and 100 years. These computations were performed by KNMI employing EQRISK and adopting the GMPEs by Campbell (1997) without considering site-specific effects. The observed induced earthquakes were characterised as follows:

- occurring at shallow depths (2.4 - 4 km);
- featuring relatively large values of peak ground acceleration (PGA) as predicted by McGarr (1984), up to 0.31 g;
- the maximum intensity in the direct vicinity of epicentres reached VI;

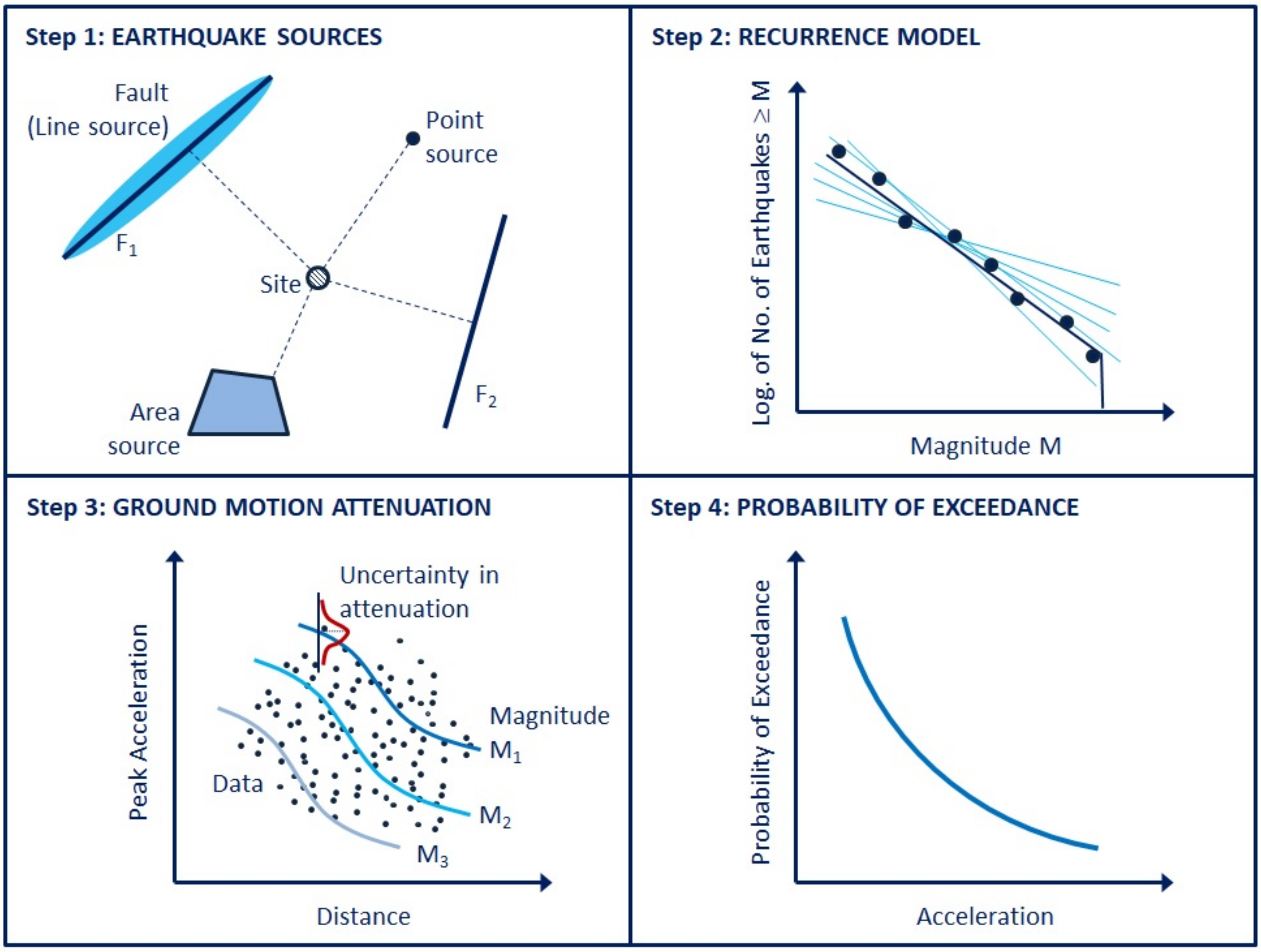

Fig. 3.1: *The fundamental steps of the traditional probabilistic seismic hazard assessment procedure*

- earthquakes are of short duration (essentially, only one cycle) and therefore, peak ground velocity (PGV) correlates better with damage statistics (Schenk et al., 1990).

Further, it was assumed that no tectonic fault instabilities will be triggered and that therefore, the maximum magnitude was assumed to M_L = 3.8 (van Eck et al., 2004) or M_L = 3.8 (van Eck et al., 2006). Already then, the authors were concluding that much information may be gained by learning if specific faults have higher probabilities of seismic movements than others.

Research into seismic hazard assessment for the Groningen field took off after the Huizinge earthquake of August 16, 2012 (Dost and Kraaijpoel, 2013). PGA values of up to 85 cm^2/s were measured corresponding to PGV values of 3.45 cm/s. Further, due to the fact that multiple S-phases had been recorded, the duration of the strongest motion was longer than stated in van Eck et al. (2004), namely from 0.2 up to 1.5 s.

Due to the by now extended data set, the hazard analysis could be updated (Dost et al., 2013):

- *the ground-motion model (GMM):* instead of the Dost et al. (2004) attenuation relation (which was developed from data collected at the Roswinkel field and thus, did not fit accelerations measured above the Groningen field), the Akkar et al. (2014) relation, based on shallow earthquakes from Europe and Middle-East was modified to fit PGA and PGV values recorded in Groningen and will be denoted as GMM version 0 (V0) in the following;

- *source zonation:* since the seismicity by now shows a clear correlation with compaction, four source zones were defined by visual inspection;
- *the seismicity trend model:* the data set is divided into two segments (1991-2003 and 2003-2012) with similar Gutenberg-Richter b-value, but different seismicity rates, which increased in time coinciding with an increasing gas production (this strategy of subdividing the hazard computations into different time periods due to varying seismicity rates is maintained by KNMI until today, since variations in the seismicity rates violate one of the basic assumptions of PSHA analysis, namely the stationarity of seismicity;
- *Mmax* is increased to M_L = 5 based on a comparison with seismicity in hydrocarbon fields outside the Netherlands;
- *soil properties:* the model contains now a correction factor for the shallow low velocity layers.

In 2013, the State Authority of Mines of the Netherlands developed a model to compute the expectation value for probability for the occurrence of earthquakes above a given magnitude and for a given time period in the future (Muntendam-Bos and de Waal, 2013). The authors conclude that the expectation value for the probability of larger magnitude earthquakes (M > 3.9) might be decreased by a factor of two, if the annual production rate is halved from the production rate at that time of $\tilde{5}$0 normal BCM/year. In January 2014, the production in five wells surrounding the most active, central region was reduced by 80%, which significantly reduced the seismic activity associated with the main NW-SE-oriented central graben (Muntendam-Bos et al., 2017). This decrease in production was at first balanced by an increase in production on other areas of the field, which lead to an increase in seismic activity in a second graben strucutre in the southwest (Muntendam-Bos et al., 2017). In addition, a medium-strength statistical correlation between seasonal fluctuations and seismic activity was identified by Nepveu et al. (2016), which led to seasonal fluctuations being minimised since March 2015 (Muntendam-Bos et al., 2017).

Since then, the KNMI PSHA computations are regularly updated, mostly due to the availability of additional data from the continuously recording monitoring network as well as due to changes in the rate of seismicity due to production measures that were employed in the meantime and updates in the GMM (for a more detailed description of the evolution of the latter, see section 3.3). The main updates to the KNMI v1 hazard model in 2015 comprised (Dost and Spetzler, 2015):

- *the GMM* is updated from V0 to V1 (see section 3.3;
- *source zonation:* the zonation model is now based on a event density map and is enlarged to

2 km outside of the Groningen field; further, b-values are computed for each zone separately, since spatial and temporal variations had been observed (Harris and Bourne, 2015);

- *the seismicity trend model* had to be updated due to production measures and a calibration period comprising the 5 most recent years is employed.

Updates in 2016 to the KNMI v2 hazard model addressed the following issues (Dost and Spetzler, 2016):

- *the GMM* is updated to version V2;
- *the PSHA method* is modified from the original method by Cornell (1968) to Bazzurro and Cornell (2004) due to the introduction of the laterally varying upper layer;
- *the weights of the logic tree describing the stress drop models* are modified to disregard the effect of low stress drop events in order for computations to be comparable to the ones performed by NAM.

In 2017, the KNMI hazard model was updated from version v2 to version v4 (Dost and Spetzler, 2017):

- *the GMM* is updated to version V4 (see section 3.3);
- *Mmax* is adopted from the outcome of the expert panel workshop (Coppersmith et al., 2016; Bommer and van Elk, 2017);
- *the seismicity trend model:* the calibration period is lowered from 5 to 3 years due to production changes in early 2014;
- *the magnitude of completeness* is decreased in order to take the installation of the G-network into account;
- *source zonation:* the ”active” and ”background” area are merged, such that only three seismic zones are evaluated;
- *the b-value* increased in the central north zone and decreased in the central south zone by 0.1, whereas activity rate shows an inverse trend;
- *the PSHA method:* due to the magnitude-distance dependence in he near-surface amplification factor introduced in the GMM V4, a more general hazard integral is implemented;
- *the distance metric:* although the rupture distance metric is introduced in the GMM V4 replacing the previous point-source metric, a point-source approach is continued to be used in the current hazard model, potentially underestimating the hazard;
- *the weights of the logic tree describing the stress drop models* are adapted for the now four stress drop models;
- *response spectra* are publicly available on a clickable map.

A very good summary of the PSHA work performed at KNMI and the advancement of essential input parameters along with developments of the monitoring network and improvement in data processing can be found in Dost et al. (2017).

3.3 Development of a Groningen-specific GMPEs

The development of GMPEs for induced earthquakes underlies specific challenges.

The choice of a suitable GMPEs is a central point in probabilistic seismic hazard assessment. Unfortunately, the development of GMPEs for induced earthquakes underlies specific challenges (Bommer et al., 2016):

1. empirical GMPEs developed using tectonic earthquakes generally cannot be extrapolated reliably to smaller magnitude ranges (Bommer et al., 2007; Atkinson and Morrison, 2009);
2. regional differences in ground motion characteristics are more apparent at smaller magnitudes (Chiou et al., 2010);
3. the shallow depth of induced earthquakes leads to in wave propagation paths that are more influenced by the heterogeneous properties of the upper crust, which further emphasizes regional differences.

As for the location of earthquakes and inversion for source mechanisms, the Zechstein layer overlying the reservoir has a significant influence due to the shallow depth of the earthquakes.

On the other hand, especially for the Groningen field, the understanding of the upper crustal structure is very detailed (Bommer et al., 2016). Since further, earthquakes occur in a limited space, they effectively occur within a single seismic source and waves propagate along a narrow range of travel paths allowing for nonergodic standard deviations to be employed (Atkinson, 2006; Lin et al., 2011; Rodriguez-Marek et al., 2013). If the area of interest is adequately instrumented, which also is the case for the Groningen field, the GMPEs can be frequently updated and improved as well as their epistemic uncertainties reduced due the high number of earthquake occurrence compared to tectonic environments (Bommer et al., 2016).

For the Groningen field, the shallow depths of earthquakes leading to a higher influence of the heterogeneous properties of the upper crust, as stated above, is exceptionally important. The Zechstein layer overlying the reservoir, with its high seismic velocity and strong topography leads not only to rapid attenuation over relatively short distances, but also high amplitudes at short epicentral distances associated with very short duration (Bommer et al., 2016). On the contrary, the motions at greater epicentral distance are of very low amplitude, but prolonged duration due to multiple ray paths (Bommer et al., 2016).

A very detailed description of the evolution of the ground motion models for the Groningen field is given by Bommer et al. (2017c) and a more concise summary by Bommer et al. (2017b). We will not provide a complete description of this evolution, but will instead summarize the main features in order to enable the reader to better understand the development of PSHA at KNMI (section 3.2) and NAM (section 3.5).

As described in section 3.2, the primary GMM version 0 (V0) was based on the relation by Akkar et al. (2014) and extended to smaller magnitudes using recorded events in Groningen (2.7 < M_L < 3.6; Dost and Spetzler, 2015).

> Whereas GMPEs for moderate-to-large magnitude earthquakes are usually derived to be transportable to different locations and applications, the characteristics of induced earthquakes require the development of application-specific models.

Version 1 (V1) of the GMM moves from the equation based on Akkar et al. (2014) towards an equation purely based on Groningen data (Bommer et al., 2016). Whereas GMPEs for moderate-to-large magnitude earthquakes are usually derived to be transportable to different locations and applications, the characteristics of induced earthquakes require the development of application-specific models (Bommer et al., 2016). The basic framework adopted is to invert the Fourier amplitude spectra of surface motions to estimate source, path, and site parameters in order to subsequently employ stochastic simulations to extend the range of validity to higher magnitudes, using attenuation Q, the kappa parameter κ, stress drop, geometrical spreading, and an average site amplification derived from the acceleration spectra of Groningen records as input (Bommer et al., 2016). Due to the high uncertainty of stress drop values, three branches of the model employing a low, a central, and a high value (Dost and Spetzler, 2016) are defined capturing the epistemic uncertainty. A magnitude-dependent near-source distance saturation term (Yenier and Atkinson, 2014) is included that also accounts for the magnitude dependence of geometric spreading (Cotton et al., 2008). The number of response spectral acceleration periods is increased to 5 periods.

Version 2 (V2) of the GMM predicts response spectral accelerations across the gas field and within a 5 km buffer area surrounding the field (Bommer et al., 2015). The Upper North Sea formation base at approximately 350 m depth is chosen as reference rock horizon. Non-linear site amplification factors are defined relative to the motions at the reference level for 167 individual zones. The model also includes equations for the prediction of the significant duration of ground shaking. The distance-dependent terms are segmented into four distance ranges. Response spectral accelerations are now computed at 16 periods. The stochastic simulations are extended to include earthquakes up to M_L 6.5.

In version 3 (V3) of the GMM, the reference horizon is shifted to the base of the North Sea supergroup at a depth of approximately 800 m (Bommer et al., 2017d) corresponding to a much clearer impedance contrast (van Dalfsen et al., 2006). Non-linear site amplification factors are defined relative to the motions at the reference level for 161 individual zones (Kruiver et al., 2017). The number of periods at which response spectral acceleration is computed is increased to 23 (Bommer et al., 2017b).

From version 4 (V4) on, finite faults simulations are employed instead of the point-source simulations, which required the introduction of the rupture distance as distance metric (Bommer et al., 2017b). The number of rock ground motion model branches is increased from 3 to 8 (4 median and two sigma branches, Bommer et al., 2017b). Non-linear site amplification factors are defined relative to the motions at the reference level for 160 individual zones (Bommer et al., 2017a). The amplification factors become dependent on magnitude and distance in addition to being functions of frequency and amplitude of motion at the reference horizon (Bommer et al., 2017b; Stafford et al., 2017).

> Starting with GMM V4, finite faults simulations are employed in the stochastic modelling of ground motions, requiring the introduction of the rupture distance as distance metric.

Version 5 (V5) mainly incorporates comments from the assurance review (Bommer et al., 2017c). A major change concerns the scaling relation between local and moment magnitude (Dost et al., 2018) and the introduction of a detailed duration model. Additional GMPEs are developed for smaller earthquakes (1.8 < M < 3.6) with epicentral distances of up to about 35 km for operational use within the context of a new damage protocol (Bommer et al., 2017e).

3.4 Maximum magnitude estimates

> Recommendations of the panel of experts discussing the maximum magnitudes comprise amongst other things the usage of data from the recently installed G-network in order to determine high-resolution hypocentral locations, focal mechanisms, moment tensors, and stress drops.

The assessment of the maximum magnitude an earthquake may potentially acquire (Mmax) requires expert judgment and the application of physical principles beyond just the earthquake catalogue (Coppersmith et al., 2016). Therefore, a panel of internationally recognised experts was assembled to follow the general principles of the Senior Seismic Hazard Analysis Committee (SSHAC; Budnitz et al., 1997) to develop a logic tree for Mmax in the Groningen field (Bommer and van Elk, 2017). The maximum magnitude has to be defined in a way that it captures both the centre, body, and range of technically defensible interpretations (Coppersmith et al., 2016). For the Groningen field, it has long been under discussion, before an agreement was reached on a workshop among a panel of experts in April 2016 (Coppersmith et al., 2016). This panel focused on developing a distribution of Mmax that includes epistemic uncertainties and is based on a consideration of factors relating to the Groningen field, earthquake physics, analogues, and experience in developing such distributions in other studies. The distribution that was achieved will not be described here, but we will repeat the recommendations that were given in order to reduce uncertainties (Coppersmith et al., 2016):

- review and analyse analogue case histories of induced seismicity associated with gas extraction with high priority on the case history of the Gazli earthquakes;
- use data from the recently installed high quality seismic network in order to determine high-resolution hypocentral locations, focal mechanisms, moment tensors, stress drops, and ground motion parameters incorporating detailed crustal velocity models as well as combining surface and downhole instruments whenever feasible;
- special attention should be given to obtaining accurate estimates of moment magnitudes;
- perform in situ stress measurements to characterise the magnitudes and orientations of the principal stresses of reservoir and Carboniferous;
- analyse and resolve the stress field in Carboniferous as well as deeper strata;
- compile and analyse regional geodetic data;
- confirm the dominance of normal faulting within the reservoir;
- analyse the potential of ruptures propagating out of the field.

3.5 PSHA at NAM and Shell: differences to the KNMI models

> The main difference between KNMI's and NAM's/Shell's PSHA is the development of an alternative seismic source model by Shell.

In order to compute probabilistic seismic hazard, NAM and Shell pursued a different strategy compared to the classical definition of seismic sources employed by KNMI, namely, the development of an alternative source model based on a reservoir compaction model (Bourne et al., 2014) combined with a Monte Carlo approach to hazard calculations (Bourne et al., 2015). In this model, the seismic moment is expressed in terms of changes in the reservoir volume and thus linked to total strain. The hazard calculations are based directly on forecasts of compaction derived from a dynamic reservoir model, which in turn is based on future production plans. Thereby, the induced seismic hazard can be computed as function of time and exposure period thus taking into account the time-variant nature of induced seismicity. In later versions, the seismicity is characterised by seismic event rates and epidemic type after shock (ETAS) models are employed to describe spatial and temporal clustering of earthquakes (Bourne and Oates, 2017). In addition, the concentration of moment release on pre-existing faults and other reservoir topographic structures is incorporated (Bourne and Oates, 2017).

In addition, NAM hazard models include only earthquakes with magnitudes above M > 2.5, whereas KNMI's hazard computations comprise also lower magnitude events (M > 1.5).

3.6 Selection of earthquake-related core parameters for hazard estimates

From our point of view, the most important parameter for hazard estimates of large earthquakes is the maximum magnitude. However, for small to intermediate sized earthquakes, there are other parameters that are at least as significant as the earthquake magnitude.

During the development of the GMPEs, two parametes require special attention, the κ parameter and the stress drop (also named stress parameter). Unfortunately, both are difficult to measure and their meaning as well as implications are widely discussed (Atkinson and Beresnev, 1997; Ktenidou et al., 2014).

κ describes the deviation at high frequencies between observed Fourier amplitude spectra calculated from seismograms and an ω^{-2} source model, such as the Brune (1970) model (Ktenidou et al., 2014). κ is often measured from the high frequency part of the acceleration Fourier amplitude spectrum of a record. In the creation and calibration of ground-motion prediction equations based on stochastic simulations, as is the case for the Groningen GMPEs, near-surface attenuation is implicitly considered through a set of κ values considered applicable to the region (Toro et al., 1997). Its physical meaning remains unclear and has been attributed to both source (e.g., Bakun et al., 1976) and site (e.g., Frankel, 1982) effects or both (e.g., Archuleta et al., 1982). The prevailing view today is that it is related to site attenuation (Ktenidou et al., 2014), but still some studies relate it to source properties (e.g., Wen and Chen, 2012). In any case, it represents a crucial parameter in the context of the Groningen field, because of its relation to the high frequency part of the source spectrum, which is influential particularly for low to intermediate levels of damage, which can be expected here.

> From our point of view, the most important parameter for hazard estimates of large earthquakes is the maximum magnitude. However, for small to intermediate sized earthquakes, there are other parameters that are at least as significant as the earthquake magnitude and which, for the case of the Groningen field, we consider to comprise κ, the stress parameter $\Delta\sigma$, source mechanisms and earthquake depth.

The stress drop or stress parameter $\Delta\sigma$ was originally introduced as static measure of final fault slip as a fraction of fault dimension and was estimated from measurements or inferences of these two parameters (Atkinson and Beresnev, 1997). It became an important earthquake source parameter after Brune (1970) showed that in the far field, the shear-wave spectrum could be interpreted as derived from a simple point source and could be described by just two parameters, seismic moment, and stress drop. Thus, the stress drop became inferable from seismic waveforms (Atkinson and Beresnev, 1997). Ever since Hanks and McGuire (1981), stress drop is one of the key predictive parameters in the development of ground motion relations (Atkinson and Beresnev, 1997), although Hanks and McGuire (1981) already pointed out that actual values of static stress drop were generally lower than what assumed during modelling of high frequency ground motion. One of the difficulties is that different definitions of stress drops result in large discrepancies in reported stress drop values, another one in the intrinsic non-uniqueness between stress drop and e.g. corner frequency (Atkinson and Beresnev, 1997).

Another parameter that is important for a better understanding of the regional tectonics and potentially, the development of a fault model that can be used alongside the zonation model, are epicentres. Precise earthquake epicentral locations are not essential for seismic hazard assessment per se, since during zonation, they will be grouped in different zones and, because seismic parameters will be deducted for zones as a whole, effectively be smoothed, but of course their general pattern contributes to the subdivision of the zonation model.

Earthquake depth, on the other side, has a dual influence, on the one hand on the GMPEs, on the other hand on the source model as implemented in hazard computations. Spetzler and Dost (2017) apply the EDT method to resolve earthquake depths (which are routinely set to 3 km in the induced seismicity catalogue). They analyse 87 events from 2014 to 2016 and found that event depths ranged from 2.2 km to 3.45 km (figure 3.2).

Earthquake depth became only important for the development of the GMPEs once the distance metric included a depth measure, namely when the distance metric was changed from epicentral distance to rupture distance in version GMM V4 (Bommer et al., 2017a). To that end, the minimum value for rupture distance was set to 3 km, since ruptures were assumed to initiate in the Rotliegend reservoir and to propagate laterally as well as downwards (Bommer et al., 2017a). Within the framework of this report, we cannot estimate the impact of shallower earthquake depths on both GMPEs and source model.

A more elaborate manner to derive earthquake source locations including depth is the inversion of full waveforms as described in the report on WP1, section 5.4. At the same time, another important parameter is gained: the earthquakes' source mechanisms. Apart from achieving knowledge on the nodal planes and thus, increasing the understanding of the tectonic and geomechanical setting, they may help in relating earthquakes to faults and rendering GMPEs more precise by allowing for the incorporation of a term describing the influence of the style of faulting (Bommer et al., 2003). Potentially, once a sufficient number of source mechanisms has been computed, they may be employed to imply stress directions. In addition, a full waveform moment tensor inversion usually delivers an independent estimate of the event magnitude.

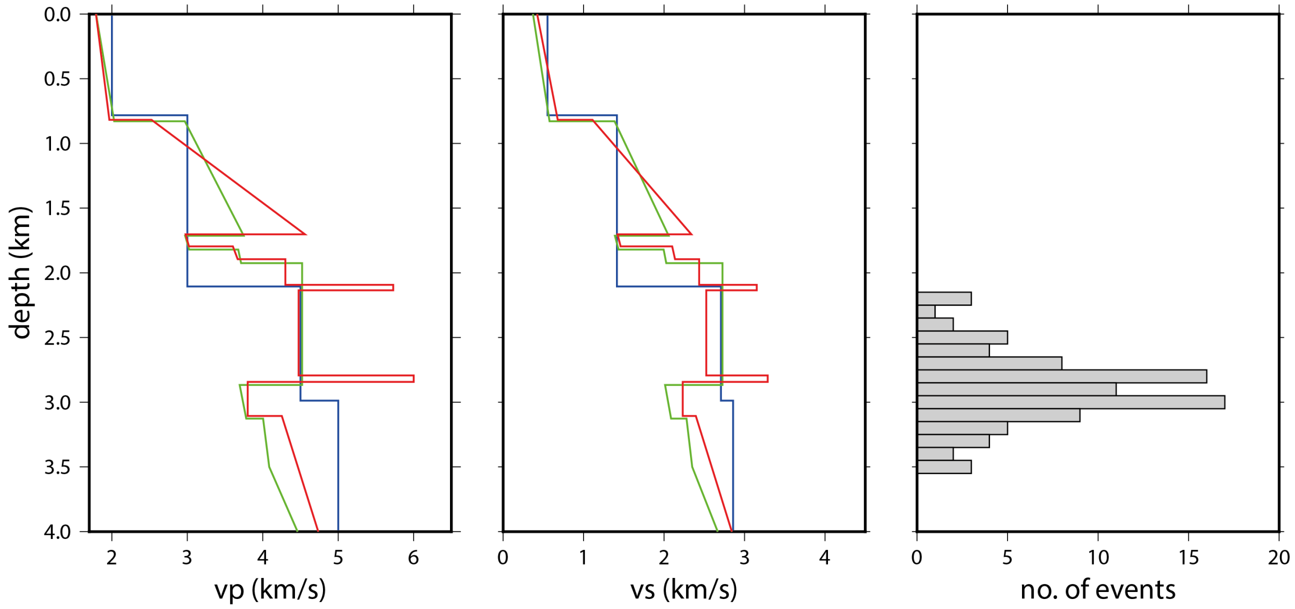

Fig. 3.2: *Comparison of velocity models. Left: P-wave velocity profile; red line: mean 1D velocity model extracted from NAM 3D velocity model in Loppersum area, green line: velocity model employed by Kraaijpoel and Dost (2013) for computation of focal mechanisms, blue line: Northern Netherlands velocity model used by KNMI to locate earthquakes within Groningen field (Spetzler and Dost, 2017). Middle: S-wave velocity profile. Right: depth distribution of relocated earthquakes listed in Spetzler and Dost (2017).*

A source of concern is that although KNMI introduced the rupture distance metric into their PSHA, they continue to employ the point source approach in the current hazard model.

So far, it remains difficult to correlate earthquakes with faults (Dost and Spetzler, 2017). Once this becomes possible, though, a fault model could be introduced into the PSHA along the zonation model (Reiter, 1991, e.g.). However, in general a point source assumption should be used only for earthquakes that are sufficiently small such that that the source dimension is negligible. A source of concern is that although KNMI introduced the rupture distance metric into their PSHA, they continue to employ the point source approach in the current hazard model (Dost and Spetzler, 2017), which may lead to a considerable underestimation of the seismic hazard (Bommer and Akkar, 2012). An alternatives is to either employ simulations of virtual fault ruptures within areal sources (Bommer and Akkar, 2012), which are by now fairly standard in most PSHA software packages. Usually, preferred fault orientations and/or dips can be specified, if such information is available. However, such simulations may be computationally intensive and sensitive to choices made for simulating the hypothetical fault ruptures (EPRI, 2004). An alternative approach is to use an empirical relationship between point-source and extended-source distance metrics (EPRI, 2004; Scherbaum et al., 2004). However, this requires the propagation of the associated variability into the sigma value of the GMPE and relations break down for epicentres close to the site (Bommer and Akkar, 2012). As solution, Bommer and Akkar (2012) propose to develop

GMPEs in pairs of models, both using a point-source metric and an extended-source metric. Since all earlier GMPEs developed for the Groningen field including GMM V3 relied on a point-source metric, it should be relatively unexpensive to further evolve the point-source metric GMPEs to an equivalent of the current GMM v5 to be used by KNMI as long as they stick to the point-source assumption.

Further parameters that play a role, but that we do not consider to be as significant for the PSHA in the case of the Groningen field as the ones described above, are seismicity rates, magnitude of completeness, b-values (which constitute derivative parameters of magnitudes, seismicity rates, and the magnitude of completeness) and the anelastic attenuation described by the quality factor Q. The relationship between local and moment magnitude only has minimal impact on the development of the GMPEs, since both the catalogued magnitudes, the seismicity model and the ground motion model is defined for local magnitudes (Bommer et al., 2015; Bommer et al., 2017c). The proportionality between the two scales counts, though, since the use of stochastic simulations is predicated on the assumption of linear scaling with seismic moment (Bommer et al., 2017c). However, the change in the relationship between local and moment magnitudes is the primary cause for the change in amplitudes at the base of the North Sea supergroup from GMM V4 to V5 (Bommer et al., 2017c). The scaling relation between local and moment magnitude needs to be taken into account, when predictions of the Groningen GMM are compared to global GMPEs, since nearly all modern equations are based on moment magnitude (Bommer et al., 2015; Bommer et al., 2017c).

Another parameter that has large implications for ground motions is of course the site amplification. However, this is not an earthquake-, but a site-related parameter. Since in addition, it has been very carefully and with great effort analysed for the Groningen field (see e.g. Bommer et al., 2015; Bommer et al., 2017a; Bommer et al., 2017b; Kruiver et al., 2017), we will disregard it in the following.

References

Akkar, S., M.A. Sandkkaya, and J.J. Bommer (2014). “Empirical ground-motion models for point-and extended-source crustal earthquake scenarios in Europe and the Middle East”. In: *Bulletin of Earthquake Engineering* 12.1, pp. 359–387.

Archuleta, R.J., E. Cranswick, C. Mueller, and P. Spudich (1982). “Source parameters of the 1980 Mammoth Lakes, California, earthquake sequence”. In: *Journal of Geophysical Research: Solid Earth* 87.B6, pp. 4595–4607.

Atkinson, G.M. (2006). “Single-station sigma”. In: *Bulletin of the Seismological Society of America* 96.2, pp. 446–455.

Atkinson, G.M. and I. Beresnev (1997). “Don’t call it stress drop”. In: *Seismological Research Letters* 68.1, pp. 3–4.

Atkinson, G.M. and M. Morrison (2009). “Observations on regional variability in ground-motion amplitudes for small-to-moderate earthquakes in North America”. In: *Bulletin of the Seismological Society of America* 99.4, pp. 2393–2409.

Bakun, W.H., C.G. Bufe, and R.M. Stewart (1976). "Body-wave spectra of central California earthquakes". In: *Bulletin of the Seismological Society of America* 66.2, pp. 363–384.

Bazzurro, P. and C.A. Cornell (2004). "Nonlinear soil-site effects in probabilistic seismic-hazard analysis". In: *Bulletin of the Seismological Society of America* 94.6, pp. 2110–2123.

Bommer, J.J., B. Dost, B. Edwards, P.P. Kruiver, P. Meijers, M. Ntinalexis, A. Rodriguez-Marek, E. Ruigrok, J. Spetzler, and P.J. Stafford (2017a). *V4 ground-motion model (GMM) for response spectral accelerations, peak ground velocity, and significant durations in the Groningen field*. Tech. rep. Nederlandse Aardolie Maatschappij BV.

Bommer, J.J., B. Dost, B. Edwards, P.P. Kruiver, M. Ntinalexis, A. Rodriguez-Marek, P.J. Stafford, and J. van Elk (2017b). "Developing a model for the prediction of ground motions due to earthquakes in the Groningen gas field". In: *Netherlands Journal of Geosciences* 96.5, s203–s213.

Bommer, J.J., B. Dost, B. Edwards, A. Rodriguez-Marek, P.P. Kruiver, P. Meijers, M. Ntinalexis, and P.J. Stafford (2015). *Development of version 2 GMPEs for response spectral accelerations and significant durations from induced earthquakes in the Groningen field*. Tech. rep. Nederlandse Aardolie Maatschappij BV.

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". In: *Bulletin of the Seismological Society of America* 106.1, pp. 158–173.

Bommer, J.J., B. Edwards, P.P. Kruiver, A. Rodriguez-Marek, P.J. Stafford, B. Dost, M. Ntinalexis, E. Ruigrok, and J. Spetzler (2017c). *V5 Ground-Motion model (GMM) for the Groningen field*. Tech. rep. Nederlandse Aardolie Maatschappij BV.

Bommer, J.J., P.J. Stafford, J.E. Alarcón, and S. Akkar (2007). "The influence of magnitude range on empirical ground-motion prediction". In: *Bulletin of the Seismological Society of America* 97.6, pp. 2152–2170.

Bommer, J.J., P.J. Stafford, B. Edwards, B. Dost, E. van Dedem, A. Rodriguez-Marek, P.P. Kruiver, J. van Elk, D. Doornhof, and M. Ntinalexis (2017d). "Framework for a ground-motion model for induced seismic hazard and risk analysis in the Groningen gas field, the Netherlands". In: *Earthquake Spectra* 33.2, pp. 481–498.

Bommer, J.J., P.J. Stafford, and M. Ntinalexis (2017e). *Empirical ground-motion prediction equations for peak ground velocity from small-magnitude earthquakes in the Groningen field using multiple definitions of the horizontal component of motion - Updated model for application to smaller earthquakes*. Tech. rep. Nederlandse Aardolie Maatschappij BV.

Bommer, J.J. and J. van Elk (2017). "Comment on "The maximum possible and the maximum expected earthquake magnitude for production-induced earthquakes at the gas field in Groningen, The Netherlands" by Gert Zöller and Matthias Holschneider". In: *Bulletin of the Seismological Society of America* 107.3, pp. 1564–1567.

Bommer, Julian J and Sinan Akkar (2012). "Consistent source-to-site distance metrics in ground-motion prediction equations and seismic source models for PSHA". In: *Earthquake Spectra* 28.1, pp. 1–15.

Bommer, Julian J, John Douglas, and Fleur O Strasser (2003). "Style-of-faulting in ground-motion prediction equations". In: *Bulletin of Earthquake Engineering* 1.2, pp. 171–203.

Bourne, S.J. and S.J. Oates (2017). "Development of statistical geomechanical models for forecasting seismicity induced by gas production from the Groningen field". In: *Netherlands Journal of Geosciences* 96.5, s175–s182.

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". In: *Bulletin of the Seismological Society of America* 105.3, pp. 1721–1738.

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". In: *Journal of Geophysical Research: Solid Earth* 119.12, pp. 8991–9015.

Brune, J.N. (1970). "Tectonic stress and the spectra of seismic shear waves from earthquakes". In: *Journal of geophysical research* 75.26, pp. 4997–5009.

Budnitz, R.J., G. Apostolakis, and D.M. Boore (1997). *Recommendations for probabilistic seismic hazard analysis: guidance on uncertainty and use of experts*. Tech. rep. U.S. Nuclear Regulatory Commission, Washington, DC (United States).

Campbell, K.W. (1997). "Empirical near-source attenuation relationships for horizontal and vertical components of peak ground acceleration, peak ground velocity, and pseudo-absolute acceleration response spectra". In: *Seismological research letters* 68.1, pp. 154–179.

Chiou, B., R. Youngs, N. Abrahamson, and K. Addo (2010). "Ground-motion attenuation model for small-to-moderate shallow crustal earthquakes in California and its implications on regionalization of ground-motion prediction models". In: *Earthquake spectra* 26.4, pp. 907–926.

Coppersmith, K., H. Bungum, A. McGarr, I. Wong, J. Ake, T. Dahm, I. Main, and B. Youngs (2016). *Report from the expert panel on maximum magnitude estimates for probabilistic seismic hazard and risk modelling in Groningen gas field*. Mmax Expert Workshop, 8 - 10 March 2016, World Trade Centre, Schiphol Airport, the Netherlands.

Cornell, C. A. (1968). "Engineering seismic risk analysis". In: *Bulletin of the seismological society of America* 58.5, pp. 1583–1606.

Cotton, F., G. Pousse, F. Bonilla, and F. Scherbaum (2008). "On the discrepancy of recent European ground-motion observations and predictions from empirical models: Analysis of KiK-net accelerometric data and point-sources stochastic simulations". In: *Bulletin of the Seismological Society of America* 98.5, pp. 2244–2261.

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*. Tech. rep. KNMI.

Dost, B., B. Edwards, and J.J. Bommer (2018). "The Relationship between M and ML: A Review and Application to Induced Seismicity in the Groningen Gas Field, The Netherlands". In: *Seismological Research Letters*.

Dost, B. and D. Kraaijpoel (2013). *The August 2016, 2012 earthquake near Huizinge (Groningen)*. Tech. rep. KNMI.

Dost, B., E. Ruigrok, and J. Spetzler (2017). "Development of seismicity and probabilistic hazard assessment for the Groningen gas field". In: *Netherlands Journal of Geosciences* 96.5, s235–s245.

Dost, B. and J. Spetzler (2015). *Probabilistic seismic hazard analysis for induced earthquakes in Groningen; update 2015*. Tech. rep. KNMI.

Dost, B. and J. Spetzler (2016). *Probabilistic seismic hazard analysis for induced earthquakes in Groningen, update June 2016*. Tech. rep. KNMI.

Dost, B. and J. Spetzler (2017). *Probabilistic seismic hazard analysis for induced earthquakes in Groningen, update June 2017*. Tech. rep. KNMI.

Dost, B., T. Van Eck, and H. Haak (2004). "Scaling of peak ground acceleration and peak ground velocity recorded in the Netherlands". In: *Bollettino di Geofisica Teorica ed Appliocata* 45.3, pp. 153–168.

EPRI (2004). *CEUS Ground motion project: final report, report 1009684*. Tech. rep. Electrical Power Research Institute.

Frankel, A. (1982). "The effects of attenuation and site response on the spectra of microearthquakes in the northeastern Caribbean". In: *Bulletin of the Seismological Society of America* 72.4, pp. 1379–1402.

Hanks, Thomas C and Robin K McGuire (1981). "The character of high-frequency strong ground motion". In: *Bulletin of the Seismological Society of America* 71.6, pp. 2071–2095.

Harris, C.K. and S.J. Bourne (2015). *Maximum likelihood estimates of b-value for induced seismicity in the Groningen field*. Tech. rep. Nederlandse Aardolie Maatschappij BV.

Kraaijpoel, D. and B. Dost (2013). "Implications of salt-related propagation and mode conversion effects on the analysis of induced seismicity". In: *Journal of Seismology* 17.1, pp. 95–107.

Kruiver, P.P., E. van Dedem, R. Romijn, G. de Lange, M. Korff, J. Stafleu, J.L. Gunnink, A. Rodriguez-Marek, J.J. Bommer, J. van Elk, et al. (2017). "An integrated shear-wave velocity model for the Groningen gas field, The Netherlands". In: *Bulletin of Earthquake Engineering* 15.9, pp. 3555–3580.

Ktenidou, O.-J., F. Cotton, N.A. Abrahamson, and J.G. Anderson (2014). "Taxonomy of κ: A review of definitions and estimation approaches targeted to applications". In: *Seismological Research Letters* 85.1, pp. 135–146.

Lin, Po-Shen, Brian Chiou, Norman Abrahamson, Melanie Walling, Chyi-Tyi Lee, and Chin-Tung Cheng (2011). "Repeatable source, site, and path effects on the standard deviation for empirical ground-motion prediction models". In: *Bulletin of the Seismological Society of America* 101.5, pp. 2281–2295.

McGarr, A. (1984). "Scaling of ground motion parameters, state of stress, and focal depth". In: *Journal of geophysical research: Solid earth* 89.B8, pp. 6969–6979.

Muntendam-Bos, A.G. and J.A. de Waal (2013). *Reassessment of the probability of higher magnitude earthquakes in the Groningen gas field including a position statement by KNMI*. Tech. rep. State Supervision of Mines.

Muntendam-Bos, A.G., J.P.A. Roest, and H.A. de Waal (2017). "The effect of imposed production measures on gas extraction induced seismic risk". In: *Netherlands Journal of Geosciences* 96.5, s271–s278.

Nepveu, M., K. van Thienen-Visser, and D. Sijacic (2016). "Statistics of seismic events at the Groningen field". In: *Bulletin of Earthquake Engineering* 14.12, pp. 3343–3362.

Reiter, Leon (1991). *Earthquake hazard analysis: issues and insights*. Columbia University Press.

Rodriguez-Marek, Adrian, Fabrice Cotton, Norman A Abrahamson, Sinan Akkar, Linda Al Atik, Ben Edwards, Gonzalo A Montalva, and Haitham M Dawood (2013). "A model for single-station standard deviation using data from various tectonic regions". In: *Bulletin of the seismological society of America* 103.6, pp. 3149–3163.

Schenk, Vladimr, Frantiek Mantlk, Michail N Zhizhin, and Alexey G Tumarkin (1990). "Relation between macroseismic intensity and instrumental parameters of strong motionsA statistical approach". In: *Natural Hazards* 3.2, pp. 111–124.

Scherbaum, Frank, Jan Schmedes, and Fabrice Cotton (2004). "On the conversion of source-to-site distance measures for extended earthquake source models". In: *Bulletin of the Seismological Society of America* 94.3, pp. 1053–1069.

Spetzler, J. and B. Dost (2017). "Hypocentre estimation of induced earthquakes in Groningen". In: *Geophysical Journal International* 209.1, pp. 453–465.

Stafford, P.J., A. Rodriguez-Marek, B. Edwards, P.P. Kruiver, and J.J. Bommer (2017). "Scenario dependence of linear site-effect factors for short-period response spectral ordinates". In: *Bulletin of the Seismological Society of America* 107.6, pp. 2859–2872.

Toro, G.R., N.A. Abrahamson, and J.F. Schneider (1997). "Model of strong ground motions from earthquakes in central and eastern North America: best estimates and uncertainties". In: *Seismological Research Letters* 68.1, pp. 41–57.

van Dalfsen, W., J.C. Doornenbal, S. Dortland, and J.L. Gunnink (2006). "A comprehensive seismic velocity model for the Netherlands based on lithostratigraphic layers". In: *Netherlands Journal of Geosciences* 85.4, pp. 277–292.

van Eck, T., F. Goutbeek, H. Haak, and B. Dost (2004). *Seismic hazard due to small shallow induced earthquakes*. Tech. rep. KNMI.

van Eck, T., F. Goutbeek, H. Haak, and B. Dost (2006). "Seismic hazard due to small-magnitude, shallow-source, induced earthquakes in The Netherlands". In: *Engineering Geology* 87.1-2, pp. 105–121.

Wen, J. and X. Chen (2012). "Variations in f max along the ruptured fault during the M w 7.9 Wenchuan earthquake of 12 May 2008". In: *Bulletin of the Seismological Society of America* 102.3, pp. 991–998.

Yenier, E. and G.M. Atkinson (2014). "Equivalent point-source modeling of moderate-to-large magnitude earthquakes and associated ground-motion saturation effects". In: *Bulletin of the Seismological Society of America* 104.3, pp. 1458–1478.

4 Earthquake catalogue-related core parameters for seismic risk assessment

4.1 Adopted process of seismic risk assessment in the Groningen field

In the current state-of-the-art practice, the process of earthquake risk estimation for a certain region (in terms of expected damages and consequences in terms of socio-economic losses) is carried out through the identification of three integral components:

1. seismic hazard providing information on the expected seismic ground motion level,
2. the vulnerability (damageability) of buildings, infrastructure facilities and the population, and
3. the exposure of these assets in terms of their inventory and spatial distribution over the respective study area (Meslem and Lang, 2017).

The present document briefly describes the implementation of this process for the case of the Groningen field. The objective is to better understand how the related risk has been estimated within the context of the existing building stock's exposure, and subsequently to identify which earthquake-related core parameters can be considered to have a major impact on the related risk and to appropriately evaluate the potential damage and loss scenarios as well as to evaluate their potential consequences.

With respect to the Groningen field, the process of seismic risk assessment associated with the local natural gas production was implemented throughout a risk framework that starts from the impact of the gas production in terms of induced seismicity, the propagation of the seismic waves from their source to the surface, and their impact on the existing building stock in terms of damage and loss as illustrated in figure 4.1 (NAM, 2014; NAM, 2015a; NAM, 2015b).

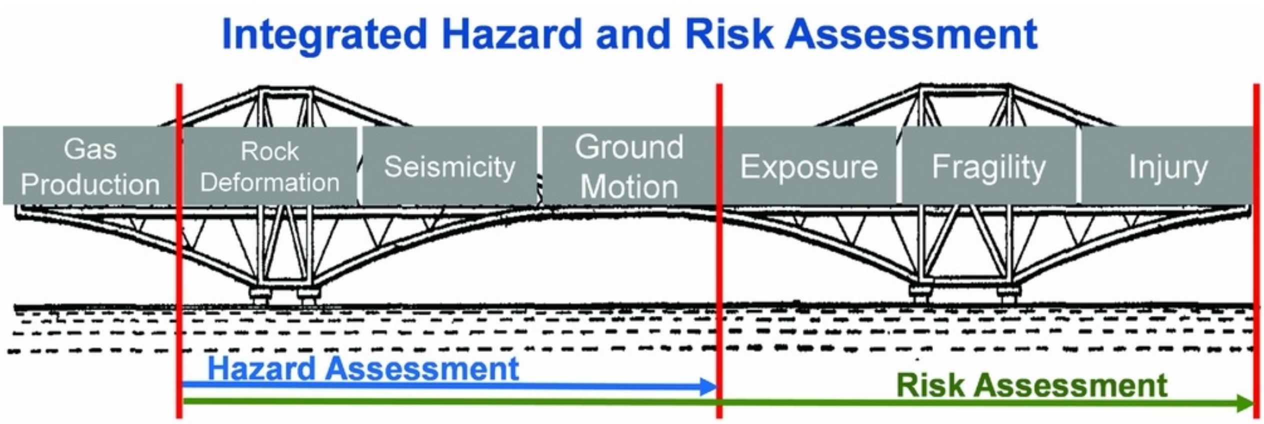

Fig. 4.1: *The integrated framework for gas production-related hazard and risk assessment in Groningen (NAM, 2014)*

With respect to the damage and loss estimates, the implementation process has involved three main steps:

1. classification of the buildings in the Groningen region into building typologies based on the concept that all buildings of a certain category have essentially the same mode of response and failure to ground shaking;
2. development of seismic fragility models using a range of earthquake magnitudes and levels of seismic ground motion expected in the Groningen field (the development of fragility models was predominantly based on analytical approaches and an experimental testing campaign; Grant et al., 2015; Pinho et al., 2015; Arup et al., 2015; Crowley et al., 2017);
3. the estimation of damage and loss consequences for the given ground motion distribution prediction models provided by the hazard assessment, presented in terms of peak ground acceleration (PGA), spectral acceleration (Sa), and duration (Crowley et al., 2015).

4.2 Earthquake-related core parameters for risk assessment

Earthquake risk, by definition, is the probability that the social and economic consequences of earthquakes (the expected or predicted losses) will equal or exceed specified values at a site during a specified exposure time. Evaluation of the level of risk involves the assessment of three components:

1. the level of the seismic hazard (which basically defines the probability of exceedance of a certain ground-motion intensity level at the site),
2. the definition of exposure (all elements at risk at the specific site, e.g. buildings, structures, population, or the community as a whole), and
3. the level of vulnerability that refers to the potential of a given physical component (building, structure, system) to be affected or damaged under a certain ground motion during an earthquake, as well as the economic and social losses that are connected to the damages either in a direct or indirect way.

Earthquake-related parameters required in the risk assessment are, in general, defined at the level of hazard assessment, and at the level of damage and loss estimates (figure 4.2).

4.3 Earthquake-related core parameters for damage/losses estimates

With respect to the estimation of physical damage as well as the economic and social losses that are connected to the damages, the main earthquake-related parameters that are required to be defined as input include:

- peak acceleration of ground shaking (PGA),
- frequency content (spectral characteristics) of the ground shaking, and
- the duration of the ground shaking.

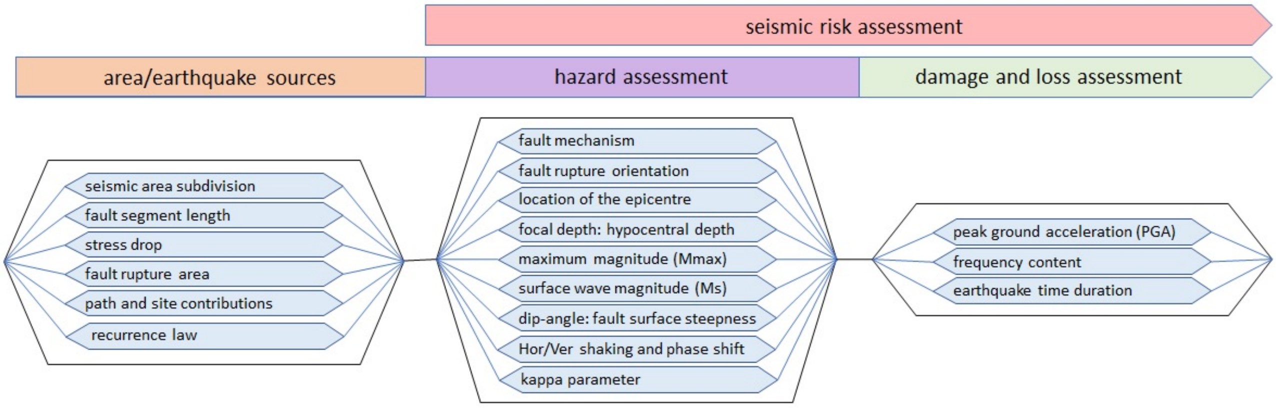

Fig. 4.2: *Earthquake-related core parameters for risk assessment*

These input parameters are directly provided as a result from the hazard assessment.

4.4 Impact of building stock characteristics on risk estimates

> 90% of the building stock consists of low-rise unreinforced masonry buildings characterised by high natural frequencies.

Most of the unreinforced masonry buildings are of low-rise height class with number of storeys ranging between 1 to 3 storeys (Grant et al., 2015) , dynamically characterised by high natural frequencies and significant initial stiffness, hence rendering them susceptible to high-frequency ground motions. According to the results of the exposure model that has been developed for the Groningen region (Arup, 2014; ARUP, 2018), the building stock contains well over 150,000 individual buildings, over 90% of which are unreinforced masonry (URM) buildings, and the remainders are concrete, steel and timber structures (table 1).

The importance of high-frequency ground motions is also relevant for other building typologies of low-rise height like reinforced concrete, steel and timber structures. If the natural frequency of a building/structure is close to the main frequency of the ground shaking, the effective duration of the earthquake shaking is of increasing importance due to the principle of resonance.

> In case that the frequency of an earthquake's ground motion coincides with the natural resonance frequency of a building, the resulting oscillations of the building will be maximized and generate most damage.

Table 1: *Existing building typologies in terms of structural material, height class, and range of natural frequency*

Building typology - structural material type	Height class/no. of storeys	Natural frequency [Hz]
masonry	low-rise; 1 - 3 storeys	6 - 20
reinforced concrete	low-rise; 1 - 3 storeys mid-rise; 2 - 4 storeys	3 - 10 1.5 - 3
steel frame	low-rise; 1 - 3 storeys mid-rise; 2 - 4 storeys	2.5 - 6 1 - 2.5

4.5 Selection of earthquake-related parameters for risk assessment

The earthquake damage potential is related to shaking, especially its absolute amplitude, its duration, its frequency content and the ratio between horizontal and vertical shaking.

In a general context, the earthquake damage potential is evidently related to the shaking intensity. The shaking intensity can be differentiated in various components such as the absolute shaking amplitudes, the ratio between horizontal and vertical shaking, the duration of the shaking, and not the least the relative distribution of shaking intensity on the different frequencies. These components are largely governed by the earthquake source, site effects, and factors related to the wave propagation path.

At Groningen, a sensitivity analysis for the risk assessment should mainly concentrate on earthquake-related parameters that may result in a high frequency content of the ground motions.

As described in the previous sections, the various findings from the hazard assessment and the damage-to-loss estimation are both based on parameters that were derived from the given earthquake catalogue (Bourne et al., 2014; Bourne and Oates, 2015a; Bourne and Oates, 2015b; Kruiver et al., 2015; Bommer et al., 2015; Pickering, 2015; Bommer et al., 2017) and thus are subjected to the same uncertainties. In the context of Groningen field, the earthquakes of interest are regional and local events. Due to the sensitivity of the existing building stock in the near field of these earthquakes to high frequencies, any sensitivity analysis should concentrate on earthquake-related parameters that may result in a high frequency content of the propagating waves and thus influence the frequency content of the ground motion (Fig. 4.3).

The influence of the propagation path is largely reflected in the Ground Motion Prediction Equations (GMPEs) of which both the mean and the variability is very important. Recent studies of Groningen data have provided significant advances on this topic, but as more data is collected, the path contribution (geometrical and inelastic damping) should be subject to renewed investigations. The

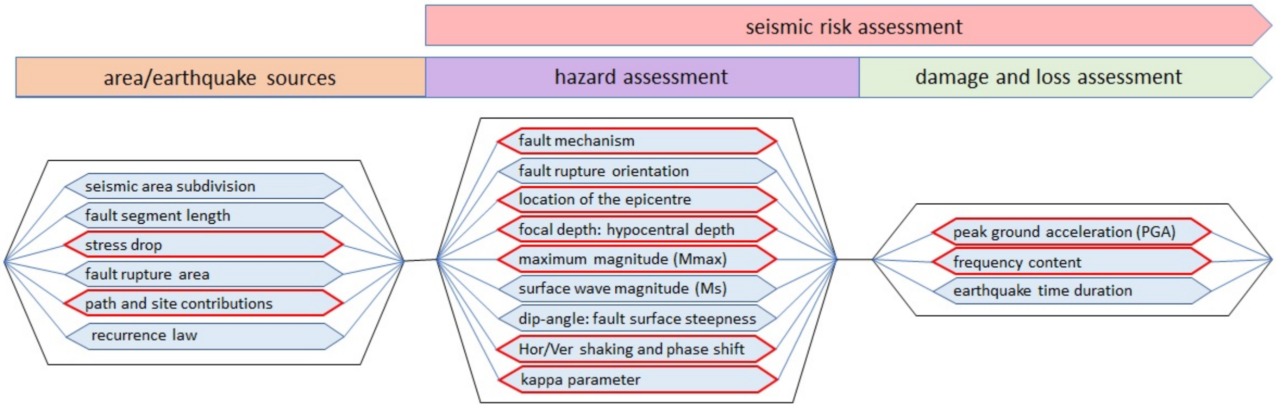

Fig. 4.3: *Priority suggestion of earthquake parameters selection (red line) based on risk and damage implications*

site influence is likewise of major importance for determination of shaking intensity and the local investigations brought together in a broader synthesis are significant. The source influence (the characteristics of the earthquake itself) remains very decisive for the earthquake shaking intensity as mentioned above. The Groningen earthquakes are historically small, and small earthquakes may generally damage structures without leading to structural collapse. However, if the risk of collapse is to be evaluated, it is of utmost importance to identify the maximum magnitude potential.

It is important that data is collected with high sampling rate that allows for a high frequency analysis.

Even in a setting like Groningen, the location precision (epicentre, depth, origin time) can be optimized and this may have direct implications on the risk evaluation. Old data may be re-analysed with new methods and reveal new facts. Important is also that new data is collected with optimal quality, among others with high sampling rate that allows for high frequency analysis.

The earthquake energy distribution over the frequencies is important for the Groningen damage potentials as well. Small earthquakes with high energy concentration on high frequencies can significantly damage old masonry structures and good mapping of the PGA levels, the high frequency energy distribution, and possibly the κ identification may significantly improve the understanding of the small-earthquake damage potential. The same applies to ”stress drop mapping”, since this is one of the major causes for the emitted shaking energy.

For small-earthquake damage, the ratio of horizontal-to-vertical shaking and a potential phase shift between horizontal and vertical maxima may be systematic and data can be used to investigate for such tendencies.

Mode of faulting is naturally an integral part of detailed seismology. After computation of fault mechanisms, the Groningen seismicity may additionally be analysed with respect to differences between shaking intensities above the hanging wall or the foot wall of the rupture. This geometry is decisive for shaking intensity of large earthquakes, but may also emerge to be important for the Groningen microseismicity shaking.

In summary, the priority suggestion of earthquake-related parameters for risk sensitivity analysis are (without their order implying their level of importance):

1. PGA and frequency content as direct input to damage and loss computations;
2. focal mechanisms (dominance and spatial differences) and hanging wall/foot wall analysis;
3. improved epicentre and focal depth;
4. maximum magnitude (Mmax);
5. ratio between horizontal-to-vertical shaking amplitudes and their possible phase shifts;
6. stress drop, kappa, and the upper frequency limit included in their analyses;
7. path and site effects.

References

ARUP (2018). *Groningen earthquakes structural upgrading - data documentation exposure database version 5*. Tech. rep. Nederlandse Aardolie Maatschappij BV.

Arup (2014). *Preliminary structural upgrading strategy for Groningen*. Tech. rep. Nederlandse Aardolie Maatschappij BV.

Arup, EUCentre, and TU Delft (2015). *EUCentre shaketable test of terraced house modelling predictions and analysis cross validation*. Tech. rep. Nederlandse Aardolie Maatschappij BV.

Bommer, J., P.J. Stafford, B. Edwards, B. Dost, and M. Ntalexis (2015). *Development of GMPEs for Response Spectral Accelerations and for Strong-Motion Durations (Version1)*. Tech. rep. Nederlandse Aardolie Maatschappij BV.

Bommer, J.J., B. Dost, B. Edwards, P.P. Kruiver, M. Ntinalexis, A. Rodriguez-Marek, P.J. Stafford, and J. van Elk (2017). “Developing a model for the prediction of ground motions due to earthquakes in the Groningen gas field”. In: *Netherlands Journal of Geosciences* 96.5, s203–s213.

Bourne, S. and S. Oates (2015a). *An activity rate model of induced seismicity within the Groningen field (part 1)*. Tech. rep. Nederlandse Aardolie Maatschappij BV.

Bourne, S. and S. Oates (2015b). *An activity rate model of induced seismicity within the Groningen field (part 2)*. Tech. rep. Nederlandse Aardolie Maatschappij BV.

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”. In: *Journal of Geophysical Research: Solid Earth* 119.12, pp. 8991–9015.

Crowley, H., R. Pinho, B. Polidoro, and P. Stafford (2015). *Development of v2 partial collapse fragility and consequency functions for the Groningen field*. Tech. rep. Nederlandse Aardolie Maatschappij BV.

Crowley, H., R. Pinho, B. Polidoro, and J. van Elk (2017). "Developing fragility and consequence models for buildings in the Groningen field". In: *Netherlands Journal of Geosciences* 96.5, s247–s257.

Grant, D., G. Magenes, and J. Rots (2015). *Groningen earthquakes structural upgrading - URM modelling and analysis cross-validation*. Tech. rep. Nederlandse Aardolie Maatschappij BV.

Kruiver, P. et al. (2015). *Geological schematisation of the shallow subsurface of Groningen. For site response to earthquakes for the Groningen gas field*. Tech. rep. Nederlandse Aardolie Maatschappij BV.

Meslem, A. and D. Lang (2017). "Physical vulnerability in earthquake risk assessment". In: *Oxford Research Encyclopedia of Natural Hazard Science*, pp. 1–46.

NAM (2014). *Addendum to: Hazard assessment for the Eemskanaal area of the Groningen field*. Tech. rep. Nederlandse Aardolie Maatschappij BV.

NAM (2015a). *Hazard and risk assessment for induced seismicity Groningen study 1: hazard assessment - update 1st May*. Tech. rep. Nederlandse Aardolie Maatschappij BV.

NAM (2015b). *Hazard and risk assessment for induced seismicity Groningen study 1: risk assessment - update 1st May*. Tech. rep. Nederlandse Aardolie Maatschappij BV.

Pickering, M. (2015). *An estimate of the earthquake hypocenter locations in the Groningen Gas Field*. Tech. rep. Nederlandse Aardolie Maatschappij BV.

Pinho, R., F. Bianchi, and R. Nascimbene (2015). *Software verification against experimental benchmark data - numerical evaluation of the seismic response of nonmasonry (nonURM) buildings in the Groningen region*. Tech. rep. Nederlandse Aardolie Maatschappij BV.

5 Relative importance of seismological parameters

In the previous sections, the earthquake catalogue-related core parameters that are important for understanding causes of seismicity (chapter 2) as well as for assessing seismic hazard (chapter 3) and seismic risk (chapter 4) have been explained. These parameters partly overlap as is demonstrated in figure 5.1.

Parameters important for seismic hazard assessment will certainly influence the risk assessment due to their impact on the response spectral acceleration. In contrast, the interconnection of both to the modelling or statistical analysis of seismicity with the aim to clarify the underlying causes of seismicity is only indirect. However, in order to rate the relative importance of these parameters, we classified them according to above sections. Parameters that turned out to be of significance for more than one or all three topics are listed in the overlapping segments of the three circles. Please note that their order does

Parameters important for seismic hazard assessment will certainly influence the risk assessment due to their impact on the response spectral acceleration. In contrast, the interconnection of both to the modelling or statistical analysis of seismicity is only indirect.

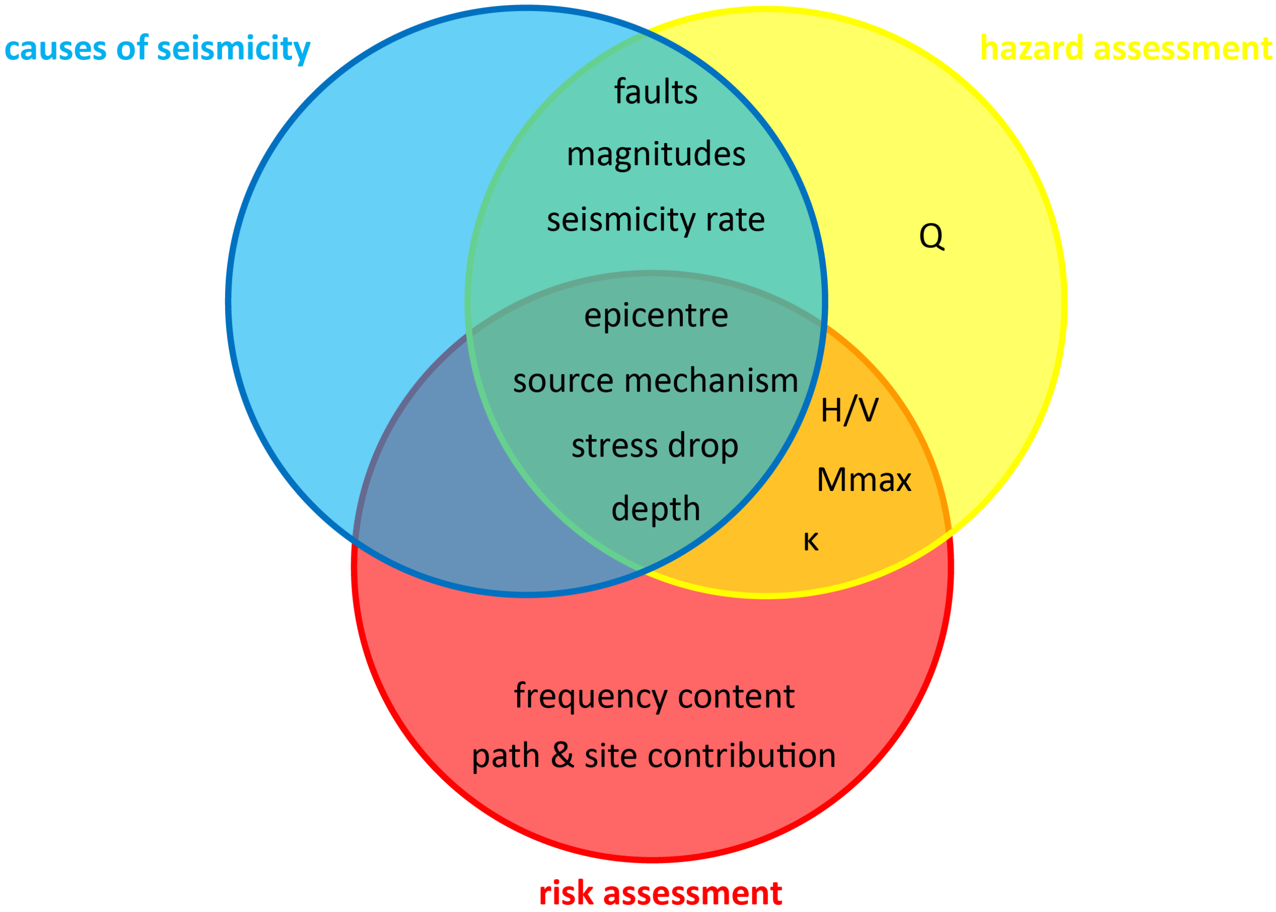

Fig. 5.1: *Relative impact of earthquake catalogue-related core parameters influencing the search for the cause of seismicity as well as seismic hazard and risk assessment*

not imply a ranking of the importance of various parameters. Parameters that play a role in all three areas under investigation are highlighted in the central part of figure 5.1. For all three topics, earthquake location, focal depth, and source mechanism emerged as significant. The placement of faults, event magnitudes, and seismicity rates prove to be influential for both finding the causes of seismicity as well as seismic hazard assessment. (Strictly speaking, the placement of faults is not a seismological parameter, but since it has direct implications for the occurrence of earthquakes, we will treat it here as such.) Parameters that influence both hazard and risk assessment are the maximum magnitude Mmax, the stress drop or stress parameter $\Delta\sigma$, κ, and the ratio of horizontal to vertical shaking and their phase shift, respectively. Other parameters are linked indirectly, e.g. a potential high-frequency content of the response spectrum that is employed in risk assessment is related to earthquake magnitude, stress drop, focal depth and κ.

To rank the seismological parameters in order of importance requires an objective.

To rank these parameters quantitatively in order of importance would require extensive sensitivity tests, which are not possible in the framework of this short-term project. Ranking them qualitatively requires an objective. If the purpose is to minimize the number of parameters to be studied, while sustaining a focus on all three topics, we recommend to concentrate on parameters that are central to all areas, namely earthquake location, depth, and source mechanism. If the goal is to identify parameters with the most far-reaching consequences, we advise to concentrate on parameters that are most significant for seismic risk analysis as analysed in chapter 4, section 4.5.

6 Assessment of earthquake-related core parameters

6.1 Earthquake-related core parameters (alphabetical order)

In the following, we list the earthquake-related core parameters that are important to describe and understand the causes of seismicity or that form an essential input to hazard and risk assessment in alphabetical order. For each parameter, we evaluate its treatment hitherto in studies related to the Groningen field and deduce required and optional measures to improve procedures.

The anelastic attenuation (represented by the quality factor Q) is one of two processes by which ground motion amplitudes decay over distance (the other one is geometric spreading) and thus belongs to the class of path effects. Path and site components of the high-frequency decay of the Fourier amplitude spectrum of acceleration (FAS) are separated in order to estimate the attenuation along the path excluding the uppermost layers (Q) and the path-independent site specific attenuation (κ_0) independently (Bommer et al., 2015). A field-wide average Q is estimated by spectral analysis of smaller magnitude earthquakes recorded at the Groningen field to be employed in the stochastic simulations used to scale the GMPEs to larger magnitudes. Thus, the Q model may be updated every time new records are introduced in the database that forms the basis for the development of new versions of the GMM. In the latest version V5, Q values of 220-250 were obtained for an average S-wave velocity of 2.6 km/s and for forward simulations, a Q value of 220 has been assumed (Bommer et al., 2017b). However, the Q value depends on the analysis method; Bommer et al. (2017a) find a value of 130 from the broadband analysis and 400 from the high-frequency analysis, but nevertheless stuck to the value of 200 used for simulation in the V3 model, since there was no discernible trend in the residual misfit. Q is not considered explicitly in the GMPE, but is instead captured in the coefficients of the geometric spreading terms (Bommer et al., 2017a). A range of simulations with progressively more complex velocity models using a variety of source mechanisms has been performed using the Shell WFD simulation code and NAM's full 3D velocity model in order to analyse the characteristic pattern of apparent changes in the rate of decay of amplitudes and resulted in a three-segmented geometrical decay function (Bommer et al., 2017a). Variations observed depending on the source mechanisms could not be taken into account, since the developed GMPE is independent of source mechanisms (Bommer et al., 2017a). A potential frequency dependence of Q has been extensively tested, but a frequency-independent model was found to be a suitable choice (Bommer et al., 2017a). Furthermore, the influence of Q is limited to greater distances, which are of little relevance to the hazard and risk estimates (Bommer et al., 2017a). Therefore, we do not consider Q to be an essential parameter for the PSHA of the Groningen field.

Earthquake depth is important both for the development of the GMPE and the implementation of the source model into the hazard computations. Routinely, the earthquake depth is set to 3 km in the induced seismicity catalogue, although efforts are made by KNMI to improve the depth estimates by employing different methods for event location (EDT, Spetzler and Dost (2017)) and employing either locally refined 1D velocity models (Spetzler and Dost, 2017) or the 3D velocity model generated by NAM (Spetzler and Dost, 2018). Earthquake depth is also important to better understand the processes causing the seismicity. Geology and fault models are a key input parameter in all geomechanical models, and should in turn be validated with observations. Erroneous assumptions on earthquake depths may lead to improper interpretation on the evolution of microseismicity and renders the comparison between modelled and observed data more difficult.

Earthquake duration is an essential parameter. From GMPE V5 on (Bommer et al., 2017b), a detailed duration model is incorporated, since in the Groningen exposure database, some building types are defined in terms of both spectral acceleration and the duration of ground shaking (defined as significant duration between 5% and 75% of the total Arias intensity). However, also earlier versions of the GMPE models contained duration models already. These duration models are developed by performing regression analyses on the outputs of the finite fault simulations. Thus, we consider earthquake duration being accounted for in an adequate manner.

Epicentral locations from the KNMI catalogue are used in the different seismological models developed for a better understanding of the causes of seismicity, often constrained geographically within the Groningen field limits or close to different production clusters. Bourne et al. (2014) observed that the distribution of earthquake epicentres is well-correlated with the reservoir compaction pattern. Precise earthquake epicentral locations are not essential for seismic hazard assessment per se, since during zonation, they will be grouped in different zones and effectively be smoothed. However, also here, they are important for a better understanding of the regional tectonics, contribute to the subdivision of the zonation model and potentially the development of a fault model.

Magnitude estimates: All catalogues of the Groningen seismicity use local magnitude (M_L) to measure event size. Although comparison to other regions may be difficult, M_L is a time-proven and robust way of determining event magnitude. Seismological parameters that are derived from the event magnitude are often used in seismological models, such as b-value, seismic moment or released seismic energy. Therefore, magnitude is important to understand causes of seismicity. It should be emphasized that the seismicity in the Groningen region is nonstationary, and time-dependent b-values are required in the hazard analysis, based mainly on $M_L < 2.5$. Therefore, measured M_L values should ideally be converted to M_W, using a suitable scaling relation, before a reliable b-value can be determined. The relationship between local and moment magnitude only has minimal impact on the development of the GMPEs, since both the catalogued magnitudes, the seismicity model and the ground motion model is defined for local magnitudes (Bommer et al., 2015; Bommer et al., 2017b). To ensure consistency, moment magnitudes (M_W) should be computed for the catalogued events and a local M_L / M_W scaling relation should be established. This was done, at least for a subset of the data, in Dost et al. (2018). Since the network was significantly upgraded, we suggest to extend this dataset with newer data.

Mmax is probably the most important single parameter for hazard estimates of large earthquakes. In 2016, a panel of internationally recognised experts was gathered following the general principles of the SSHAC (Budnitz et al., 1997) in establishing an Mmax distribution for the Groningen field (Bommer and van Elk, 2017) capturing both the centre, body, and range of technically defensible interpretations (Coppersmith et al., 2016). This distribution has been adopted both in the KNMI hazard model version v4 (Dost and Spetzler, 2017) and NAM's/Shell's hazard model (Bourne and Oates, 2017). Therefore, we do not see any necessity to redo the work of this panel, but we would like to emphasize that their recommendations for further work should be kept in mind when defining research tasks for the Groningen field.

The magnitude of completeness: The temporal evolution of the completeness magnitude is important when comparing the seismicity rate with reservoir parameters. To rule out artifacts arising from network improvements, correlations to reservoir parameters should only include seismicity above the highest M_C of the analysis period. We have discussed the determination of M_C in depth in the WP1 report section 3.4) and concluded that M_C is sufficiently constrained. Temporal changes of magnitude of completeness should be analysed using a continuous sliding time window, better suited for real-time application.

The κ parameter may be even more important in the context of the Groningen field than elsewhere due to its influence on low to intermediate levels of damage due to its relation to the high frequency part of the source spectrum, since 90% of the building stock consists of low-rise masonry buildings with relatively high natural frequencies. κ values were estimated independently using the method of Anderson and Hough (1984) (extended to lower frequencies based on the method specified by e.g. Scherbaum (1990) and described in detail in Edwards et al. (2011)) to reduce the numbers of degrees of freedom in the inversion of the Fourier amplitude spectra of surface motions during the development of the GMPEs (Bommer et al., 2017a). In general, high quality high frequency data is required in order to estimate κ. Both the original shallow borehole instruments, the B-network accelerometer as well as the G-network instruments record data with a sample rate of 200 Hz. The recently installed G-network represents one of the most extensive monitoring networks worldwide. Records of the G-network stations are an important contribution to the database on which the Groningen GMM are based, e.g. the M_L 2.6 Slochteren earthquake on 27 May 2017 increased the number of records in the database employed to derive GMM V5 by 40%, predominantly recorded by G-network stations. The inversion employed in GMM V5 was refined by implementing a Bayesian approach to reduce the strong trade-off between event stress parameter and κ. Thus, we regard the κ parameter to be taken care of in a satisfactory manner.

Seismicity rates: In order to understand the causes of seismicity, seismicity rate is important, since the evolution of seismicity with time is the most direct observation that can be correlated with other non-seismological parameters such as production rates. However, seismicity rates on their own are not a sufficient parameter to derive physical explanations. For the PSHA of the Groningen field, we do not consider seismicity rates to be one of the essential input parameters. An important point, however, is that their nonstationarity has to be considered, which violates one of the basic assumptions of PSHA analysis. In the KNMI hazard model, this is taken into account by employing a seismicity trend model with a calibration period of 3 years in the latest version (Dost and Spetzler, 2017). In this model, M_C, activity rate, and b-value are estimated from the induced seismcity catalogue using the maximum likelihood method (Wiemer and Wyss, 2000) as well as the maximum likelihood estimator by Tinti and Mulargia (1987). In the current context, these methodologies are considered as adequate.

Source mechanisms are of particular importance for a better understanding of the processes inducing seismicity, not only to retrieve nodal planes and thus, in connection with earthquake hypocentres, potentially help to associate an event with a specific fault, but also as input for a style-of-faulting term in GMPEs (Bommer et al., 2003) and - once a sufficient number of source mechanisms has been inverted - to imply stress directions. Fault maps, in turn, are important as input for more realistic geomechanical models, since faults will both influence the gas production and the development of the seismicity cloud. A very detailed fault mapping has been made by Kortekaas and Jaarsma (2017) using ant-tracking of some seismic attributes from a depth-imaged 3D seismic volume. So far, it remains difficult to correlate earthquakes with faults (Dost and Spetzler, 2017). Once this becomes possible, though, a fault model could be introduced into the PSHA along the zonation model (Reiter, 1991, e.g.). As stated in the WP1 report section 5.4, we strongly recommend to use full waveform methods for full moment tensor inversion on a larger population of earthquakes in the Groningen region. In addition, through the use of full waveform methods, an independent earthquake location and event magnitude may be obtained.

The stress parameter (stress drop): Ever since Hanks and McGuire (1981), stress drop is known as one of the key predictive parameters in the development of ground motion relations (Atkinson and Beresnev, 1997), although Hanks and McGuire (1981) already pointed out that actual values of static stress drop were generally lower than what is assumed during modelling of high frequency ground motion. In general, the higher the corner frequency, the higher the spectral acceleration amplitude of the event, and accordingly, the higher will be the predicted ground motion for the event. An accurate estimate of stress drop is therefore required for a reliable prediction of ground motions. In both the KNMI hazard models (Dost and Spetzler, 2015; Dost and Spetzler, 2016; Dost and Spetzler, 2017) as well as the NAM hazard models (van Elk et al., 2017), the number of logic tree branches is adapted to the number of stress drop branches in the respective GMM model. Also, in some of the geomechanical models, moment magnitudes are determined from the modelled rupture length and stress drop. The latter was calibrated to field observations. Stress drop is a source parameter estimated with usually large uncertainties. The two most common sources of epistemic uncertainty and bias in stress drop estimates are a limited bandwidth of the analysed data and the well known trade-off between source corner frequency and travel-path attenuation. A model-dependent method, known to have difficulties resolving the trade-off between source- and attenuation effects, was used to estimate stress drops of selected events in Groningen. In particular, absolute values of stress drop are very much model dependent and may not be considered reliable.

The vertical component of motion: Jansen and Herber (2017) draw attention to the fact that current GMPEs focus on shear wave motions (since the horizontal components affect the ground movement and thus, also damage to buildings the most), but that in several damage case in the Groningen area, the vertical component emerges as influential as well. Unfortunately, they do not give a references for their claim, such that we could not verify the statement and evaluate its importance.

6.2 Recommendations for priorities of additional work tasks

From these considerations, we extract a set of tasks for which we see a need for action. We further divided these tasks corresponding to their importance for the three areas of interest analysed in this report (causes of seismicity, seismic hazard assessment, seismic risk assessment). The list ranks the tasks by relevance to be conducted.

Recommended high priority tasks:

- estimation of earthquake depth;
- source mechanism determination;
- moment magnitude estimates;
- temporal changes of the magnitude of completeness.

Tasks that we recommend in addition:

- improved determination of epicentral locations;
- estimation of stress drop;
- estimation of the ratio horizontal to vertical component of motion and potential phase shifts.

These tasks partially follow the recommendations given by the SSHAC expert panel with the aim to reduce uncertainties in the estimation of the maximum magnitude (Coppersmith et al., 2016), especially the suggestions to (a) use data from the recently installed high quality seismic network in order to determine high-resolution hypocentral locations, focal mechanisms, moment tensors, and stress drops, (b) to obtain accurate estimates of moment magnitudes, (c) further research focusing on resolving the orientation of principal stresses of reservoir and underlying strata and (d) confirming the dominance of normal faulting within the reservoir.

References

Anderson, J.G. and S.E. Hough (1984). “A model for the shape of the Fourier amplitude spectrum of acceleration at high frequencies”. In: *Bulletin of the Seismological Society of America* 74.5, pp. 1969–1993.

Atkinson, G.M. and I. Beresnev (1997). “Don’t call it stress drop”. In: *Seismological Research Letters* 68.1, pp. 3–4.

Bommer, J.J., B. Dost, B. Edwards, P.P. Kruiver, P. Meijers, M. Ntinalexis, A. Rodriguez-Marek, E. Ruigrok, J. Spetzler, and P.J. Stafford (2017a). *V4 ground-motion model (GMM) for response spectral accelerations, peak ground velocity, and significant durations in the Groningen field*. Tech. rep. Nederlandse Aardolie Maatschappij BV.

Bommer, J.J., B. Dost, B. Edwards, A. Rodriguez-Marek, P.P. Kruiver, P. Meijers, M. Ntinalexis, and P.J. Stafford (2015). *Development of version 2 GMPEs for response spectral accelerations and significant durations from induced earthquakes in the Groningen field*. Tech. rep. Nederlandse Aardolie Maatschappij BV.

Bommer, J.J., B. Edwards, P.P. Kruiver, A. Rodriguez-Marek, P.J. Stafford, B. Dost, M. Ntinalexis, E. Ruigrok, and J. Spetzler (2017b). *V5 Ground-Motion model (GMM) for the Groningen field*. Tech. rep. Nederlandse Aardolie Maatschappij BV.

Bommer, J.J. and J. van Elk (2017). “Comment on “The maximum possible and the maximum expected earthquake magnitude for production-induced earthquakes at the gas field in Groningen, The Netherlands” by Gert Zöller and Matthias Holschneider”. In: *Bulletin of the Seismological Society of America* 107.3, pp. 1564–1567.

Bommer, Julian J, John Douglas, and Fleur O Strasser (2003). “Style-of-faulting in ground-motion prediction equations”. In: *Bulletin of Earthquake Engineering* 1.2, pp. 171–203.

Bourne, S.J. and S.J. Oates (2017). “Development of statistical geomechanical models for forecasting seismicity induced by gas production from the Groningen field”. In: *Netherlands Journal of Geosciences* 96.5, s175–s182.

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”. In: *Journal of Geophysical Research: Solid Earth* 119.12, pp. 8991–9015.

Budnitz, R.J., G. Apostolakis, and D.M. Boore (1997). *Recommendations for probabilistic seismic hazard analysis: guidance on uncertainty and use of experts*. Tech. rep. U.S. Nuclear Regulatory Commission, Washington, DC (United States).

Coppersmith, K., H. Bungum, A. McGarr, I. Wong, J. Ake, T. Dahm, I. Main, and B. Youngs (2016). *Report from the expert panel on maximum magnitude estimates for probabilistic seismic hazard and risk modelling in Groningen gas field*. Mmax Expert Workshop, 8 - 10 March 2016, World Trade Centre, Schiphol Airport, the Netherlands.

Dost, B., B. Edwards, and J.J. Bommer (2018). “The Relationship between M and ML: A Review and Application to Induced Seismicity in the Groningen Gas Field, The Netherlands”. In: *Seismological Research Letters*.

Dost, B. and J. Spetzler (2015). *Probabilistic seismic hazard analysis for induced earthquakes in Groningen; update 2015*. Tech. rep. KNMI.

Dost, B. and J. Spetzler (2016). *Probabilistic seismic hazard analysis for induced earthquakes in Groningen, update June 2016*. Tech. rep. KNMI.

Dost, B. and J. Spetzler (2017). *Probabilistic seismic hazard analysis for induced earthquakes in Groningen, update June 2017*. Tech. rep. KNMI.

Edwards, B., D. Fäh, and D. Giardini (2011). “Attenuation of seismic shear wave energy in Switzerland”. In: *Geophysical Journal International* 185.2, pp. 967–984.

Hanks, Thomas C and Robin K McGuire (1981). “The character of high-frequency strong ground motion”. In: *Bulletin of the Seismological Society of America* 71.6, pp. 2071–2095.

Jansen, J.-D. and R. Herber (2017). “Research into induced seismicity in the Groningen field–further studies”. In: *Netherlands Journal of Geosciences* 96.5, s279–s284.

Kortekaas, M. and B. Jaarsma (2017). “Improved definition of faults in the Groningen field using seismic attributes”. In: *Netherlands Journal of Geosciences* 96.5, s71–s85.

Reiter, Leon (1991). *Earthquake hazard analysis: issues and insights*. Columbia University Press.

Scherbaum, F. (1990). “Combined inversion for the three-dimensional Q structure and source parameters using microearthquake spectra”. In: *Journal of Geophysical Research: Solid Earth* 95.B8, pp. 12423–12438.

Spetzler, J. and B. Dost (2017). “Hypocentre estimation of induced earthquakes in Groningen”. In: *Geophysical Journal International* 209.1, pp. 453–465.

Spetzler, J. and B. Dost (2018). *Hypocenter estimation of induced earthquakes in Groningen*. NAC (Nederlands Aardwetenschappelijk Congres), Veldhoven, 15 - 16 March. Poster presentation.

Tinti, Stefano and Francesco Mulargia (1987). “Confidence intervals of b values for grouped magnitudes”. In: *Bulletin of the Seismological Society of America* 77.6, pp. 2125–2134.

van Elk, J., D. Doornhof, J.J. Bommer, S.J. Bourne, S.J. Oates, R. Pinho, and H. Crowley (2017). “Hazard and risk assessments for induced seismicity in Groningen”. In: *Netherlands Journal of Geosciences* 96.5, s259–s269.

Wiemer, S. and M. Wyss (2000). “Minimum magnitude of completeness in earthquake catalogs: Examples from Alaska, the western United States, and Japan”. In: *Bulletin of the Seismological Society of America* 90.4, pp. 859–869.

A Literature on Groningen gas field causes of seismicity

Bourne, S.J. and S.J. Oates (2017). “Development of statistical geomechanical models for forecasting seismicity induced by gas production from the Groningen field”. In: *Netherlands Journal of Geosciences* 96.5, s175–s182.

Bourne, S.J., S.J. Oates, and J. van Elk (2018). “The exponential rise of induced seismicity with increasing stress levels in the Groningen gas field and its implications for controlling seismic risk”. In: *Geophysical Journal International*.

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”. In: *Journal of Geophysical Research: Solid Earth* 119.12, pp. 8991–9015.

Buijze, L., B. Orlic, B.B.T. Wassing, and G.J. Schreppers (2015). “Dynamic rupture modeling of injection-induced seismicity: influence of pressure diffusion below porous aquifers”. In: *Proceedings of the 49th US Rock Mechanics/Geomechanics Symposium (ARMA), San Francisco*.

Buijze, L., P.A.J. van den Bogert, B.B.T. Wassing, and J. Orlic B.and ten Veen (2017). “Fault reactivation mechanisms and dynamic rupture modelling of depletion-induced seismic events in a Rotliegend gas reservoir”. In: *Netherlands Journal of Geosciences* 96.5, s131–s148.

de Waal, J.A., A.G. Muntendam-Bos, and J.P.A. Roest (2015). “Production induced subsidence and seismicity in the Groningen gas field-can it be managed?” In: *Proceedings of the International Association of Hydrological Sciences* 372, p. 129.

Dempsey, D. and J. Suckale (2017). “Physics-based forecasting of induced seismicity at Groningen gas field, the Netherlands”. In: *Geophysical Research Letters* 44.15, pp. 7773–7782.

Dost, B. and H.W. Haak (2007). “Natural and induced seismicity”. In: *Geology of the Netherlands*. Ed. by T.E. Wong. Royal Netherlands Academy of Arts and Sciences, Amsterdam, The Netherlands, pp. 223–239.

Hettema, M.H.H., B. Jaarsma, B.M. Schroot, and G.C.N. van Yperen (2017). “An empirical relationship for the seismic activity rate of the Groningen gas field”. In: *Netherlands Journal of Geosciences* 96.5, s149–s161.

Jansen, J.-D. and R. Herber (2017). “Research into induced seismicity in the Groningen field–further studies”. In: *Netherlands Journal of Geosciences* 96.5, s279–s284.

Kettermann, M., S. Abe, A.F. Raith, J. de Jager, and J.L. Urai (2017). “The effect of salt in dilatant faults on rates and magnitudes of induced seismicity–first results building on the geological setting of the Groningen Rotliegend reservoirs”. In: *Netherlands Journal of Geosciences* 96.5, s87–s104.

Kortekaas, M. and B. Jaarsma (2017). “Improved definition of faults in the Groningen field using seismic attributes”. In: *Netherlands Journal of Geosciences* 96.5, s71–s85.

Mossop, A. (n.d.). *Anomalous time dependent subsidence*. Oral presentation.

Mulders, F.M.M. (2003). “Modelling of stress development and fault slip in and around a production gas reservoir”. PhD thesis. TU Delft, Delft University of Technology.

NAM (2016). *Technical Addendum to the Winningsplan Groningen 2016: Production, subsidence, induced earthquakes and seismic hazard and risk assessment in the Groningen field, Part III Hazard*. Tech. rep. Nederlandse Aardolie Maatschappij BV.

Nepveu, M., K. van Thienen-Visser, and D. Sijacic (2016). “Statistics of seismic events at the Groningen field”. In: *Bulletin of Earthquake Engineering* 14.12, pp. 3343–3362.

Pijpers, F.P. (2016a). *A phenomenological relationship between reservoir pressure and tremor rates in Groningen*. Tech. rep. Statistics Netherlands.

Pijpers, F.P. (2016b). *Trend changes in tremor rates in Groningen*. Tech. rep. Statistics Netherlands.

Pijpers, F.P. (2017). *Interim report: correlations between reservoir pressure and earthquake rate*. Tech. rep. Statistics Netherlands.

Postma, T.J.W. (2017). “A poro-elastic model for triggering of production-induced earthquakes in the Groningen natural gas field by abrupt changes in well rates”. MA thesis. TU Delft, Delft University of Technology, The Netherlands.

Richter, G., S. Hainzl, G. Zöller, and T. Dahm (2018). *Seismicity model based on frictional response: application to the Groningen gas field*. SECURE Status Meeting, March 19, 2018, Potsdam. Oral presentation.

Sijacic, D., F. Pijpers, M. Nepveu, and K. van Thienen-Visser (2017). “Statistical evidence on the effect of production changes on induced seismicity”. In: *Netherlands Journal of Geosciences* 96.5, s27–s38.

ter Heege, J., S. Osinga, B. Wassing, T. Candela, B. Orlic, L. Buijze, and A. Chitu (2018). “Mitigating induced seismicity around depleted gas fields based on geomechanical modeling”. In: *The Leading Edge*, pp. 334–342.

van Eijs, R.M.H.E., F.M.M. Mulders, M. Nepveu, C.J. Kenter, and B.C. Scheffers (2006). “Correlation between hydrocarbon reservoir properties and induced seismicity in the Netherlands”. In: *Engineering Geology* 84.3-4, pp. 99–111.

van Thienen-Visser, K., D. Sijacic, J.D. van Wees, D. Kraaijpoel, and J. Roholl (2016). *Groningen field 2013 to present: gas production and induced seismicity*. Tech. rep. TNO.

van Wees, J.-D., P.A. Fokker, K. van Thienen-Visser, B.B.T. Wassing, S. Osinga, B. Orlic, S.A. Ghouri, L. Buijze, and M. Pluymaekers (2017). “Geomechanical models for induced seismicity in the Netherlands: inferences from simplified analytical, finite element and rupture model approaches”. In: *Netherlands Journal of Geosciences* 96.5, s183–s202.

Wassing, B.B.T. (2015). “Modeling of fault reactivation and fault slip in producing gas fields”. In: *2nd EAGE Workshop on Geomechanics and Energy: The Ground as Energy Source and Storage*.

Wassing, B.B.T., L. Buijze, and B. Orlic (2016). “Modelling of fault reactivation and fault slip in producing gas fields using a slip-weakening friction lay”. In: *Proceedings of the 50th US Rock Mechanics/Geomechanics Symposium (ARMA), Houston*.

B Literature on Groningen gas field seismic hazard assessment

B.1 Peer-reviewed papers (chronological order)

Bommer, J.J., B. Dost, B. Edwards, P.P. Kruiver, M. Ntinalexis, A. Rodriguez-Marek, P.J. Stafford, and J. van Elk (2017a). “Developing a model for the prediction of ground motions due to earthquakes in the Groningen gas field”. In: *Netherlands Journal of Geosciences* 96.5, s203–s213.

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”. In: *Bulletin of the Seismological Society of America* 106.1, pp. 158–173.

Bommer, J.J., P.J. Stafford, B. Edwards, B. Dost, E. van Dedem, A. Rodriguez-Marek, P.P. Kruiver, J. van Elk, D. Doornhof, and M. Ntinalexis (2017b). “Framework for a ground-motion model for induced seismic hazard and risk analysis in the Groningen gas field, the Netherlands”. In: *Earthquake Spectra* 33.2, pp. 481–498.

Bommer, J.J. and J. van Elk (2017). “Comment on “The maximum possible and the maximum expected earthquake magnitude for production-induced earthquakes at the gas field in Groningen, The Netherlands” by Gert Zöller and Matthias Holschneider”. In: *Bulletin of the Seismological Society of America* 107.3, pp. 1564–1567.

Bourne, S.J. and S.J. Oates (2017). “Development of statistical geomechanical models for forecasting seismicity induced by gas production from the Groningen field”. In: *Netherlands Journal of Geosciences* 96.5, s175–s182.

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”. In: *Bulletin of the Seismological Society of America* 105.3, pp. 1721–1738.

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”. In: *Journal of Geophysical Research: Solid Earth* 119.12, pp. 8991–9015.

deCrook, T. (1996). “A seismic zoning map conforming to Eurocode 8, and practical earthquake parameter relations for the Netherlands”. In: *Geologie en Mijnbouw* 75.1, pp. 11–18.

Dost, B. and H.W. Haak (2007). “Natural and induced seismicity”. In: *Geology of the Netherlands*. Ed. by T.E. Wong. Royal Netherlands Academy of Arts and Sciences, Amsterdam, The Netherlands, pp. 223–239.

Dost, B., E. Ruigrok, and J. Spetzler (2017). “Development of seismicity and probabilistic hazard assessment for the Groningen gas field”. In: *Netherlands Journal of Geosciences* 96.5, s235–s245.

Dost, B., T. Van Eck, and H. Haak (2004). “Scaling of peak ground acceleration and peak ground velocity recorded in the Netherlands”. In: *Bollettino di Geofisica Teorica ed Appliocata* 45.3, pp. 153–168.

Hofman, L.J., E. Ruigrok, B. Dost, and H. Paulssen (2017). “A shallow seismic velocity model for the Groningen area in the Netherlands”. In: *Journal of Geophysical Research: Solid Earth* 122.10, pp. 8035–8050.

Jansen, J.-D. and R. Herber (2017). “Research into induced seismicity in the Groningen field–further studies”. In: *Netherlands Journal of Geosciences* 96.5, s279–s284.

Kruiver, P.P., E. van Dedem, R. Romijn, G. de Lange, M. Korff, J. Stafleu, J.L. Gunnink, A. Rodriguez-Marek, J.J. Bommer, J. van Elk, et al. (2017a). “An integrated shear-wave velocity model for the Groningen gas field, The Netherlands”. In: *Bulletin of Earthquake Engineering* 15.9, pp. 3555–3580.

Kruiver, P.P., A. Wiersma, F.H. Kloosterman, G. de Lange, M. Korff, J. Stafleu, F.S. Busschers, R. Harting, J.L. Gunnink, R.A. Green, et al. (2017b). “Characterisation of the Groningen subsurface for seismic hazard and risk modelling”. In: *Netherlands Journal of Geosciences* 96.5, s215–s233.

Muntendam-Bos, A.G., J.P.A. Roest, and H.A. de Waal (2017). “The effect of imposed production measures on gas extraction induced seismic risk”. In: *Netherlands Journal of Geosciences* 96.5, s271–s278.

Noorlandt, R., P.P. Kruiver, M.P.E. de Kleine, M. Karaoulis, G. de Lange, A. Di Matteo, J. von Ketelhodt, E. Ruigrok, B. Edwards, A. Rodriguez-Marek, et al. (2018). “Characterisation of ground motion recording stations in the Groningen gas field”. In: *Journal of Seismology*, pp. 1–19.

Rodriguez-Marek, A., P.P. Kruiver, P. Meijers, J.J. Bommer, B. Dost, J. van Elk, and D. Doornhof (2017). “A Regional Site-Response Model for the Groningen Gas Field”. In: *Bulletin of the Seismological Society of America* 107.5, pp. 2067–2077.

Stafford, P.J., A. Rodriguez-Marek, B. Edwards, P.P. Kruiver, and J.J. Bommer (2017). “Scenario dependence of linear site-effect factors for short-period response spectral ordinates”. In: *Bulletin of the Seismological Society of America* 107.6, pp. 2859–2872.

van Eck, T., F. Goutbeek, H. Haak, and B. Dost (2006). “Seismic hazard due to small-magnitude, shallow-source, induced earthquakes in The Netherlands”. In: *Engineering Geology* 87.1-2, pp. 105–121.

van Eijs, R.M.H.E., F.M.M. Mulders, M. Nepveu, C.J. Kenter, and B.C. Scheffers (2006). “Correlation between hydrocarbon reservoir properties and induced seismicity in the Netherlands”. In: *Engineering Geology* 84.3-4, pp. 99–111.

van Elk, J., D. Doornhof, J.J. Bommer, S.J. Bourne, S.J. Oates, R. Pinho, and H. Crowley (2017). “Hazard and risk assessments for induced seismicity in Groningen”. In: *Netherlands Journal of Geosciences* 96.5, s259–s269.

Zöller, G. and M. Holschneider (2016). “The maximum possible and the maximum expected earthquake magnitude for production-induced earthquakes at the gas field in Groningen, The Netherlands”. In: *Bulletin of the Seismological Society of America* 106.6, pp. 2917–2921.

Zurek, B., W. Burnett, N. Dedontney, G. Gist, et al. (2017). “The effect of modeling kinematic finite faults on deterministic formulation of ground motion prediction equations-Groningen, an induced seismicity case study”. In: *2017 SEG International Exposition and Annual Meeting*. Society of Exploration Geophysicists.

B.2 Reports by KNMI (chronological order)

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*. Tech. rep. KNMI.

Dost, B. and D. Kraaijpoel (2013). *The August 2016, 2012 earthquake near Huizinge (Groningen)*. Tech. rep. KNMI.

Dost, B. and J. Spetzler (2015). *Probabilistic seismic hazard analysis for induced earthquakes in Groningen; update 2015*. Tech. rep. KNMI.

Dost, B. and J. Spetzler (2016). *Probabilistic seismic hazard analysis for induced earthquakes in Groningen, update June 2016*. Tech. rep. KNMI.

Dost, B. and J. Spetzler (2017). *Probabilistic seismic hazard analysis for induced earthquakes in Groningen, update June 2017*. Tech. rep. KNMI.

Spetzler, J. and B. Dost (2018). *Hypocenter estimation of induced earthquakes in Groningen*. NAC (Nederlands Aardwetenschappelijk Congres), Veldhoven, 15 - 16 March. Poster presentation.

van Eck, T., F. Goutbeek, H. Haak, and B. Dost (2004). *Seismic hazard due to small shallow induced earthquakes*. Tech. rep. KNMI.

B.3 Reports by NAM (chronological order)

Bommer, J.J., B. Dost, B. Edwards, P.P. Kruiver, P. Meijers, M. Ntinalexis, A. Rodriguez-Marek, E. Ruigrok, J. Spetzler, and P.J. Stafford (2017a). *V4 ground-motion model (GMM) for response spectral accelerations, peak ground velocity, and significant durations in the Groningen field*. Tech. rep. Nederlandse Aardolie Maatschappij BV.

Bommer, J.J., B. Dost, B. Edwards, A. Rodriguez-Marek, P.P. Kruiver, P. Meijers, M. Ntinalexis, and P.J. Stafford (2015a). *Development of version 2 GMPEs for response spectral accelerations and significant durations from induced earthquakes in the Groningen field*. Tech. rep. Nederlandse Aardolie Maatschappij BV.

Bommer, J.J., B. Edwards, P.P. Kruiver, A. Rodriguez-Marek, P.J. Stafford, B. Dost, M. Ntinalexis, E. Ruigrok, and J. Spetzler (2017b). *V5 Ground-Motion model (GMM) for the Groningen field*. Tech. rep. Nederlandse Aardolie Maatschappij BV.

Bommer, J.J., P.J. Stafford, B. Edwards, B. Dost, and M. Ntinalexis (2015b). *Development of GMPEs for response spectral accelerations and for strong-motion durations (version 1)*. Tech. rep. Nederlandse Aardolie Maatschappij BV.

Bommer, J.J., P.J. Stafford, and M. Ntinalexis (2017c). *Empirical ground-motion prediction equations for peak ground velocity from small-magnitude earthquakes in the Groningen field using multiple definitions of the horizontal component of motion - Updated model for application to smaller earthquakes*. Tech. rep. Nederlandse Aardolie Maatschappij BV.

DeDontney, N. et al. (2016). *Maximum Magnitude of Induced Earthquakes in the Groningen Gas Field*. Tech. rep. Nederlandse Aardolie Maatschappij BV.

Hamburger, R.O. (2016). *Appendix I: Review of the building strength and fragility workstream - Ron. O. Hamburger*. Tech. rep. Nederlandse Aardolie Maatschappij BV.

Harris, C.K. and S.J. Bourne (2015). *Maximum likelihood estimates of b-value for induced seismicity in the Groningen field*. Tech. rep. Nederlandse Aardolie Maatschappij BV.

McGarr, A. and B. Ellsworth (2016). *Appendix H: Review of the report Hazard and Risk assessment by the USGS - November 2015*. Tech. rep. Nederlandse Aardolie Maatschappij BV.

NAM (2016). *Technical Addendum to the Winningsplan Groningen 2016: Production, subsidence, induced earthquakes and seismic hazard and risk assessment in the Groningen field, Part III Hazard*. Tech. rep. Nederlandse Aardolie Maatschappij BV.

Wiemer, S. (2016). *Appendix G: Review of the report Hazard and Risk assessment by the SED - November 2015*. Tech. rep. Nederlandse Aardolie Maatschappij BV.

B.4 Others (chronological order)

Coppersmith, K., H. Bungum, A. McGarr, I. Wong, J. Ake, T. Dahm, I. Main, and B. Youngs (2016). *Report from the expert panel on maximum magnitude estimates for probabilistic seismic hazard and risk modelling in Groningen gas field*. Mmax Expert Workshop, 8 - 10 March 2016, World Trade Centre, Schiphol Airport, the Netherlands.

Kruiver, P., M. Korff, P. Meijers, G. de Lange, A. Wiersma, J. Stafleu, E. van Dedem, R. Romijn, A. Rodriguez-Marek, and J. Bommer (2016). *Shear-wave velocity model from base of the North Sea supergroup to the ground surface in the Groningen field*. Groningen Event Location Workshop, 20 October 2016. Oral presentation.

Muntendam-Bos, A.G. and J.A. de Waal (2013). *Reassessment of the probability of higher magnitude earthquakes in the Groningen gas field including a position statement by KNMI*. Tech. rep. State Supervision of Mines.

Wassing, B.B.T., P.S. Waarts, W. Roos, M. Nepveu, A.G. Muntendam-Bos, T. van Eck, and O. Leeuwenburgh (2010). “Seismic risk analysis of small earthquakes induced by hydrocarbon production in The Netherlands”. In: *72nd EAGE Conference and Exhibition incorporating SPE EUROPEC 2010, Barcelona, Spain*.

C Literature on Groningen gas field seismic risk assessment

C.1 Peer-reviewed papers (chronological order)

Bommer, J.J., B. Dost, B. Edwards, P.P. Kruiver, M. Ntinalexis, A. Rodriguez-Marek, P.J. Stafford, and J. van Elk (2017). "Developing a model for the prediction of ground motions due to earthquakes in the Groningen gas field". In: *Netherlands Journal of Geosciences* 96.5, s203–s213.

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". In: *Journal of Geophysical Research: Solid Earth* 119.12, pp. 8991–9015.

Crowley, H., R. Pinho, B. Polidoro, and J. van Elk (2017). "Developing fragility and consequence models for buildings in the Groningen field". In: *Netherlands Journal of Geosciences* 96.5, s247–s257.

Dost, B., E. Ruigrok, and J. Spetzler (2017). "Development of seismicity and probabilistic hazard assessment for the Groningen gas field". In: *Netherlands Journal of Geosciences* 96.5, s235–s245.

Hettema, M.H.H., B. Jaarsma, B.M. Schroot, and G.C.N. van Yperen (2017). "An empirical relationship for the seismic activity rate of the Groningen gas field". In: *Netherlands Journal of Geosciences* 96.5, s149–s161.

Kruiver, P.P., A. Wiersma, F.H. Kloosterman, G. de Lange, M. Korff, J. Stafleu, F.S. Busschers, R. Harting, J.L. Gunnink, R.A. Green, et al. (2017). "Characterisation of the Groningen subsurface for seismic hazard and risk modelling". In: *Netherlands Journal of Geosciences* 96.5, s215–s233.

van Elk, J., D. Doornhof, J.J. Bommer, S.J. Bourne, S.J. Oates, R. Pinho, and H. Crowley (2017). "Hazard and risk assessments for induced seismicity in Groningen". In: *Netherlands Journal of Geosciences* 96.5, s259–s269.

C.2 Reports by NAM (chronological order)

ARUP (2018). *Groningen earthquakes structural upgrading - data documentation exposure database version 5*. Tech. rep. Nederlandse Aardolie Maatschappij BV.

Arup (2014). *Preliminary structural upgrading strategy for Groningen*. Tech. rep. Nederlandse Aardolie Maatschappij BV.

Arup, EUCentre, and TU Delft (2015). *EUCentre shaketable test of terraced house modelling predictions and analysis cross validation*. Tech. rep. Nederlandse Aardolie Maatschappij BV.

Bommer, J., P.J. Stafford, B. Edwards, B. Dost, and M. Ntalexis (2015). *Development of GMPEs for Response Spectral Accelerations and for Strong-Motion Durations (Version1)*. Tech. rep. Nederlandse Aardolie Maatschappij BV.

Bourne, S. and S. Oates (2015a). *An activity rate model of induced seismicity within the Groningen field (part 1)*. Tech. rep. Nederlandse Aardolie Maatschappij BV.

Bourne, S. and S. Oates (2015b). *An activity rate model of induced seismicity within the Groningen field (part 2)*. Tech. rep. Nederlandse Aardolie Maatschappij BV.

Crowley, H., R. Pinho, B. Polidoro, and P. Stafford (2015). *Development of v2 partial collapse fragility and consequency functions for the Groningen field*. Tech. rep. Nederlandse Aardolie Maatschappij BV.

Grant, D., G. Magenes, and J. Rots (2015). *Groningen earthquakes structural upgrading - URM modelling and analysis cross-validation*. Tech. rep. Nederlandse Aardolie Maatschappij BV.

Kruiver, P. et al. (2015). *Geological schematisation of the shallow subsurface of Groningen. For site response to earthquakes for the Groningen gas field*. Tech. rep. Nederlandse Aardolie Maatschappij BV.

NAM (2014). *Addendum to: Hazard assessment for the Eemskanaal area of the Groningen field*. Tech. rep. Nederlandse Aardolie Maatschappij BV.

NAM (2015a). *Hazard and risk assessment for induced seismicity Groningen study 1: hazard assessment - update 1st May*. Tech. rep. Nederlandse Aardolie Maatschappij BV.

NAM (2015b). *Hazard and risk assessment for induced seismicity Groningen study 1: risk assessment - update 1st May*. Tech. rep. Nederlandse Aardolie Maatschappij BV.

Pickering, M. (2015). *An estimate of the earthquake hypocenter locations in the Groningen Gas Field*. Tech. rep. Nederlandse Aardolie Maatschappij BV.

Pinho, R., F. Bianchi, and R. Nascimbene (2015). *Software verification against experimental benchmark data - numerical evaluation of the seismic response of nonmasonry (nonURM) buildings in the Groningen region*. Tech. rep. Nederlandse Aardolie Maatschappij BV.

Romijn, R. (2017). *Groningen velocity model 2017 - Groningen full elastic velocity model September 2017*. Tech. rep. Nederlandse Aardolie Maatschappij BV.

van Elk, J. and D. Doornhof (2018). *Seismic Hazard and Risk Assessment in Groningen*. Symposium on seismicity induced by gas production from the Groningen Field. Oral presentation.

Report Number: 18-006	Confidential: X Unlimited:	External: X Internal:	NORSAR Project No.: 10150
Title:	Review of the public KNMI induced earthquake catalogue from the Groningen gas field (report project phase 1, WP2: Qualitative sensitivity analysis		
Client:	Staatstoezicht op de Mijnen, Netherlands		
Project manager:	D. Kühn		
Authors/prepared by:	B. Goertz-Allmann, D. Kühn, N. Langet, C. Lindholm, A. Meslem, V. Oye (alphabetical order)		
Submitted to:	Staatstoezicht op de Mijnen, Netherlands		
Contract reference:			
Archive reference:			
Approved by: Department head: CEO:	Name: V. Oye A. Strømmen Lycke	Signature:	Date: 18/6-2018 17/6-2018

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