Summary

This proposal to Staatstoezicht op de Mijnen (SodM) is a follow-up on the project completed by NORSAR, titled 'Review of the existing induced earthquake catalogue from the Groningen area' and referred to as phase 1. This second phase will involve reprocessing of data related to the KNMI induced seismicity catalogue to provide independent insight in the uncertainties associated with the earthquake characteristics listed in the KNMI catalogue with the aim to construct a KNMI research bulletin.

The proposed work packages are based on findings from the first phase of the project and are reflected in the objectives and scope of work for this proposal. The proposal is a joint NORSAR – KNMI proposal.

Phase 2 project objectives

The primary project objective is to build upon the current induced seismicity catalogue, such that its value for understanding the induced seismicity at Groningen is enhanced. In particular, the improvements will target: the consistency of the methodologies and results; the data/metadata completeness; earthquake characteristics and their uncertainties. The objectives will be met via:

- reprocessing of data associated with the KNMI induced seismicity catalogue and construction of a KNMI research bulletin;
- performing new analyses using different methodologies that will provide added value;
- applying new methodologies to ensure that state of the art processing is being performed.

Scope of work

To achieve the project objectives, the following scope of work is outlined. For each stage of the project NORSAR and KNMI will seek to ensure that SodM is fully informed on both the progress and the methodologies being used. Video meetings will be used to discuss results, with powerpoint presentations distributed to SodM as a record of the project's progress in addition to the final deliverables.

We propose to divide the project into 5 work packages:

- WP1: Data preparation and publication (KNMI)
- WP2: Independent estimates of uncertainties in earthquake parameters (NORSAR)
- WP3: Advancement of methodologies (KNMI/NORSAR)
- WP4: Evaluation of the current catalogue with respect to the uncertainties derived (NORSAR)
- WP5: Implications for the KNMI research bulletin (KNMI)

The scope of work proposed here should be understood as a proposal of optional tasks. The final compilation of work packages will be selected by SodM according to their preferences. It should be noted, however, that some work packages are dependent on the completion of earlier work packages. This is addressed in section “Commercial qualifications”.

At the start of the project, a workshop is planned with participants from both KNMI and NORSAR to discuss the methodology and previous experiences of KNMI for travel time computation, velocity model and potentially, degree of smoothing, seismic phase arrivals to be employed, calculation of the objective function, integration of sensors in the inversion, and procedure to compute location uncertainties. Further, intermediate workshops are foreseen to compare results for event relocation and moment tensor inversion. In each case, the ultimately proposed methodology based on these workshops will be an independent decision by NORSAR but guided by KNMI's past experience.

On completion of each work package, NORSAR and KNMI will present and discuss the results to ensure that the project progresses in accordance with the expectations of SodM.

Description of work packages

WP1: Data preparation and publication (KNMI)

Most of the event waveform data, required to pick phases that are subsequently employed to calculate the locations listed in the event database, are available through the KNMI website (http://rdsa.knmi.nl/dataportal/). However, this database is not yet complete, and the metadata needs to be checked for completeness of information. This task concerns both the data recorded on the regular network as well as from temporary stations. In addition, KNMI improved earthquake locations in a number of special studies, determined orientation angles of the geophone strings using different techniques and carried out research on e.g. moment tensor inversion and magnitude scaling. Results will be collected and integrated in the KNMI research bulletin.

After completion of the work package, KNMI will publish all event waveform data and related metadata on their website.

WP1 Deliverables

- homogeneous waveform database, including up-to-date metadata
- KNMI research bulletin
- open data access through KNMI website.

WP2: Independent estimates of uncertainties in earthquake parameters (NORSAR)

In the report on project phase 1, WP2, NORSAR identified precise event locations as being important to both understanding the causes of seismicity and the computation of earthquake risk. Further, NORSAR pointed out that earthquake depth is a significant parameter in earthquake hazard analysis, especially in areas where small to intermediate sized earthquakes predominate. Its influence is dual, affecting both the GMPEs (once the distance metric includes a depth measure, which is the case in the Groningen GMM V4 and V5; Bommer et al., 2018) and also the source model implemented in hazard computations, although most probablythe effect is limited in case of the Groningen field. On the other hand, earthquake depth is also important to better understand the processes causing the seismicity. Geology and fault models are key input parameters in all geomechanical models and should in turn be validated with observations. Erroneous assumptions on earthquake depths may lead to improper interpretation of the evolution of microseismicity and render the comparison between modelled and observed data more difficult. Thus, high quality event locations, particularly earthquake depths, emerged as a high priority task.

In the report on project phase 1, WP1, NORSAR summarised that KNMI has consistently employed an iteratively linearised inversion for event location throughout the catalogue period. Pick consistency for the bulletin data was judged to be good overall. However, the data within the bulletin shows inconsistencies in terms of how travel-time residuals are recorded. Additionally, no location uncertainties are provided in the publicly available catalogue or in the bulletin data. Throughout the catalogue, the event depth is fixed to 3 km, although the availability of a 3D velocity model for Groningen offers the potential to improve event location accuracy including event depth.

Improving the earthquake depth determination at Groningen is an important factor for monitoring the induced seismicity. If earthquakes are occurring in the crystalline basement, there is the potential for higher magnitudes and thus higher seismic hazard, while events above the reservoir have implications for processes occurring within the cap-rock. Unfortunately, constraining event depth can be problematic, since there is a trade-off between event origin time and depth. This issue was recognized by KNMI and lead to the implementation of the EDT method. The uncertainty in event depth becomes even more apparent when only distant P-wave readings are used in the event location process. NORSAR has identified that the KNMI event catalogue contains a significant number of entries where the event depth should theoretically be resolvable. Moreover, S-wave data are available but have not been used routinely. Including S-wave information will offer the potential for additional depth resolution, provided picking can be performed accurately.

Estimating event location uncertainties and their influence is a core component of this project. However, methodologies will only be tested on a subset of events (approx. 10%) distributed between different phases of network installation, magnitude classes and regions of the field.

2.1 - Determining event locations

NORSAR will use all available event detection data - including the results from WP1 and the existing KNMI induced seismicity research bulletin - as the basis for this task. This detection data, for the subset of events, will be used to compute new event locations. Together with KNMI, NORSAR will investigate using the NAM 3D velocity model, the updated and spatially varying time-distance curves characterizing the underburden (Langemeijer 2017; Ruigrok et al., under review), a direct-search location algorithm, multiple phases (i.e. P- and S-waves wherever possible), and additional sensors from the borehole networks (e.g. the G-network). Whereas the duplication of geophones within one borehole will not necessarily improve the event location directly, the analysis of seismograms recorded in the same borehole allows for a better phase identification. NORSAR will systematically assess the depth resolvability for each event and attempt to estimate an improved event depth where the resolvability is sufficient. The recomputation of event location is necessary groundwork to compute location uncertainties.

2.2 – Estimating the effect of velocity model uncertainty on travel-times

To understand the effect of the velocity model on event locations, NORSAR will model travel-time changes using systematic changes to the velocity model. The results will be used in Task 2.3 to compute improved estimates of location uncertainties.

2.3 - Determining event location uncertainties and event quality metrics

For each event, NORSAR will systematically determine the location uncertainty using a Monte Carlo approach based on estimated picking errors and travel-time uncertainties estimate from the velocity model in Task 2.2. The resulting set of Monte Carlo derived event locations will be used to generate an error ellipsoid, such that formal location uncertainties are reported. Furthermore, for each event NORSAR will determine an event quality metric, based on the station count, the azimuthal distribution of stations, and which phases were used for the event location.

2.4 - Storing of parametric data

To provide transparency, accountability and repeatability for the methodologies used in determining new event locations, NORSAR will record all necessary parametric data relating to the event locations, such that it is available for future research. This will include all phase information including defining pick times, defining stations, their residuals, event location methodology and related data, and location uncertainty parameters. Quality control of the parametric data including pick consistency will also be included.

WP2 Deliverables:

- formal location uncertainties for each analysed event
- all parametric data related to the processing of each event allowing repeatability of results
- description of the all methodologies used for both the event locations and their associated uncertainties
- results from the analysis used to determine depth resolvability for each event and the event quality metrics.

WP3: Advancement of methodologies (KNMI/NORSAR)

WP3a – Reducing location uncertainties using relative event relocation

In the report on project phase 1, WP1, NORSAR stated that recent work by KNMI has involved trying to improve both the lateral locations of the Groningen seismicity and resolving the depth of the events. The EDT method, which KNMI has investigated, shows good potential for use with the expanded network, and has recently taken advantage of the 3D velocity model generated by NAM (Spetzler & Dost, 2017). However, the methodology relies on a dense network with short interstation distance making it incompatible with events occurring before the network expansion in 2014 and limits itself to the P-wave data, which provides limitations in terms of the resolvability of event locations.

Relative location methods can reduce biasing effects due to unmodeled velocity structure and by using differential travel-times based on cross-correlation techniques, provide a significant improvement in the measurement precision, compared with absolute travel-times – ultimately reducing event location uncertainties. Being able to better tie event locations to fault structures represents an important contribution to both geomechanical models aimed at understanding the causes of seismicity as well as to fault models for seismic hazard assessment. KNMI implemented a double-difference scheme based on P-S delay times resulting in improved locations for a few event clusters only in the 2010-2014 testing database (Jagt et al., 2017). NORSAR thus recommended continued research into alternative earthquake location and relocation methodologies such as the double-difference method to better link the seismicity to structural features and to act as independent assessment of the induced seismicity catalogue in terms of event precision.

While the work of WP2 will provide a new set of event locations and their uncertainties by processing individual events, NORSAR also proposes to generate an additional set of locations with uncertainties based on simultaneously relocating all events within the selected subset using a double-difference approach. NORSAR will use their own implementation of the double-difference method to incorporate the NAM 3D velocity model for Groningen and - if appropriate - use back-azimuth data to provide additional constraints.

3a.1 - Parameterisation testing

Due to the size of the dataset to be used for the relative relocations and the possible parameterisation and regularisation that can be imposed, detailed testing of the parameterisation will be required to understand the sensitivity and stability of the results. This will include: assessment of which phase data and event pairs are used, how different weighting schemes are implemented, and damping of the inversion.

3a.2 - Double-difference relocation analysis and uncertainty analysis

After parameter testing, NORSAR will provide a detailed analysis of the event relocations. In addition to the new relative event locations, NORSAR will compute location uncertainties using a bootstrap sampling approach for the double difference method and compare with the location uncertainties derived from WP2.

3a.3 - Storing of parametric data

Similar to WP2, NORSAR will store all parametric data related to the relative event relocations and the uncertainty estimation. This will contain all phase information and data relating to the methodology and parameterisation used and will be made in an accessible format for researchers to use. By providing actual event pairs used in the double-difference methodology, together with the differential travel-times (and azimuths if appropriate), cross-correlation values, and weighting scheme, repeatability of results will be possible for researchers.

WP3b – stress drop

In the report on project phase 1, WP2, NORSAR identified stress drop to be a significant measure for earthquake hazard analysis, especially in the case of occurrence of small to intermediate sized earthquakes as in the case of Groningen. Stress drop is one of the key predictive parameters in the development of ground motion relations. Due to the old masonry structures prevalent in the area of the Groningen field, which are particularly affected by small earthquakes with high energy concentration at high frequencies, the earthquake energy distribution over frequencies emerges as important for the damage potential. Since stress drop is one of the major influences on emitted shaking energy, it thus strongly affects the earthquake risk analysis. In both the KNMI and NAM hazard models, the number of logic tree branches is adapted to the number of stress drop branches in the respective ground motion model. In the report on project phase 1, WP1, NORSAR pointed out that so far, only few events have been analysed and the uncertainties of individual stress drop estimates are too large to derive a statistically significant trend.

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. Stress drops were estimated by KNMI from the recorded amplitude spectra of events, but results turned out to be not very stable due to the trade-off between corner frequency and attenuation. NORSAR's recommendation was thus to re-estimate stress drop using data from the recently installed high quality seismic network and to attempt a verification of the obtained stress drop estimates with model-independent methods (e.g., Allmann & Shearer, 2007, Oye et al., 2005). However, owned to the comparatively small size of the catalogue, the results need to be carefully evaluated with respect to sample size, coverage and reliability.

The so-called multiple empirical Green's function (MEGF) method (Oye et al., 2005) requires collocated events for its execution. KNMI carried out a cluster analysis to identify events that can be used for determining empirical Green's functions (Jagt, 2017). Only for the recent Zeerijp event (2018-01-08), a precise estimate could be made by identifying a suitable EGF (Ruigrok, in prep.). Also NORSAR could only detect limited event clustering within the Groningen catalogue (5%-10%) from a previous analysis. Thus, defining appropriate EGFs can be a challenge and may be limited to selected events. The spectral stacking method (Allmann & Shearer, 2007), on the other hand. relies only on a suitable source-receiver geometry. NORSAR will investigate the potential of computing source parameters such as M_W and stress drop using an empirical Green's function analysis.

3b.1 - M_W computation for consistent magnitudes

For all events selected for source parameter estimation NORSAR will compute M_W together with its uncertainty estimate in order to have a consistent base for stress drop estimation.

3b.2 - Investigate the potential of source parameter estimation

NORSAR will first investigate the potential of computing stress drop using two different empirical Green's function analysis methods (MEGF, spectral stacking). This will involve collation of all potential source and receiver pairs and an assessment of the data quality and source-receiver path distribution.

3b.3 - Stress drop computations

If the task 3b.2 shows potential for reliable results, NORSAR will apply one or both EGF methods to determine stress drop for individual events.

WP3c– source mechanisms

In the report on project phase 1, WP2, NORSAR considered earthquake source mechanisms to be an important parameter for seismic hazard assessment. In addition, source mechanisms influence the risk assessment, since the faulting geometry is decisive for shaking intensity, and therefore, source mechanism computations were identified as high priority task. In addition, if an inversion of full waveforms is employed, earthquake centroid locations (denoting the centre of energy release) may be improved simultaneously, and independent estimates of event magnitudes are obtained. Further, source mechanisms are of particular importance for a better understanding of the processes inducing seismicity, not only to help associating an event with a specific fault, but also as input for a style-of-faulting term in the ground motion prediction equations. Once earthquakes have been correlated with faults, a fault model can be introduced into the seismic hazard assessment along the zonation model. As soon as a sufficient number of source mechanisms has been determined, stress directions may be implied.

In the report on project phase 1, WP1, NORSAR advised against the use of first motion P- and S-polarities or amplitudes in focal mechanism inversion due to the complexity of the wavefield as recorded on the stations above the Groningen field and recommended employing full waveform analysis methods instead. Recently, moment tensors have been determined by NORSAR and

KNMI (Dost et al., in prep.; Kühn and Heimann, in prep.; Stiphout, 2018) for events with magnitudes larger than M > 1.2 recorded since the installation of the G-network (i.e. since the data coverage is sufficient) employing a probabilistic moment tensor inversion code, the suitability of which has been described in detail in the WP1 report, section 5.4.4. An advantage of such a probabilistic methodology is that it provides uncertainties of the parameters and NORSAR regarded the application of probabilistic algorithms for moment tensor inversion as technically mature and state-of-the-art. However, NORSAR and KNMI restricted themselves to average 1D velocity models for the subsurface. Shell, on the contrary, employed NAM's 3D velocity model for the computation of Green's functions, which certainly can be considered as beyond state-of-the-art and requires extraordinary knowledge of the subsurface as well as adequate computational resources. NORSAR recommended to develop a 3D Green's function database independently from Shell's in order to compare 1D with 3D source mechanism solutions.

In this work package, we will advance the analysis of source mechanisms. This task will be performed in cooperation with the GFZ German Research Centre for Geosciences, Potsdam.

3c.1 - 3D full waveform modelling

In this task, NORSAR will determine the need for computing 3D Green's function databases to replace the local 1D databases computed in the previous task. To this end, NORSAR will use the spectral element method as employed by the SPECFEM3D software package to compute the Green's function database. Therefore, efforts will be concentrated on a region of 12 x 12 km, for which a SPECFEM3D model from NAM's 3D velocity model has already been developed. NORSAR will determine a subset of events located within this area and compute a 3D Green's functions database. Green's functions generated by the full waveform modelling will be compared with their 1D versions to assess if the differences are significant enough to warrant the computation of source mechanisms using the full waveform modelling results.

3c.2 - 3D moment tensor inversion

Depending on the outcome of the 3D full waveform modelling, NORSAR will perform the moment tensor inversion using the Green's functions generated from the full waveform modelling using the 3D velocity model for selected events occurring within the 2 x 12 km SPECFEM3D model. The usage of both P-wave and S-wave data as well as data from multiple sensors within a given borehole will be tested to improve the reliability of the moment tensor inversion. An advantage of the full waveform method is that in addition to the source mechanisms, independent estimates of event epicentral location, depth and magnitude become available, which will be compared to the results of WP2 and WP3. Note that although `Grond' is prepared to deal with 3D Green's function databases, the 3D moment tensor inversion has not been tested to date due to the unavailability of a suitable data set. Therefore, this task will require additional testing of the methodologies implemented, although the basic inversion setup will be unchanged.

3c.3 - 1D moment tensor inversion

In order to compare the results of 1D and 3D moment tensor inversion, NORSAR will compute Green's function databases for different 1D velocity models depending on event location, which will be extracted from the NAM 3D velocity model, in order to perform a 1D moment tensor inversion for the same events as selected for WP3c.

WP3 Deliverables:

- results of the parameter testing for the double-difference relative relocations
- results of the relocated event locations and their uncertainties
- assessment of the applicability of empirical Green's function analysis
- stress drop computations for events depending on the assessment of applicability
- comparison of 1D and 3D computed Green's functions
- source mechanisms derived from the 3D moment tensor inversion and a comparison with 1D results for a subset of events.

WP4: Evaluation of the current catalogue and research bulletin with respect to the uncertainties derived (NORSAR)

With new location uncertainties computed for WP2 and WP3a, NORSAR will assess the impact of these uncertainties on interpreting the current KNMI induced seismicity catalogue and research bulletin. In the report on project phase 1, WP2, NORSAR observed that some events have the necessary data in terms of station coverage and phase data to obtain an independent estimate of depth for the location, rather than the fixed 3 km value that is currently used. Since the depth of events has implications for understanding the seismic hazard as well as the causes of seismicity, any improvements that can be made to depth estimates are important. The results from WP2 and WP3a will therefore be used to show where there are significant discrepancies between the NORSAR derived locations and their uncertainties compared with the KNMI induced seismicity catalogue and research bulletin, paying particular attention to the depth values.

4.1 Comparing NORSAR derived location uncertainties

Location uncertainties for WP2 will be derived from the reanalysis of individual events using additional data and velocity model information to improve the resolvability where possible. WP3a will compute location uncertainties by relocating multiple events simultaneously using a relative relocation algorithm. NORSAR will compare the different location uncertainties from WP2 and WP3a and present the benefits of each method and their applicability. This will provide the guidance of how to achieve the optimum location uncertainty for Groningen.

4.2 Comparing event quality metrics with the KNMI induced seismicity catalogue and bulletin

For each event in WP2, NORSAR will compute an event quality metric to determine how well we can resolve each event. This will be the basis for the decision whether the location uncertainty can be improved. This information will be based on station count, azimuthal distribution of stations, and usable phases. In this task, NORSAR will compare this metric with the original KNMI induced seismicity catalogue and research bulletin metadata to show where event uncertainties have been improved and highlight events that could not be resolved better than the original KNMI estimates.

4.3 Comparing location uncertainties to the KNMI induced seismicity catalogue and bulletin

For this task, NORSAR will compare the location uncertainties derived in WP2 and WP3a with the locations published in the KNMI induced seismicity catalogue and research bulletin. NORSAR will systematically assess whether the published KNMI locations fall within the NORSAR derived uncertainty ellipsoids. KNMI will make an assessment of the causes if an event relocated by NORSAR falls outside the epicentre and uncertainty range. Due to the implications for hazard and risk analysis, particular focus will be on the uncertainties related to event depth i.e. whether events are likely occurring outside of the reservoir interval.

WP4 Deliverables:

- comparison of locations and their uncertainties derived by NORSAR (single event processing vs. relative relocation analysis)
- results comparing the NORSAR derived event quality estimates with the KNMI induced seismicity catalogue and research bulletin to highlight events with the potential for reduced uncertainties
- comparison of the NORSAR derived locations and their uncertainties with the KNMI induced seismicity catalogue research bulletin locations.

WP5: Implications for the KNMI research bulletin (KNMI)

In addition to the near real-time KNMI event catalogue (https://www.knmi.nl/kennis-en-datacentrum/dataset/aardbevingscatalogus), a separate research bulletin is in preparation, containing results from off-line re-processing of data. This research bulletin contains e.g. hypocentre relocations using the latest implementation of the EDT method using 3D raytracing, NonLinLoc (Lomax) using the 3D NAM model, results from moment tensor inversion and local and moment magnitude measurements. All parameter uncertainties are also quantified.

Results from the previous work packages will be evaluated and, if applicable, added to the research catalogue. In addition, methodologies that greatly improve the present parameters and their uncertainties will be implemented in the data processing. New parameters will be introduced (e.g. stress-drop in a transparent way, using existing standard protocols.

WP5 deliverables:

- description of methods used to process KNMI data
- updated research bulletin.

Long-term continuation of cooperation between KNMI and NORSAR

Throughout the last 4 years, NORSAR has acquired significant knowledge and detailed insights on induced seismicity associated to the Groningen gas field. Primarily stimulated by a collaboration project between NORSAR, KNMI and NAM, funded through the Norwegian state company Gassnova, with the aim to study mechanisms of induced seismicity and network configurations in a complex geological setting. The recent 'Review of the existing induced earthquake catalogue from the Groningen area' project initiated by SodM then further deepened NORSAR's understanding on the work processes conducted at KNMI, primarily associated to the induced earthquake catalogue. We consider NORSAR a valuable, yet independent, scientific discussion partner for KNMI

We therefore strongly recommend SodM to financially support a continued discussion forum with discussion meetings between NORSAR, KNMI and on occasion also including NAM and SodM.. A frame-work agreement between NORSAR, KNMI and SodM will likely be the preferred model to establish this long-term technical forum on Groningen induced seismicity.

Quality assurance

At NORSAR, quality assurance applies to two main areas:

- operational quality or processes that ensure a robust, consistent and professional business. This is controlled through the use of NORSAR's management system. The management system is based on principles from the ISO 9001 standards.
- quality of primary functions. This has been controlled for each project through project planning and quality assurance.

Risk management is the basis for prioritisations and corrective measures both at a management level and for each individual activity. Risk is assessed with the use of risk matrices for both business operations and for HSE. Risk is regularly followed up at management meetings and is always defined before beginning work on a new primary activity. NORSAR is a member of Achilles Joint Qualification System ensuring sustainable management of Quality, Safety, Health and Environment.

At KNMI research outcome is published in international peer-reviewed journals. In addition, a regular international research review is part of the quality assurance.

Commercial qualifications

It is not required that all work packages or tasks are selected for completion for this project. A final list of work packages and tasks will be agreed between NORSAR, KNMI and SodM prior to the start of the project. However, it should be noted that some work packages depend on the completion of earlier work packages. These include:

- WP3c.2 is dependent on the full waveform computations performed in WP3c.1.
- WP4 is dependent on the completion of WP2 and WP3a.

Moreover, some work packages involve an assessment task for whether a particular methodology is viable, prior to the complete execution of the methodology. In the case of a method proving unviable after completion of the assessment task, with the agreement of SodM, the follow-up task will not be completed, and thus will not be included in the final invoice.

KNMI and NORSAR will send in their budget to SodM separately. In addition, both institutes will send their invoices independently. NORSAR will invoice all incurring costs (working hours and direct costs) quarterly. Invoices shall be paid within 30 days after issue date.