KEM Innovation/Research Question (max. 4 pages + annex)

TITLE ***Seismogenic Source Models for the Groningen Gas Reservoir***

Objective

The production of gas from gas fields can be accompanied by induced seismicity, either by re-activating faults or by the creation and slip of newly formed faults. The objective of this research is to (1) review the existing seismicity modelling approaches applied to Groningen induced seismicity and to (2) propose alternative seismicity modelling tool(s) to better forecast induced seismicity. These forecast models must consider also temporal and spatial changes in gas production and also include faults outside the reservoir. Progress in correlating faults and induced seismicity thanks to improved hypocentre locations should be considered.

State of the art, background

Subsurface mining activities alter the state of stress in the Earth crust and can cause seismicity in a number of different ways: Increases in pore-pressure will move faults closer to failure, deformation such as subsidence or poro-elastic effects can lead to loading of pre-existing faults, but chemical alternation or changes in the frictional properties of faults may also play a role. Often induced earthquakes occur on pre-existing faults, re-activating them in a shearing mode, but new faults can also be created and opening modes rather than shearing can play a role.

The increase of induced seismicity in the Groningen gas field with time is not only a nuisance to the population but a considerable seismic hazard and risk, it also is causing heated debates in the Dutch society. Last but not least has considerable economic impact through change sin production and the need for strengthening thousands of buildings. Improving the ability to forecast the induced seismicity reliably, and to optimise production in ways that minimise the risk posed by induced earthquakes, remains an urgent need.

Various approaches exist in the literature for forecasting seismicity associated with gas production. In the risk model train used by the operator (NAM) for the Groningen gas field as part of the 'Winningsplan Groningen', a seismogenic source model is used as described in the reference (Bourne et al., 2014 and later). Other approaches have been proposed and applied as well (e.g., Dempsey and Suckdale, 2017). The currently operational NAM model uses compaction as a driver for seismicity and is calibrated to observed seismicity and production rates. It is capable to forecast seismicity under different production scenarios. However, the performance of the model is mixed, its ability to be used in mitigation in the context of the 'Hand aan de kraan' protocol limited, and in past reviews it has been pointed out that relying only on one possible modelling approach is too limited and may not well represent the uncertainties (both epistemic and aleatory) in the forecasting. The Te NAM existing seismogenic model is also the part of the risk train least influenced or reviewed by external experts so far. Finally, the model is not considering fault information within the reservoir nor does it consider faults outside of the reservoir (in particular above and below), which may also be re-activated through production.

To be able to assess seismic risk under different production scenarios it is important to research how the existing method can be improved or alternatives could be applied.

Research Question

The objective of this research is to review existing seismicity modelling approach and to define improve the approach and seismicity modelling tool(s) to better predict seismicity under different time- and space varying gas production and rate regimes, including the potential for re-activation of faults outside the immediate reservoir. The work should be structure into three parts:

Task 1: Review of the existing NAM seismogenic source model

- Provide a comprehensive critical review of the modelling approach used by NAM for the Groningen induced seismicity. The review should discuss all relevant model elements of the seismogenic source model, including for example the b-values evolution, strain thickening, the smoothing, declustering etc.
- The review should discuss strength and weaknesses of the approach chosen, but also evaluate quantitatively the performance of the model against subsequent observations.
- It is not expected to implement the model and this review should not cover GMPE's, site condition or buildings. Discussion of Mmax is also not expected.

Task 2: Review of existing alternative approaches and possible gaps

- Review and discuss all alternative approaches for seismogenic source representation used in other case studies of induced seismicity and compare their strength and limitations relative to the Groningen case (in terms for example of data availability) data and existing NAM model. An expert judgement of the applicability of each alternative modelling to the Groningen case is expected. This includes statistical models, data driven approaches, geomechanical/physics-based modeling or hybrid approaches.
- Discuss possible gaps in current modeling approaches and relevant major gaps in knowledge. For example: So far, research projects have been focussing on faults in the reservoir (Slochteren Formation) as the source of man-

induced earth quakes. Could shallower faults (e.g. as seen in Cretaceous Formations) now or in the near future also be sources of induced earthquakes? It is feasible that fault planes above the salt formations be reactivated by continued subsidence or stress build-up caused by earthquakes? What is the potential that faults in the basement, or currently a-seismic areas become activated in the future and how could this be considered in seismicity forecasts? What is the role of relaxation? How can the better correlation of faults and high precision relocated seismicity be exploited?

- This review may be based on literature review, exerts knowledge, expert elicitation but may also include the actual implementation/ try out of selected models or model components to evaluate the feasibility and applicability. Availability of the modelling framework (licenses, code) and computational demands should also be considered.

Task 3: Proposal for alternative seismogenic source representation

- Based on task 1 and 2, propose an alternative seismogenic source modelling approach that adequately represents the existing uncertainties in data and understanding. This could be achieved for example by using a combination of models using logic trees, in a way typically using in probabilistic seismic hazard assessment. Models should reflect on the requirement to be mutually exclusive and cumulatively exhaustive.
- This model or combination of models most also be able to provide seismicity forecast for a range of production scenarios. This proposal could include a discussion or roadmap for a new modeling framework to be developed if deemed necessary.
- Provide a rough implementation roadmap for your proposed approach that discusses which software/codes are available, what developments and resources would be needed, how the calibration of the model or models could be performed, what the data needs of each models are, etc.

Deliverables expected

1. Report on task 1
2. Report on task 2
3. Report on task 3

All deliverables are open access, publication of results is explicitly encouraged.

Timeline

The project is expected to take one year.
Task 1. Delivered 4 months after the start of the project
Task 2. Delivered 8 months after the start of the project
Task 3. Delivered 12 months after the start of the project
We anticipate about 3 project meetings: Initial kick-off, mid-term and an

Expected use

The deliverables will be used as

(i) Input for planning the further development of the seismogenic source module in the Groningen seismic risk model, to be used by NAM and/or TNO.

(ii) Support to SODM and MEA in evaluating the quality and limitations of the existing seismogenic source model and for answering question by the public/media or decision makers.

Expertise and tools preferred for the team

Reservoir engineering and geomechanical expertise is required, along with a proven record of experience in analysing and modelling induced seismicity.

Quality assurance, Organisational and communication requirements

Organisation: Steering and communication by SodM.
Access to all relevant data and software will be assured.
The project will have access to relevant members of the seismogenic source teams at NAM and TNO team.
The KEM panel will review the deliverables.