KEM Research review, evaluation and interpretation (max. 4 pages + annex)

TITLE: *Preliminary assessment of effects of nitrogen injection in depleted reservoirs*

KEM Quality review

Description of the scientific quality of the results (team, research method, research results, quality of the products, …), if needed external review result (project evaluation text website)

This project was set up as a follow up to KEM-24 project, entitled "Effect of pressure maintenance by fluid injection on seismic risk". The goal of that project was to investigate potential effects of fluid injection on the expected seismicity risk profile. At the end of that project, a conclusive judgement on the value of fluid injection for reservoir pressure maintenance of and reducing seismic hazard could not be made. However, indications for the potential positive effects of gas injection, especially nitrogen, were found. So, the objective of this follow-up project was to establish whether a large-scale injection of nitrogen gas into the depleted Groningen gas field can decrease the number of earthquakes, and consequently reduce the seismic hazard and risk.

The project was contracted to TNO. It started in December 2023, the draft final report was submitted in July 2024, and the final report was submitted in October 2024. The research team expertise covered all areas of the project in a very good manner. The research team members were knowledgeable and skilled in their research areas and invested time and effort in all work packages. The work performed by the research team has been of high quality. The final report is well written and well structured.

Various parts of the project and the corresponding ***research methods and research results*** were as follows:

1. ***A literature study***, which was centred around three main goals: i) summarizing the available knowledge on injection-induced seismicity and risk mitigation strategies, ii) identifying analogous cases (e.g., gas storage) and providing lessons learned that are relevant to the Groningen case, iii) describing differences with other injection activities (e.g., wastewater disposal) and what those differences imply for mitigation strategies.
The study showed that the injection of nitrogen into a depleted gas reservoir with the aim of reducing seismicity has not been done anywhere in the world. Nevertheless, the magnitudes of seismic events observed in cases of fluid injection that are relatively analogous to the Groningen case (in terms of expected possible geomechanical failure mechanisms, injection depth, and reservoir properties), have been relatively small (magnitudes ≤ 1.7). This has been so far the case also in other projects in the Netherlands, such as underground gas storage, geothermal heat production, and production water disposal. However, the Groningen case has its own characteristics, and a reliable analogue doesn't exist.

2. ***Identification of scenarios for nitrogen injection***. Relatively simple injection scenarios were considered, assuming constant nitrogen generation and constant and uniform gas injection rates. Compositional and thermal effects were not included in the main scenarios. In total, eight injection scenarios were considered. The unit of gas injection rate was selected to be 1 ZB = 1,58 billion m^3/year (equivalent to the production capacity of Zuidbroek nitrogen factory). In three scenarios, the injection rates were set to 1 ZB. In five other scenarios, injection rates of 10 ZB were considered. The latter scenarios, although unfeasible based on current situation, were considered to determine the upper bound of nitrogen injection effect and to illustrate some mechanisms associated with re-pressurization and their impact on seismicity. The effect of each scenario on the re-pressurization of the reservoir was determined using Eclipse 100 simulation model. Additional simple calculations (for a single-cell box) were performed using Eclipse 300 model, to account for compositional effects on pressure (or volume) results.
Results show that nitrogen injection at rates currently possible will result in a noticeable pressure increase (up to 90 psi over 30 years of injection) compared to no injection, and will lead to a reduced pressure gradient across the field. With 10 times larger injection rates, the pressure increase will be much faster and much higher (up to 700 psi over 30 years of injection). Regarding compositional effects, it was found that the injection of nitrogen gas mixture containing light gaseous hydrocarbons, CO2, and water vapor will result in a faster increase in pressure than injecting pure nitrogen.

3. ***Seismic hazard and risk analysis***, which considered the potential beneficial effects of gas injection and the resulting pressure changes on the overall seismicity. This research was done using the TNO Model chain for Groningen.
Results show that the injection of nitrogen can lead to a reduction of predicted seismicity compared to no injection case. The reduction is significantly larger for higher injection rates. Correspondingly, there is a significant reduction in the seismic risk and the number of buildings that do not conform to the safety norm decreases significantly. The extent of possible reduction depends on the injection rates, spatial and temporal injection patterns, and the duration of injection. It should be emphasized that, in reaching these conclusions, only beneficial effects were considered in the project. Therefore, these results cannot be considered conclusive with respect to the effects on hazard and risk.

4. ***Exploring necessary adjustments to the seismic source model***. Using the theory of linear poroelasticity, combined with thermal effects, and characteristics of the Groningen reservoir (its permeability, current pressures, faults, etc.), the need for improving the current seismic source model was investigated. This is particularly important for investigating potential negative effects of nitrogen injection. It is concluded that the source model, which is a linearly elastic model, should be updated by adding a non-linear rate-type compaction branch to it. This will allow for including potential consequences of temperature reduction due to injection, which is potentially significant for determining full range of effects of nitrogen injection.

KEM Evaluation of the results

Evaluation whether the research questions are addressed adequately (questions answered, precision and uncertainties on outcomes, potential consequences on current practice addressed, ..) (project evaluation text website)

Below, specific research questions of the study are listed, and answers to those questions are mentioned:

1. *What can be learned from examples of fluid (including gas) injection in reservoirs similar to the Groningen reservoir?*
The magnitudes of seismic events observed in cases of fluid injection (e.g., underground gas storage, geothermal heat production, and production water disposal) in situations that are relatively analogous to the Groningen have been relatively small.

2. *Which injection scenarios for mitigating seismicity could be applied after production has stopped?*
High-rate continuous injection with a judiciously chosen spatial pattern should be considered.

3. *How can the existing SHRA (Seismic Hazard and Risk Assessment, https://www.nlog.nl/publieke-sdra-groningen) model chain be adapted to include fluid injection?*
The current seismic source model has been developed for the simulation of gas production, and has been calibrated on seismicity generated by gas production. Thus, it does not account for certain processes that are relevant in the case of gas injection. So, the source model should be updated to make it suitable for the study of nitrogen injection. In particular, non-linear rate-dependent deformation and thermal effects should be included. Also, compositional effects must be accounted for. These modifications are feasible.

4. What is the potential beneficial effect of fluid injection on the overall seismicity, seismic hazard and seismic risk?
If the injection of nitrogen has a potential for reduction of overall seismicity, seismic hazard and seismic risk cannot be established on this project alone, as the potential adverse effect of injection were not considered.

While, this study has been limited in scope, all research questions have been effectively addressed. The study has investigated beneficial effects of nitrogen injection only. It has worked with simple injection scenarios with very simple spatial distribution of injection wells. The model that is used here had been developed for the simulation of gas production, and not gas injection into a depleted gas reservoir. Therefore, some potentially significant effects, such as compositional and thermal effects, have not been included.

KEM interpretation of the outcome

The interpretation of the results (consequences on methods/data to be used in practice, con risk instrument modules, on inspection procedures and operator procedures, ..) (project evaluation text website)

Based on the results of this study, nitrogen injection could possibly be an option for reducing seismic risk and hazard of the Groningen reservoir region. However, determining its feasibility requires a comprehensive study and cost-benefit analysis, using suitable models that account for nonlinear deformation, thermal and compositional effects, so that potential negative consequences can be fully quantified. Also, aspects related to the required volumes of nitrogen and the potential for its production and technological requirements need to be investigated.

KEM interpretation of the outcome

A summary in simple terms of the goal, the outcome and impact on mining policies or toolboxes of the research project (project evaluation text website)

This project was set up as a follow up to KEM-24 project (which was entitled "Effect of pressure maintenance by fluid injection on seismic risk"). At the end of that project, a conclusive judgement on the value of fluid injection for reservoir pressure maintenance of and reducing seismic hazard could not be made. However, indications for the potential (only) positive effects of gas injection, especially nitrogen, were found. So, the objective of this follow-up project was to establish whether a large-scale injection of nitrogen gas into the depleted Groningen gas field can decrease the number of earthquakes, and consequently reduce the seismic hazard and risk. In other words, at this stage, only potential beneficial effects of nitrogen injection were studied.

There were four research tasks in this project. Those tasks and results can be summarized as follows.
A literature study, in which the available knowledge on fluid-injection-induced seismicity and risk mitigation strategies was compiled, with particular attention on lessons that can be learned from existing cases (e.g., wastewater disposal, gas storage, geothermal heat production) and are relevant to the Groningen case. The study showed that the injection of nitrogen into a depleted gas reservoir with the aim of reducing seismicity has not been done anywhere in the world. Nevertheless, the magnitudes of seismic events observed in cases of fluid injection that are relatively analogous to the Groningen case (in terms of expected possible geomechanical failure mechanisms, injection depth, and reservoir properties) have been relatively small (magnitudes ≤ 1.7).

Identification of scenarios for nitrogen injection. In total, eight scenarios were considered. The unit of gas injection rate was selected to be 1 ZB = 1,58 billion m^3/year (equivalent to the production capacity of Zuidbroek nitrogen factory). In three scenarios, the injection rates were set to 1 ZB. In five other scenarios, injection rates of 10 ZB were considered. The latter scenarios, although unfeasible based on current nitrogen production capacities, were considered to determine the upper bound of nitrogen injection effect and to illustrate some mechanisms associated with re-pressurization and their impact on seismicity. Results show that nitrogen injection at rates currently possible will result in a noticeable pressure increase (up to 90 psi over 30 years of injection) compared to no injection, and will lead to a reduced pressure gradient across the field. With 10 times larger injection rates, the pressure increase will be much faster and much higher (up to 700 psi over 30 years of injection).

Seismic hazard and risk analysis, which considered the potential (only) beneficial effects of gas injection and the resulting pressure changes on the overall seismicity. Results show that the injection of nitrogen can lead to a reduction of predicted seismicity compared to no injection case. The reduction is significantly larger for higher injection rates. Correspondingly, there is a significant reduction in the seismic risk and the number of buildings that do not conform to the safety norm decreases significantly. The extent of possible reduction depends on the injection rates, spatial and temporal injection patterns, and the duration of injection. However, negative effects should be added for conclusive results on this matter.

Exploring necessary adjustments to the seismic source model. The need for improving the current seismic source model was investigated, with particular attention on the ability to investigate potential negative effects of nitrogen injection. It was concluded that the source model should be updated by adding a non-linear rate-type compaction branch, so that potential consequences of temperature reduction due to injection can be investigated.

In summary, the injection of nitrogen seems to have a potential for reduction of overall seismicity. However, seismic hazard and seismic risk cannot be established on this project alone, as the potential adverse effects of injection were not considered. Determining the feasibility of risk reduction requires a comprehensive study and cost-benefit analysis, using suitable models that account for nonlinear deformation, thermal and compositional effects, so that potential negative consequences can be fully quantified. Also, aspects related to the required volumes of nitrogen and the potential for its production and technological requirements need to be investigated.