KEM Research review, evaluation and interpretation (max. 4 pages + annex)			
TITLE *Effect of pressure maintenance by fluid injection on seismic risk*			
Title acronym	*Long term fluid migration, leakage risks and monitoring strategies*		
Initiator	*EZK*		
Project owner	*Mariska Schimmel*		
Contact person	*Karin van Thienen-Visser*	**Max. duration**	*X man month*
KEM subtheme	*Seismicity*	**Est. Budget**	*XX range in euros*
KEM project code	*KEM-24*	**Contractors**	*See below*
Research category	*ST/MT*	**Contractors**	*second*
Risk instr. Innovation	*yes*	**Contractors**	*third*

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)

The objectives of this project were twofold: i) to investigate and identify the best method of modelling and quantifying the effect of fluid injection on the expected seismicity risk profile, ii) to find a reliable method to assess possible additional seismic risks associated with fluid injection itself (as it might locally trigger seismicity) and to determine which factors, circumstances or injection configuration and volumes may increase the probability of seismicity and vice versa. Injection fluids to be considered were N_2, CO_2 and water, or a mixture of natural gas and one of the injected fluids. Also, different injection scheme options, including reusing existing production facilities, had to be considered. The overall objective was to assess whether the net effect of fluid injection on the seismic risk profile can be positive and to give recommendations to optimise the risk reduction at minimum injection costs. Specific research questions of the study were as follows:

1. What are possible injection scenarios for pressure maintenance during production and for minimising the pressure difference across the field once production has stopped?
2. What are the reservoir stresses and pressures for various fluid injection scenarios (defined in question 1) around wells and over the entire gas field?
3. How to adapt the Groningen seismic model for injection for pressure increase as well as pressure decrease?
4. What is the effect of fluid injection on the overall seismic risk?
5. What is the effect of fluid injection on seismicity near injection wells?
6. What is the most optimal configuration of injection wells?
7. What is the overall effect of fluid injection on seismicity and what are the recommendations for the Groningen HRA model?

The project was contracted to a consortium of Fugro and Dynafrax companies, with Fugro in charge of the project management. The project started in August 2020 and the final reports were submitted in August 2022.

The project consisted of five main work packages: i) Modelling of production-induced seismicity in Groningen gas field using 2D hydro-mechanical coupled discrete element modelling, ii) Modelling of various fluid injection scenarios in the Groningen gas field and induced seismicity using 2D hydro-mechanical coupled discrete element modelling, iii) Modelling of multiphase/gas-mixture injection using TOUGH3, iv) Modelling of fluid injection induced fault activation using 3D hydro-mechanical coupled discrete element model, v) Induced seismic hazard and risk assessment (HRA). In addition to the main tasks, a preliminary task was added as WP0: literature review and compilation of input data/parameters for Groningen gas field modelling.

The research team expertise covered all areas of the project quite well. The research team members were knowledgeable and skilled in their research areas and invested time and effort in all work packages. However, not all research questions and modelling tasks could be addressed (see below). The research tools that were originally mentioned in the proposal (namely PFC3D and TOUGH3) for numerical modelling could not be used due to computational costs. As a result, some of the original research questions (see above) have been only partially answered or have remained unanswered. Relevant conclusions and recommendations are provided based on (somewhat incomplete) results. The amount of work performed by the research team has been high. The final reports are well written and well structured.

Optional: Confidential comments and recommendation for EZK and SodM (KEM only)

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)

The deliverables are presented in three final reports: a 35-page report on literature review and input data compilation, a 121-page report on numerical modelling of pressure evolution during reservoir depletion and for various injection scenarios, and a 64-page report on the effect of fluid injection on seismic hazard. In addition, an umbrella report in two versions, Dutch and English, has been provided. This umbrella report provides a useful summary of the research objectives, methodologies, results, conclusions, and recommendations. Results presented in the three reports are briefly described below.

1. The presented literature review is not so much about the review of literature on fluid injection techniques and/or case studies, but it is a compilation of literature that contained input data/parameters for Groningen gas field modelling. It provides a useful compilation of data that was needed for the numerical modelling. While many essential data was collected, there are input data/parameters, specially related to faults properties and seismic modelling, that are simply not available. This has had adverse effect on modelling capabilities.

2. The numerical study report is well written and well-structured. Preparation and selection of input data has been done carefully. Unfortunately, not all necessary data, specially parameters needed for reliable modelling of seismic effects, could be obtained. The report contains accounts of 2D modelling of the entire Groningen gas field (using PFC2D), for the depletion period until 2020, and for determining future seismicity for a period of 30 years after stopping production either at 2010 or 2020. Results of depletion period are compared to observed data. An acceptable match is found between the simulated and observed seismicity for the time period between 1990 and 2020 for the seismic events with ML larger than 2.0. This, however, seems to have been possible at the expense of getting too high-pressure values compared to observed pressures, as the simulated pressure distribution doesn't match the observed one. Results of PFC2D modelling shows that after stopping production considerably fewer seismic events will occur.

Effect of fluid injection on future seismicity has been simulated using PFC2D code. First, a comparison is made between injecting CO_2 versus injecting N_2. The simulation considers injection of fluid in the east central region only for a period of 15 years after production stop in 2020 (all other regions no production and no injection), and then simulates pressure evolution and seismicity for another 15 years after total shut in. Results showed that CO_2 injection does not lead to significant pressure increase whereas N_2 does so specially near injection points. On the other hand, N_2 injection results in larger induced seismicity in areas of pressure increase. It was concluded that N_2 injection would be a more effective measure for increasing the reservoir pressure in highly depleted areas. Therefore, four hypothetical injection scenarios were defined based on injecting N_2. The scenarios differed in terms of different combination of injection in some regions and continued production in some other regions, or injection in some regions and total stop of production. In all scenarios, it was found that the largest magnitude seismic event occurred at the Loppersum region.

The only three-dimensional simulation of fluid injection scenarios that could be carried out was the simulation of fluid pressure distribution using TOUGH3 code. Two hypothetical scenarios of injection CO_2 or N_2 were studied. Findings corroborated results of PFC2D modelling. That is, the reservoir pressure increases (as intended for pressure maintenance purposes) is significantly more when N2 is injected.

3. The seismic hazard report contains a good review of previous regional seismic hazard studies, the methodology for probabilistic seismic hazard analysis, a summary of the characteristics of the developed seismic catalogue as well as an induced seismicity catalogue for four different injection scenarios, details of two seismotectonic models and an induced seismicity model based on seismic catalogues for four different injection scenarios, separate ground motion prediction equations for natural and induced seismicity, and finally results of probabilistic induced seismicity modelling. The study considered the four hypothetical scenarios of injecting N_2 that were defined in PFC2D modelling. A seismic occurrence distribution has been determined for each one of the four injection scenarios and for two periods of time (injection time only or injection with a shut-in period), and the results are used to estimate the seismic hazard. In all cases, it was found that the seismic occurrence distribution shows higher seismic activity levels than the natural seismotectonic zone. However, induced seismic activity hazard will be still very low. It was also found that the induced change in seismic hazard will occur for a short period only (1, 5 or 10 years depending on the scenario chosen) and then seismic hazard returns to its natural baseline. This modelling work is sound but its value is limited by the input data.

Optional: Confidential comments and recommendation for EZK and SodM (KEM only)

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, answers to the original research questions can be summarized as follows:

1. Regarding possible injection scenarios for pressure maintenance during production, it is not possible to give a definite answer. Injection should be avoided near the Loppersum area because of the stress-criticality of Loppersum fault system and near production wells in order to avoid sharp pressure variations.
Regarding possible injection scenarios after stopping production, it is concluded that seismic activities will decrease sharply after shut in anyway and injection will not lead to any significant reduction of seismicity.

2. Regarding the evolution of reservoir stresses and pressures for various fluid injection scenarios, no conclusive recommendation can be made.

3. The question of how to adapt the Groningen seismic module for injection to account for pressure increase or decrease cannot be answered.

4. Regarding the effect of fluid injection on the overall seismic risk, as mentioned above, fluid injection seems to be not necessary or preferable. In case of opting for injection, the effect will obviously depend on type of injection, injection rate, and location.

5. Regarding fluid injection effect on seismicity near injection wells, no significant seismicity is expected. additional study will be needed.

6. The question of most optimal configuration of injection wells is not really relevant according to this study, as injection has either no effect or is not preferable.

7. Regarding the overall effect of fluid injection on seismicity, no conclusive statement can be made. The fluid injection may be positive during significant production as average depletion and compaction can be stopped.

The main reason that conclusive answers to above questions could not be provided is that the main code used for numerical studies and its underlying assumptions proved not to be quite suitable for simulating Groningen field. The codes PFC2D and PFC3D are based on the Discrete Element Modelling (DEM) approach. DEM simulates the interactions of large pieces of rock with each other and their relative movement. Each rock element is assumed to be spherical with diameters ranging from 180 m to 260 m. DEM is in principle suitable for modelling the stress field and relative movement of pieces rocks. Thus, fault behavior and activation can be modelled based on DEM approach. However, at this scale DEM approach is not suitable for simulating flow of fluids. The fluid flow in PFC2D and PFC3D is simulated as if it occurs in between large masses of rock (which are modelling blocks of PFC2D and PFC3D). This does not represent realistic flow processes that occur within pores of the reservoir. Moreover, as seismicity is significantly affected by the behavior of faults that mainly extend in the vertical direction, on needs to employ a 3D model for this purpose. So, while PFC2D can be used for some preliminary study, it is not really suitable for conclusive study of seismicity. One can argue that the very small thickness of reservoir compared to its horizontal thickness, would justify the 2D assumption; this is, however, acceptable for modelling fluid flow and pressure distribution only and not for seismicity modelling. So, for simulating faults and fault movements, the use of PFC3D would have been necessary. However, due to limitation of PFC3D in modelling fluid flow, the best option would have been to couple TOUGH3 code with PFC3D, as was originally planned. This option, however, proved to be unfeasible due to the high computational effort that was needed.

So, a conclusive judgement on the value of fluid injection for reservoir pressure maintenance and reducing seismic hazard cannot be made yet. Additional research in this regard is recommended. In general, results of this project and its recommendations are useful to the government and the regulators in formulating policies, and determining research priorities related to mitigating measures for seismic risk reduction.

Optional: Confidential comments and recommendation for EZK and SodM (KEM only)

Closure text for the website

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)

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The deliverables are presented in three final reports: a report on literature review and input data compilation, a report on numerical modelling of pressure evolution during reservoir depletion and for various injection scenarios, and a report on the effect of fluid injection on seismic hazard. In addition, an umbrella report in two versions, Dutch and English, has been provided. This umbrella report provides a useful summary of the research objectives, methodologies, results, conclusions, and recommendations.

The research team members of Fugro and Dynafrax were knowledgeable and skilled in their research areas and invested time and effort in all work packages. However, not all research questions and modelling tasks could be addressed (see below). The research tools that were originally mentioned in the proposal (namely PFC3D and TOUGH3) for numerical modelling could not be used due to computational costs. As a result, some of the original research questions have been only partially answered or have remained unanswered.

Based on the results of this study, answers to the original research questions can be summarized as follows:

1. Regarding the overall effect of fluid injection on seismicity no conclusive statement can be made. The fluid injection may be positive during significant production as average depletion and compaction can be stopped. Regarding possible

injection scenarios after stopping production, it is concluded that seismic activities will decrease sharply after shut in anyway and injection will not lead to any significant reduction of seismicity.

2. Regarding possible injection scenarios for pressure maintenance during production, it is not possible to give a definite answer. Injection should be avoided near Loppersum area because of the stress-criticality of Loppersum fault system and near production wells in order to avoid sharp pressure variations.

The main reason that conclusive answers to above questions could not be provided is that the main code used for numerical studies and its underlying assumptions proved not to be quite suitable for simulating Groningen field. The best option for numerical modelling would have been to couple TOUGH3 code with PFC3D, as was originally planned or an alternative code with similar capabilities. The question of how to adapt the Groningen seismic module for injection to account for pressure increase or decrease can therefore not be answered.

Additional research on this topic is recommended to better address the original research questions.