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

TITLE ***Long term fluid migration, leakage risks and monitoring strategies***

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 main objectives of this project were the formulation of a validated approach, and the development of tools, to quantify and predict the long-term effects of hydro-mechanical fluid pressure and stress redistribution in a region hosting gas extraction reservoirs. Another objective was quantifying possibility of subsequent leakage of fluids to groundwater and potentials of ground motions, which could cause risks to drinking water aquifers and the built environment at the surface. The research result had to provide quantitative assessment of long-term leakage hazards for unwanted emissions in drinking water aquifers and at the surface, as well as post abandonment ground motion risks.

The research had to define the regional hazard and risk assessment method and practices, taking into account post abandonment vertical and horizontal pressure (re-)distribution and migration of fluids (gases and formation water) through aquifers, faults and existing abandoned wells. The assessment method also needed to include ground motions (subsidence and small earthquakes) associated with the fluid migration up to the moment that a new equilibrium in the subsurface is reached. It was requested to consider the application of the research to the abandonment of the Groningen gas field.

The project was contracted to a consortium of TNO and Deltares. TNO did project management as well as research work. Deltares conducted the research on leakages.

The work consisted of four main tasks: i) a literature review on processes and impacts associated with long-term fluid migration and wellbore leakage in abandoned gas reservoirs, ii) quantitative analysis of post-abandonment pressure redistribution and its effect on ground motion, iii) quantitative analysis of fluid migration along wells and development of conceptual models for migration along geological pathways, and iv) recommendations for a quantitative risk assessment framework and monitoring strategies for effects of subsurface mining activities in the Netherlands after their abandonment.

The project started in September 2020 and the final reports were submitted in June 2022. The deliverables were presented in two final reports: an 80-page report on literature review, and a 160-page report on the other three tasks.

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 performed all four research tasks with due care and diligence, given the time frame of the project. All relevant issues and questions were addressed, and all deliverables were met. Both quality and quantity of the work performed in this project was high. The literature review was extensive and comprehensive. Numerical studies were performed using proper tools, based on appropriate assumptions/simplifications, and to a sufficient extent. Relevant conclusions and recommendations were provided. The final reports are well written and well structured. So, the project can be judged to have been a success.

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 literature review, presented in the Phase I report, is quite extensive (in terms of references studied) and exhaustive (covering all relevant research questions). It provides a useful overview of i) evidence of connectivity between gas reservoirs and connectivity to adjacent/overlying aquifers and the potential for long-term fluid migration and pressure equilibration, ii) potential leakage of gas to the (near) surface and its consequences, and iii) possible consequences of fluid migration and pressure redistribution in terms of subsidence and seismicity.

The Phase II report starts, after an introduction, with laying out and describing the framework for risk identification and management of gas fields after abandonment. Based on this framework, after establishing the context, four main components were identified: risk identification and screening, quantitative hazard and risk assessment, monitoring and risk treatment, and stakeholder communication and risk review. Given the complexity of gas reservoirs, the multitude of processes involved, and very long spatial/temporal scales, providing such a framework is important as it sets the context and boundary conditions for the extent of the study and selection of research tools and methodology.

To provide data for the quantitative hazard and risk assessment, numerical modelling tools were employed. This resulted in modelling pressure evolution during the gas production phase, and pressure redistribution after abandonment. Afterwards the effect of pressure redistribution on the change of pressure and stress in overlying strata and accompanying uplift and/or subsidence have been properly modelled. Maps of subsidence for various alternative scenarios given the modelling uncertainties have been produced. As a first step toward assessing risk of induced seismicity, potential fault reactivation has been modelled by slip tendency assessment. Two different classes of scenarios have been considered, namely faults with no offset and faults with offset. The largest events in Groningen have been observed on faults with small or zero offset, and for this case, extensive sensitivity analysis was carried out. Numerical modelling of fluid migration along a well with assumed damage in casing have been performed, and other geological pathways have also been evaluated qualitatively considering the

potentials for gas leakage to the (near) surface. Finally, potential interferences with future geothermal energy production, fluids storage projects or salt caverns have been studied.

The wealth of information obtained from hazard identification and quantitative modelling and analyses has been integrated into a workflow for regional hazard assessment and formulating recommendations for regional quantitative risk assessment and monitoring.

The Phase II report is supplemented with four appendices providing details about conceptual modelling of fluid migration along geological pathways, regional pressure distribution modelling, fluid migration along wells, and subsidence, as well information about input data.

The KEM panel considers all research questions to have been adequately addressed and all deliverables to have been provided.

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)

The approach for identifying various hazards and assessment of risks associated with abandoned gas reservoirs is solid and state of the art. Given uncertainties in input data and reservoir characterization as well limitations of numerical modelling, the results are trustworthy. However, due to the regional character of the study, they should be seen as rough first estimates of future developments in terms of occurrence of gas leakage to the (near) surface, ground movement in the form of subsidence and/or induced seismicity, and interference with future geothermal energy production or fluid storage projects. The best use of project results has been to formulate recommendations for future studies and monitoring studies. The project team has done a good job in this regard. Local studies with more detail will be needed to provide specific recommendations for a given site.

The most important conclusions/recommendations are:

- Based on pressure modelling, the maximum subsidence expected after 100 years is between 9 and 13 cm in the area to the northwest of the Groningen field and between 4 to 7 cm to the west of the reservoir.

- Areas with large pressure drops in overlying aquifers and with higher uncertainty, as well as areas with neighbouring smaller depleted gas fields have been identified. In those areas, aquifer pressure monitoring should be carried out and collected data, as well as InSAR data should be used for calibrating the corresponding models.

- Better characterisation of fault geometries and their mechanical and hydraulic properties are needed for further quantitative assessment of fault re-activation and induced seismicity related to specific sites. It is necessary to follow up the present study with more in-depth geomechanical analysis of the aquifers in the southwest and northwest of the Groningen field. The modelling provides limited detail but shows that offset faults and bounding faults which are present in these regions potentially can be reactivated.

- The highly depleted gas reservoir is not a likely source for gas leakage as the pressure is not sufficient to drive upward flow along possible leakage pathways, along wells, or geological pathways. Smaller depleted reservoirs with an active water-drive can re-pressurize the reservoir after abandonment and be a potential leak source. However, even a worst-case scenario of leakage along an extremely damaged well cement sheath would only lead to a leakage rate of a few tons per year. The presence of geological leakage paths seems to be unlikely because of the depleted conditions in the reservoir and the seal conditions.

- Current study of gas migration along wells to the (near) surface has been limited to a typical gas well and the gas plume spreading does not account for the groundwater flow. Even though associated risks are found to be small, a systematic study of all gas wells and their screening for leakage potential (based on their integrity and the presence of pressurized gas pockets) are needed. Afterwards, more site-specific modelling study of vulnerable wells has to be carried out.

Results of this project and its recommendations are useful to the government and the regulators in formulating policies, informing the public, and companies that are involved in subsurface production or storage activities in the Netherlands.

The KEM Panel supports the suggestion of defining and delineating an Area of Influence (AoI) for past and/or ongoing major mining activities (e.g., gas generation) and respecting that domain when designing new subsurface activities (such as geothermal or fluid storage). The KEM Panel further supports a more in-depth analysis of the southwest and northwest aquifers related to hydromechanical properties of the aquifer, nearby gas fields and the related fault system. Priority should be given to the southwest aquifers as the northwest aquifer does not have gas fields nearby and the depletion is mainly below the Wadden Sea so that the consequence of seismic hazard is low.

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)

The goal of the project was to develop a regional hazard and risk assessment approach related to fluid migration and ground motion after the abandonment of multiple gas extraction and/or gas storage reservoirs in the Netherlands. Post-abandonment risks can occur 10's to 100's of years after production at 100's to 1000's of metres away from production sites. Risks which are studied are related to subsidence and uplift, induced seismicity, fluid migration from the reservoir, and interference of depleted reservoirs with new subsurface activities. The project has investigated into all of these factors based on regional data for the Groningen area since this area has multiple gas fields and a lot of data accessible.

For the Groningen gas field, the maximum additional subsidence expected after 100 years is largest to the northwest of the Groningen gas reservoir, between 9 and 13 cm, and to the west of the reservoir, between 4 to 7 cm. The maximum uplift has been calculated to about 1 cm above the southern part of the gas reservoir. There is some uncertainty to these results related to the pressure in the reservoir and the degree to which the aquifer compacts.

Related to the risk of induced seismicity, which can cause damage to the built environment at the surface, it is shown that re-activation of the type of faults which earlier has caused the largest earthquakes in Groningen (faults with no offset) is very unlikely to happen as it would require pressure reductions that are far from what is expected in the aquifers. In aquifer zones with zones of significant pressure reduction, re-activation of other fault types (faults that acts as boundaries to the aquifers and faults with offsets) can occur because of pressure depletion, as confirmed by previous seismic events related to the Groningen field. Additional local analysis is needed in the southwest aquifers of the Groningen field to better assess the seismic risk related to specific sites.

The project has, further, revealed that leakage along wells or geological pathways, which potentially can cause risk to drinking water, is unlikely for the Groningen field. In a worst-case scenario of leakage along a damaged well, the leakage would still be small (a few tons per year into aquifers and the atmosphere). Shallow gas accumulations could be a potential risk of leakage but are to a small degree present in the Groningen area. Further investigation of local sites is necessary to draw a more definite conclusion related to this leakage risk.

The results of the project form basis for defining local risk assessment studies and long-term monitoring strategies in specific regions, also related to possible interference with new subsurface activities.