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

TITLE: ***Cumulative effects due to mining, in general and in the Grijpskerk area (KEM-48)***

KEM Quality review

Description of the scientific quality of the results (team, research method, research results, quality of the products, …), if needed external review.

Research Team

The project was contracted to CRUX Engineering, Geodelta, Q-Con, and Cohere Consultants. CRUX Engineering was in charge of the project management. The quality of the project team is, in general, assessed as high, with team members who have a broad expertise covering various areas of the project: geohydrology, geotechnics, geology, mining, reservoir technology, seismology, and geodesy. Scientific oversight was provided by an advisory group of two scientists affiliated with TU Delft, who have been attached to the project.

The project started in May 2022 and the final draft reports were submitted in November 2023. There were substantial comments from EZK supervisors, KEM panel supervision team and local residents supervision team and a couple of meetings were held to discuss those comments, additional work, how to improve the reports. Final reports were submitted in June 2025.

Research objectives

The overall objective of this project was to determine and clearly formulate the cumulative effects and interactions among different mining activities around the Lauwers Sea trough and the interactions among the UGS Grijpskerk, the surrounding small gas fields, and the Groningen gas field. In particular, the research should have addressed cumulative subsidence effects, induced seismicity, the potential of leakage form wells in the area, and the expected redistribution of reservoir-aquifer pressure and formation water after the abandonment of gas fields in the Grijpskerk area.

The work was divided into two phases:
Phase I with the following objective:
- literature review focussing on subsidence, induced seismicity, methane leakage, cumulative interactions among those processes, and their effects on the surface,
- obtaining input from local stakeholders, and
- developing the Phase II research plan.

Phase II with the following objective:
- analysing the impacts of gas extraction and gas storage in the Grijpskerk area, including their cumulative effects for both past activities and projected into the future, employing a comprehensive model-driven approach, accounting for subsidence aspects, induced seismicity, methane leakage, and other sources,
- analysing possible indirect impacts from the mining activities in terms of shallow subsidence and the effects on groundwater and methane leakage.

Research methodology

Phase I study: The research in Phase I relies on a structured literature review and a feasibility assessment of innovative methodologies. The literature study is comprehensive and addresses: subsidence (natural and anthropogenic), induced seismicity, methane leakage, cumulative and interactive effects, monitoring techniques, and modelling approaches.
The study applies clearly defined classification schemes (e.g., shallow vs. deep subsidence), integrates empirical data (e.g., NAP elevation benchmarks), and discusses a variety of modelling approaches (poroelastic, geotechnical, semi-analytical, etc.).
In the feasibility study, the novel DELTA method is introduced, which utilizes raw NAP data for subsidence analysis with improved precision. This innovation strengthens the methodological quality and is a promising foundation for Phase II.

Phase II study: The methodological framework of Phase II is a system-oriented integration of monitoring, modeling, and interpretation tools aimed at assessing cumulative effects in the Grijpskerk area. The following studies have been performed:
- Geodetic analysis: high-resolution evaluation of subsidence and surface deformation using raw NAP data and the DELTA method developed in Phase I.
- Reservoir compaction modeling: modeling of gas extraction–induced deformation and subsidence was performed using a simple linear-elastic compaction model. Results were compared against field data.
- Seismicity assessment: probabilistic and deterministic evaluation of induced earthquakes in relation to gas field

operations, with considerations of magnitude thresholds and source mechanisms.
- Leakage pathway identification: conceptual assessment of pressure migration and well integrity, supplemented by fault and wellbore data.
- Interaction zone mapping: The interactions between the Grijpskerk UGS, nearby fields (e.g. Pieterzijl and Kommerzijl), and the Groningen gas field are evaluated by comparing their respective pressure, subsidence, and stress footprints, and by mapping zones of overlap and influence. Innovative use of lateral and vertical distance buffers to infer potential coupling between subsurface activities.

Research results
Phase I study: The findings of Phase I provide a systematic synthesis of: the magnitudes and causes of subsidence and seismicity across different depths and origins, the significance of well integrity and fault structures for methane leakage, the mechanisms and spatial extents of interaction zones between mining activities.
The results are well-structured, extensively referenced, and contextualized within national research (e.g., DeepNL and previous KEM projects). The report integrates scientific insights with stakeholder concerns, particularly in relation to the Grijpskerk region.

Phase II study: The scientific findings presented are well-structured and cover:
- Quantification of compaction and deep subsidence in the Grijpskerk area from multiple gas fields, with spatial footprints of subsidence modeled over time.
- Quantification of compaction and deep subsidence from Grijpskerk UGS and its radius of influence.
- Quantification of shallow subsidence rate, also based on InSAR data.
- Mapping of induced seismicity probabilities and evaluation of existing data on earthquakes and vibrations.
- Interpretation of uncertainties related to input parameters (e.g., InSAR observations, shallow subsurface maps, compaction coefficients, boundary conditions, fault transmissivity), modelling results, and water management practices.

Recommendations for risk mitigation and monitoring strategies, tailored to different stakeholder concerns (e.g., damage to buildings, groundwater salinization, public perception).

Quality of the products
The deliverables were presented in two final reports and two collections of documents:
- A Phase I report of 239 pages on literature review (task i), including an executive summary in English and Dutch, and eight appendices. Also, a structured project plan for Phase II, including specific modelling strategies and workflows was included.
- A Phase II report of 106 pages, presenting results of tasks (ii)-(iv).
- A collection of 75 maps and illustrations.
- A collection of documents providing detailed information about the bike excursion that was held at the start of the project.

These deliverables are clearly presented, scientifically robust, and directly tied to the project objectives. The inclusion of an English executive summary, structured annexes, and auxiliary documents enhance accessibility and traceability. The quality of analysis is high: each module (subsidence, seismicity, leakage) follows a consistent problem-definition–method–result–conclusion structure, ensuring traceability and scientific clarity.

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,

Phase I
Below, we mention each research question first and then provide our evaluation of the study regarding how well it has been addressed.
Research Question I.1. ***What is known about the interactions between different adjacent underground activities and the cumulative effect of those interactions? The following topics should be addressed separately: a. Subsidence, b. Induced seismicity, c. Leakage, d. Other.***
Research Question I.1.a. The report presents a comprehensive synthesis of both natural and anthropogenic causes of subsidence. It classifies processes into shallow, intermediate, and deep mechanisms and quantifies the expected rates of each (e.g., shallow anthropogenic: 12 mm/year; gas storage: up to 20 mm/year). The interactions between different sources of subsidence are clearly explained, including:

- The superposition of effects from gas extraction, salt mining, and groundwater extraction.
- Use of literature, case studies, and observational data to demonstrate real-world interactions (e.g., subsidence in Veendam area).

- Explanation of modelling limitations, e.g., compaction coefficient uncertainties, spatial variability.

This research question is adequately addressed with precision and illustrative case studies. Uncertainties are acknowledged, especially concerning the spatial variation and limitations of current models.

Research Question I.1.b. Induced Seismicity

The report extensively reviews induced seismicity caused by: gas extraction, gas storage (pressure cycling), geothermal exploitation, water injection, and hydraulic fracturing.

It identifies key mechanisms, such as stress transfer, fault activation, and static/dynamic triggering, and explains detection limitations in densely exploited regions. Examples from the Groningen field and international projects are integrated.

This research question is adequately addressed. The difficulty of attributing seismicity to specific sources is explicitly addressed. Model sensitivity and observational uncertainties are discussed.

Research Question I.1.c. Leakage

The report explores wellbore leakage, fault-related leakage, and long-term fluid migration, particularly in decommissioned wells. It provides a well-structured overview of causes (e.g., poor cementation, aging infrastructure), risk factors, and knowledge from international experience.

The cumulative effects, such as pressure redistribution between fields and multi-decadal to centennial migration in systems like Groningen, are highlighted as areas needing more study.

This research question is adequately addressed. Leakage uncertainties and knowledge gaps are explicitly acknowledged, with appropriate recommendations for further research.

Research Question I.1.d. Other Interactions

Additional interactions considered include:

- Feedbacks between subsidence and groundwater levels
- Shallow geohydrological processes (e.g., salinization, aquifer pressure changes)
- Low-frequency vibrations and infrastructure response

  These are outlined in Chapter 9 as "topics for Phase II" based on stakeholder consultation and field visits.

This research question is addressed to an appropriate extent for Phase I. The distinction between major topics and emerging concerns is well-handled.

Research Question I.2. *What is the distance (both in depth as well as lateral) which would exclude cumulative effects between mining activities for subsidence, induced seismicity, leakage, and other?*

This question is addressed in Chapter 6 ("Interactions and Influence Distances"). Lateral influence zones and factors affecting them are discussed in details for: deep oil/gas extraction, salt mining, vibrations from infrastructure, Regarding vertical interactions, effects coming from faults or compromised wellbores, pressure communication between stratigraphic layers, and lithological barriers and sealing formations are discussed.

The report stresses that defining safe separation distances is highly site-specific, depending on geology, operation type, and monitoring data. It provides general guidance and uses diagrams (e.g., Figure 31) to illustrate interactions.

Research Question I.3. What should be studied in more detail in Phase II for the Grijpskerk area?" (Including a project plan with research questions, use of Phase I results, methodology, and planning.

This is addressed in detail in Chapters 7–9, which together form the Project Plan for Phase II.

In Chapter 7, The case study area Grijpskerk is described in terms of its geology, landscape, human impact, and subsurface activity footprint. Results of field observations (bicycle tour, stakeholder input) are used to identify concerns and data gaps.

In Chapter 8, the main approach for a comprehensive feasibility study is presented. In particular, the DELTA method for subsidence modelling using raw NAP data is introduced, and its successful application in the Annerveen area is demonstrated. Thus, the groundwork for expanding the method to Grijpskerk area is established.

In Chapter 9, recommendations and workflows for Phase II are formulated. The following research topics are identified: inelastic reservoir compaction, methane leakage pathways, effect of salinization and sea-level rise, and impact on aquifers and infrastructure

It is explained how results of Phase I literature review and data analysis directly inform the Phase II modelling strategy, and helps to identify knowledge gaps guide prioritization.

Workflows are defined for: geodetic data assimilation, seismicity observation and interpretation, and infrastructure impact assessment.

A phased, multi-topic investigation planning for Phase II is proposed with clear deliverables, modelling strategies, and stakeholder engagement points. The Phase II plan is detailed, methodologically sound, and builds logically on Phase I outcomes. It integrates stakeholder feedback and technical innovation, providing a strong bridge between literature study and applied modelling.

Phase II.

The main research question is: **What are the cumulative effects and interactions of the different specific mining activities (subsurface and surface) around the Lauwers Sea trough and the interaction of the UGS Grijpskerk, the surrounding small gas fields and the Groningen gas field? The sub-questions are as follows:**

a. Subsidence:

- Deep subsidence in the Grijpskerk area over the last 66 years ranges between 1 and 9 centimetres, with seasonal variations of approximately 0.5 centimetres. This amounts to a subsidence rate of 0.2 to 1.8 mm/yr.
- Additional subsidence in the future (by 2035) is found to be in the order of 5 mm. In this figure, potential aquifer compaction around the Groningen gas field is not taken into account.
- Effects due to mining activities, e.g. drilling, operation and abandonment, are deemed to be significant in contributing to subsidence.
- Deep subsidence due to the gas storage from InSAR measurements over a 7-year period, is found to less than 0.5 cm and diminish beyond a 5-kilometer radius from the UGS site.
- The autonomous shallow subsidence rate, mainly caused by shallow soil compaction, is approximately 2 mm/yr.
- Effects related to liquid loading, salt creep and lateral fluid migration are considered to be negligible and are not investigated.
- Regarding changes in surface water levels and freeboard level due to deep subsidence, they fall largely within the operational error margins (due to water management practices) and are thus considered insignificant. However, the deep subsidence may contribute to relative sea-level rise, increasing the burden on pumping stations.
- The cumulative predicted effects of a 0.5 m sea-level rise, land subsidence, and autonomous processes together on salinization may occur locally in the northern part of the project area. Even there, this effect is expected to be counteracted by the ongoing movement of the fresh-saltwater interface.
- In areas with peat soil, shallow subsidence maybe significant and cumulative effects should be better quantified.
- Vibrations caused by gas transportation pipelines and other infrastructure is not expected to contribute to soil compaction.
- The effect of subsidence and seismic events on the water holding capacity of water supply aquifers is expected to be negligible.
- As the indirect effects of deep subsidence on the shallow subsurface is insignificant, it impact on local infrastructure is negligible at the spatial scale of the study (this implies that local effects may occur).

b. Induced Seismicity:

- While subsurface activities (drilling, hydraulic stimulation, fracking, and water injection) can cause local stress perturbations, they are not considered to have produced detectable seismic events in the project area.
- The pressure communication between the UGS Grijpskerk and surrounding small fields, such as Kommerzijl and Pieterzijl cannot have caused the observed induced seismic events. Those events are easily explained by other causes.
- Dynamic stress from induced earthquakes in the Netherlands is too small to trigger distant events, and static stress effects are very localized (negligible beyond ~1.75 km). Thus, induced earthquakes are not expected to lead to interactions among different subsurface activities and fields.
- The question of whether permanent changes in permeability of faults may occur due to seismicity or fracking was studied in Phase I. The answer is that seismicity may cause fault permeability changes (an increase due to fracturing rocks or a decrease due to deposition of sheared clay-like material) and fracking can increase permeability near faults.
- The enhanced pressure decrease close to a well is not expected to be an additional source of seismicity in the reservoir. Also, no subsidence signature was found nearby wells.
- The Grijpskerk UGS operation (switching from gas injection to production and vice versa) cannot be linked to any seismic activity in the area.
- The research question on potential effects of specific soils on amplification of the seismicity signal in Grijpskerk area is not explicitly answered because this effect is already included in the GMM for hazard assessment for Groningen, and the upcoming KNMI PGV model for small gas fields will incorporate amplification too.

c. Leakage

- The risk of uncontrolled methane leakage from wells in the Grijpskerk area remains minimal due to robust safety measures, except possibly for the well GRK-43, which is not further studied in this project.
- The reservoir-aquifer pressure and formation water redistribution after the abandonment of gas fields in the Grijpskerk area is not a significant issue within the project area, except for the far eastern rim around the Groningen Gas Field.

d. Additional questions

- Discrepancies in published UGS Grijpskerk production data (between NLOG and European gas productions data) are found to be within a few percent and thus deemed to have no significant effect on results of the study.
- There are vibrations reported by local citizens that are not associated with earthquakes reported by the KNMI. They are not expected to be caused by earthquakes occurring at a depth of several kilometers. The likely causes of those felt vibrations must of a local origin at or near the Earth's surface, such as strong wind or traffic.
- Can the extraction of cushion gas before abandonment pose an augmented risk for subsidence and induced seismicity events? The answer to this question is found to be "yes".
- Are there clay soils in the project area that are susceptible to swelling and shrinking? The answer to this question is found to be: yes, there are susceptible areas, where the clay thickness is large. This is specially the case in the south and southwest of the project area due to the presence of peat layers.
- Do the deeper (over) consolidated clays such as the Pottery Clay ("Potklei") also contribute to swell-shrink deformations of building foundations? The answer to this question is negative because this clay is pre-consolidated and it is found at greater depths in the Grijpskerk area.
- Is there any cumulative effect expected between swelling and shrinking and deep subsidence due to gas extraction? The answer to this question is negative.
- Can movement in the underlying reservoirs and UGS or salt creep in the Zechstein formation trigger movement in the shallower faults? And if so, what could be the impact at the surface? Can it create seismicity? The answer to this question is negative.
- How do the identified risks of mining-induced damage compare with the non-mining-related processes in the region? The response is that damage from mining-related subsidence is likely to be overshadowed by shallow processes.

KEM interpretation of the outcome

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

This project aimed to understand the combined (cumulative) impacts of different mining and subsurface activities in and around the Grijpskerk area and the Lauwers Sea trough. The following effects were considered: subsidence (ground sinking), induced earthquakes, methane or gas leakage, pressure changes in reservoirs and aquifers, and how different fields influence each other (e.g., Groningen gas field, Grijpskerk UGS storage, nearby small fields). The goal was not just to study each effect, but to see how they interact and add up over time.
The study shows that gas extraction and storage activities around Grijpskerk and the Lauwers Sea trough have caused only small and predictable effects. All observed earthquakes can be attributed to gas production from Groningen field or from small fields in the project area (Kommerzijl, Munnekezijl, and Grijpskerk). There are no indications of induced seismicity due to other gas-related subsurface operations (drilling, hydraulic stimulation, hydraulic fracturing, and water injection). The risk of methane leakage is considered to be very low. Different mining projects in the area do not appear to reinforce each other's impacts.
The study in this project had a generic nature. For each specific site and specific project, one must carry out detailed studies and employ integrated assessment methods that look at deep subsidence, leakage, pressure development, and shallow subsidence effects together rather than separately. In preparation for such studies, even small effects must be monitored carefully and locally, using tools such as InSAR, GNSS and pressure monitoring.
These insights support the development of smarter mining policies and monitoring systems, with more transparency, better coordination between operators, and attention to site-specific risks—especially when fields are closed or used for other purposes such as (gas) storage.
In short: while the current situation is stable, one must continuously improve the way that mining effects are assessed and monitored to stay ahead of future challenges.

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.

This project aimed to understand the combined (cumulative) impacts of different mining and subsurface activities in and around the Grijpskerk area and the Lauwers Sea trough. The following effects were considered: Subsidence (ground sinking), Induced earthquakes, Methane or gas leakage, Pressure changes in reservoirs and aquifers, How different fields influence each other (e.g., Groningen gas field, Grijpskerk UGS storage, nearby small fields). The goal was not just to study each effect, but to see how they interact and add up over time.
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The study in this project had a generic nature. For each specific site, one must carry out detailed studies and employ integrated assessment methods that look at deep subsidence, leakage, pressure development, and shallow subsidence effects together rather than separately. In preparation for such studies, even small effects must be monitored carefully and locally, using tools such as InSAR, GNSS and pressure monitoring.
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