

KEM Research review, evaluation and interpretation (max. 4 pages + annex)			
TITLE <i>Geomechanical factors determining fault criticality during pressure cycling of underground gas storage in reservoirs.</i>			
Title acronym	Gas storage geomechanical bounds for pressure cycling bandwidth		
Initiator	<i>SodM</i>		
Project owner	<i>Hans de Waal</i>		
Contact person	<i>Nico Hardebol</i>	Max. duration	<i>12 man month</i>
KEM subtheme	<i>Seismic risks</i>	Est. Budget	<i>ca. 150 range in euros</i>
KEM project code	KEM-01	Contractors	<i>University of Padova</i>
Research category	<i>ST</i>	Contractors	<i>n.a.</i>
Risk instr. Innovation	<i>yes</i>	Contractors	<i>n.a.</i>

Deliverables

The research has been commissioned to the University of Padova. The project started in April 2017 and finished in February 2019. Main product is the Final Report on Project KEM-01, "Safe Operational Bandwidth of Gas Storage Reservoirs" and WP reports, by P. Teatini *et al.*

The final report describes a very thorough and rigorous investigation of the problem of defining a safe operational bandwidth for pressure fluctuations in underground gas storage reservoirs. Safety has been defined in terms of avoiding slippage on faults, although the modelling approach did not distinguish between seismic and aseismic slip. The analysis has been carried out by performing geomechanical simulations using the finite element method. Generic reservoir models were constructed using depths, rock properties, and pressure variations that are typical of gas storage reservoirs in the Netherlands. Detailed comparisons, along with critical discussion, were made with two recent papers that have addressed this issue (Wassing *et al.*, ARMA, 2017; Haug *et al.*, GEE, 2018). The results of the project have been summarised in the form of generic, qualitative guidelines. Based on the sensitivities observed during the simulations, it was recommended that, in order to conduct a safety analysis for a specific gas storage reservoir, effort be devoted to estimating the *in situ* stress state, and the hydraulic and geomechanical properties of the reservoir and faults.

Overall, the work performed in this study is of a very high technical quality. Excellent knowledge and understanding of the relevant geomechanical issues was exhibited. Lacking more detailed data on specific reservoirs, the project has probably gone as far as possible, and in doing so has developed some useful guidelines. I therefore consider that the work that has been completed has adequately fulfilled the intended goals of Project KEM-1. The report was generally well written. However, I have several suggestions for some improvements that would render the report more useful to the intended readership.

The KEM-01 final reports are public and can be downloaded at www.kemprogramma.nl

KEM Evaluation of the results

The project has answered efficiently the main research question posed in KEM-01, as summarised below.

Which main factors control the reactivation of faults and seismicity under cyclic storage conditions?

- Provide an overview of induced events related to UGS facilities globally, focussing on both the re-injection and the production phases. **For answers see report of WP1. Similar seismic behaviour as in the survey has been noticed in Dutch gas storage in gas reservoirs.**
- Relate the induced events to possible physical mechanisms that explain their occurrence during both phases. **For answer see report WP2. A clear relation of seismic events at maximum depletion pressures and at increasing injection has been found, especially when seismicity occurs during first cycle of depletion.**
- Find root causes for seismicity during reinjection, during depletion at peak production rates and under minimum gas pressures (average and near-well), as well as during injection at peak injection rates and at maximum (average and near well) gas pressures. **For answers see WP3-6. Root causes at maximum depletion (before storage) and maximum injection (taking into account irreversible compaction) have been found and illustrated by modelling a representative gas storage reservoir.**
- Identify critical factors influencing the activation of faults and seismicity during re-injection and storage operations, which could be used as hazard indicators in a risk matrix risk assessment. **For answers see WP3-6. The critical factors are the history of seismicity, size of and fluid pressures inside faults and changing storage reservoir solid-fluid conditions. The magnitudes of induced earthquakes (related to slip surface) seem not to be bigger than earlier seismicity during depletion.**

The study should focus on underexplored natural and operational conditions for which fault criticality is perceivable upon re-evaluation. Previous focus has been on seismicity under peak depletion conditions. Identify, if possible, generic guidelines for a safe operational bandwidth (e.g. pressure range/rates). **For answer and recommended strategy see recommendations in the final report where the guidelines for different situations have been presented.**

KEM interpretation of the outcome

The KEM scientific expert panel recommends to EZK and SodM to use the insight obtained and guideline recommended. To achieve this information needs to be disseminated (and challenged) and Dutch knowledge institutes need to be involved in next steps for consolidation.

Recommended actions for SodM are:

1. to re-evaluate current gas storage sites
2. to adjust the accepted injection regime where needed
3. to adjust or extend monitoring systems in gas storage sites for early detection of changes in seismicity
4. to prescribe the evaluation method for forthcoming gas storage license requests and operational plans

It was stated that there is currently no need for more research on this research question.

Closure text for the website

The research has been commissioned to the University of Padova. The project started in April 2017 and finished in February 2019.

Empty gas fields can be used as storage by injecting natural gas into them. This natural gas is then extracted when demand is high, for example during the winter. Earthquakes are caused by movements along faults in the deep subsurface. These faults move because stresses are built up on the fault surfaces when the gas pressure in the rock decreases, as is the case when gas is extracted. The research showed that the seismic movements along faults in gas storage reservoirs can be modelled with the proper simulation tools using local parameters.

The computations executed show that in the case of gas injection, pressure rises and the slippage-inducing stress on faults initially decreases, but can increase as the gas pressure in the rock increases towards the initial reservoir pressure. Gas storage reservoirs that have been seismically active during initial gas production stage have a higher chance of inducing earthquakes along faults during filling than the gas storage reservoirs that did not show seismic activity in that stage.

The research also shows that the fault surface that is critically stressed during injection is smaller than the fault surface that is critically stressed during gas production. In other words, the risk of earthquakes in underground storage facilities is mainly determined by extracting natural gas, and to a lesser extent by injection.

Based on these new insights, guidelines have been drafted how to compute a safe operational bandwidth for specific gas storage reservoirs.

The project KEM-01 consisted of two phases and resulted in total six deliverables, including the final report:

- [WP1 literature inventory](#)
- [WP2 mechanism identification](#)
- [WP3 phase 1 geomechanical model computations](#)
- [WP4 phase 1 analysis intermediate results](#)
- [WP5-6 phase 2 geomechanical model computations](#)
- [WP7 final report phases 1 and 2](#)