| KEM Research Question (max. 4 pages + annex) |
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| **TITLE** Constraining the *maximum earthquake magnitude for the small gas fields (KEM-56)* |

**Objective**

This project focuses on assessing the maximum earthquake magnitude (Mmax), that could be induced by gas production from the small gas fields in the Netherlands.

Numerical (physics-based) models shall be developed for the currently 12 producing onshore gas fields, which are associated or can be associated with induced seismicity if earthquake location uncertainty is considered (i.e., active class A and B fields using the definition of KEM-07). Each model shall be calibrated using its production history and the observed seismicity (data available via nlog.nl). Scenario simulations, associating earthquakes with different faults within their location errors, shall be performed to account for the (large) uncertainties of earthquake location.

Earthquake evolution during future production shall be simulated for each scenario, yielding Mmax estimates for the most likely and end-member scenarios. These estimates shall be compared to the current approach of estimating Mmax based on the available fault area (see section below). Recommendations on a general approach to assessing Mmax for arbitrary gas fields in the Netherlands shall be provided, based on numerical considerations of background stresses, slip extension and variability of the latter within the simulations.

**State of the art, background**

Gas production is the environmentally cleanest form of energy to bridge the gap between fossil fuels and new regenerative energy sources as Photovoltaics and Geothermal. However, in the political decision to further exploit this resource, the concern of an escalation of earthquake magnitude by regional authorities, regulators and local citizens likewise plays an important role. In the Netherlands, 38 gas fields have been associated with production-induced seismicity with some of the larger events introducing non-structural damage to buildings. Associated earthquakes occurred predominantly in the largest Groningen gas field, but also in smaller gas fields, such as Roswinkel and Bergermeer.

The seismic risk assessment for the small Dutch gas fields follows a three-level procedure, in which Mmax is a key parameter in levels 1 and 2 [1]. At level 1, the potential for induced seismicity is initially assessed based on empirical correlation parameters. The underlying procedure is named DHAIS and has been repeatedly updated [2]. Mmax is additionally estimated in level 1 based on the available fault area available for slip and based on the produced gas volume, respectively. In case a gas field exhibits a non-negligible risk according to the empirical correlation parameters and a Mmax ≥2.5, a risk matrix approach (level 2) is required. The scoring scheme in level 2 incorporates surface and sub-surface influence factors, as well as the realistically strongest earthquake Mmax [3].

Even though the two deterministic methods to estimate Mmax in the current framework of seismic risk assessment rest on a conceptual geomechanical model, they both critically depend on ad hoc parameter assumptions. Consequently, Mmax estimates may be overly conservative, or underestimate the strength of future seismicity. A recent study reviewing the seismic hazard assessment procedure for the Netherlands suggested replacing the current Mmax assessment with a probabilistic approach, assuming a log-linear magnitude-frequency distribution (MFD) [4]. Nevertheless, most small fields do not exhibit a log-linear MFD, e.g. [1], [5].
A different strategy for assessing Mmax could be based on numerical simulations of subsurface stress changes and associated seismicity. Generally, the geomechanical processes leading to gas production-induced seismicity are well understood and have been investigated in numerous studies (see [6] for an overview). Nonetheless, the computational costs of numerical 3-D models of reservoir deformation and associated seismicity are enormous. Existing approaches for simulating compaction-induced stresses and seismicity are frequently limited to 2-D, e.g. [7], [8], [9]. Alternatively, 3-D analytical solutions in a hybrid approach are commonly employed, in which earthquake magnitude is determined statistically assuming a log-linear MFD [10], [11], [12], [13], [14]. A recent study of gas production-induced seismicity demonstrates that physics-based, 3-D models become computationally manageable when using a slider-bock approach for simulating fault stability and the post-failure process [5]. In this study, Mmax model forecasts for future gas production show little parameter sensitivity if the models are history-matched. Consistent with previous findings [8], [13] earthquake slip nucleates at fault intersections with reservoir over-and underburden and may propagate into non-reservoir layers, thus questioning the current approach for assessing Mmax.

**Research Question**

This project will target the following research questions:

1. What is the maximum magnitude for the producing small gas fields, considering production history, reservoir geometry, fault geometry, material parameters, local geological and stress conditions, and uncertainties associated with earthquake observations?
    a. Which faults within the small fields are identified as seismogenic and why?
    b. What is the maximum magnitude for the respective faults within the fields?
2. How does Mmax compare to the value derived from the maximum available fault area?
3. Can the findings be generalized? Can a stress-based criterion be formulated that is applicable for all fields (those considered here and possibly other fields in NL)?
    a. What are the main parameters influencing the vertical extension of slip?
    b. What is the maximum vertical extension of fault slip with a variation of these parameters and accounting for model uncertainties (sensitivity study)?

**Deliverables expected**

The expected deliverables comprise:

1. Full scientific report, including
    a. Introduction, scope and research questions
    b. Description of the setup of each model (data basis, data analysis, model setup, model calibration, model uncertainties)
    c. Modelling results (seismogenic faults, earthquake timing and magnitude evolution for each fault with time, maximum magnitudes for seismogenic faults and fields, respectively)
    d. Sensitivity study identifying and constraining the parameters influencing the maximum magnitude
    e. Discussion of the results, especially with respect to research questions 2 and 3
    f. Conclusions
    g. Summary and plain language summary (English and Dutch)
2. Final presentation with project outline, results and conclusions

**Timeline**

It is expected that this project will last 18 months.

**Expected use**

This study will promote a better understanding about the expected maximum magnitudes of earthquakes associated with small gas fields in the Netherlands with ongoing gas production. The output of the modelled maximum magnitudes will provide valuable information for regional authorities and operators in their evaluation of the seismic risk and may even possibly reduce concerns of the local population, especially if the characteristic earthquake distribution (no seismic escalation) proves to be an appropriate model for the induced seismicity.

**Expertise and tools preferred for the team**

- Expertise in physics-based, numerical modelling of induced seismicity associated with gas reservoirs.
- Seismological expertise, knowledge of uncertainties regarding earthquake detection, localization and error bounds.
- Knowledge of results of KEM-07.

**Quality assurance, Organisational and communication requirements**

- Formation of an advisory panel (KEM, KNMI)
- Progress meeting every 3 months, informing the advisory panel of the state of the project
- Presentation of the study at bi-annual KEM meetings
- Final presentation (20 minutes) with project outline and discussion of the results

**Remarks and Suggestions**

**References**


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