KEM Innovation/Research Question (max. 4 pages + annex)

TITLE: ***Cavern collapse and possible sinkhole development***

Objective

The formation of a sinkhole at the surface above a salt cavern is the ultimate result of the upward migration of the void space by a collapsing cavern roof. The collapsing roof is in competition with the filling of this space by the volumetric expansion of the rubble (so-called 'bulking'[1]). Falling rubble is known to take up more space in volume compared to the in-situ rock. This will, in case where sufficient rock is present above the cavern, ultimately fill the cavern and supporting the roof, halting the migration. In cases where a sinkhole forms at the surface, the bulking was insufficient to stabilize the cavern before the roof of the void reached the surface[2]. In the Netherlands it is likely that migration to the base of the unconsolidated sediments accelerates the last phase of collapse and the formation of the sinkhole.

The Netherlands has over 250 relatively small, shallow caverns (mainly in Twente) and about 30 relatively large (0,5-5 mln m^3), deep caverns (in Groningen and Friesland) for salt mining and energy storage. A few cases of cavern migration are known from the Twente area[3], some of which actually reached the surface[4]. This prompted State Supervision of Mines (SSM/SodM) to make "understanding the long-term stability and (if required) the long-term stabilization of these caverns" a priority in the Twente-Rijn concession[5].

The KEM-17[6] study concluded that more knowledge is needed for assessing and managing cavern failure risks after abandonment for the relatively large and deep caverns. Sinkhole formation is a possible consequence of cavern failure. This study will focus on large and deep caverns, although learnings might be applied to the smaller caverns. Given the current move towards the creation of hydrogen storage caverns, we will also include the formation of sinkholes during the operational phase of these gasfilled caverns.

This study has two main ultimate aims:

1) <u>To Gain insight into cavern collapse:</u>
   a. What are the (unambiguous) indicators of a collapsing cavern?
   b. How much time does collapse of the entire cavern take (relevant to understand possible mitigations)?

2) <u>To gain insight into the consequences:</u>
   a. What kind of effects can be expected at the surface?
   b. What is the areal extend of these sinkholes?

We think that a sinkhole-model, specific for the Northern Dutch situation, is needed to further understand such events. The *causes* of sinkhole formation, for example the long-term behaviour of the caverns themselves, is *not* the objective of this proposal. Those issues are currently being studied by the operators, with the help of researchers they hire. This research project is focused on the understanding of the migration of the cavern and the sinkhole formation process (speed, precursor effects, dimension, etc.), and the affected area at the surface. The starting condition is that a cavern starts collapsing.

It seems that the technology to model collapse and sinkhole formation is relatively mature (see references 5-8) but focusses mostly on the formation of sinkholes in competent rocks. The first step of this project should therefore be to understand if existing models can be modified and calibrated for the Northern Dutch situation specifically, or salt caverns underlying partially soft(er) sediment in general.

To this end we propose three phases:

A. Investigate whether the current numerical tools are suited to study large and deep caverns underlying partially soft sediments.
B. Develop and calibrate such a model for a number of generalized cavern shapes and depths.
C. Use this model to run a series of theoretical, but realistic endmember models. The goal is to investigate the possible parameter space in the development and effects of sinkholes from salt caverns underlying partially soft sediments. These should help the regulator to gain insights in aims (1) and (2).

Between these phases, a go/no-go decision shall be taken.

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[1] https://www.nrc.gov/docs/ML0807/ML080700314.pdf
[2] Pierre Bérest (2017) Cases, causes and classifications of craters above salt caverns. International Journal of Rock Mechanics and Mining Sciences, Volume 100, Pages 318-329.
[3] https://www.rtvoost.nl/nieuws/2080256/zoutwinner-nobian-vindt-vermist-zoutgat-onder-twence-terug
[4] https://www.tubantia.nl/overig/twente-hoeft-zich-volgens-akzonobel-niet-druk-te-maken-om-zinkgaten~a0d944f5/?referrer=https%3A%2F%2Fwww.google.com%2F
[5] https://www.sodm.nl/documenten/brieven/2022/09/02/voortgang-nobian-verscherpt-toezicht-juli-2022
[6] KEM-17 Onderzoek naar de langetermijnrisico's van het afsluiten van zoutcavernes | Rapport | Staatstoezicht op de Mijnen (sodm.nl)

State of the art, background

Two decades ago, research was carried out on sinkhole formation in The Netherlands (see references 2-4). Analytical, empirical, and finite element models were developed and applied for relatively shallow (400-500 m) caverns in Twente. The current state of the art in the Netherlands is the empirical-analytical model of Bekendam, used by mining companies or authorities (for example reference 15), although the operator is currently refining these models.

In the scientific literature, several different numerical tools[7] are available to model the formation of sinkholes (see references 5-8). The applicability of these tools to the relatively large and deep caverns in Northern Netherlands, overlain by salt, competent rocks, and unconsolidated sediments, is unclear. However, these tools can be used to validate empirical-analytical models and could provide more consistent tools for assessing sinkhole formation hazards and mitigation measures. New numerical opportunities are presently proposed in the literature, taking advantage of more advanced geomechanical modelling tools to calculate the flow of granular material and large deformations using, DEM or MPM.

Research Question

Main questions

Phase A

1. Are there existing models for sinkhole formation, to allow the development of a numerical tool specifically to model sinkhole formation due to collapsing salt caverns underlying soft sediment?
    a. What are the numerical requirements to model a collapsing salt cavern underlying a section of relatively competent rock, and very weak surface sediments?
    b. What parameters (geometry, strength, elasticity, etc) are required? Are these parameters available or can they be made available without too much additional work? What analogues/proxies could be used if certain parameters are not available?
    c. Does such a tool already exist? Is it possible to adapt an existing tool to do this?
    d. Which tool would be most suited for this? Are there more than one such tools?

Phase B:

If the answer to question (1) is "yes," such a model should be developed, or collaboration with the group that has developed suitable models should be sought. Once this model is developed:

2. Can such a model be calibrated using existing/documented examples of collapsing caverns?
    a. What data are needed for this calibration, both in the sense of overburden geometries, and strength / elasticity parameters, as well as potential pre-cursor events?
    b. Calibration using cases from the Northern Netherlands, or equivalents are likely not available. Possible candidates for calibration are:
        i. The much smaller and shallower collapsing caverns in Twente-Rijn, as these studies by the operator are available at SSM. For example indications of the required bulking factor to halt migration, the timeframe in which these caverns collapse and the development of "delamination" of overburden layers, prior to full collapse.
        ii. The collapsing cavern Bayou Corne, Napoleonville, USA, which has published examples of GPS, InSAR and seismic data both from before and during the collapse, see for example references 8 and 9, but more exist.
        iii. The sinkhole near Hull, Texas (2008) – references 10 and 11
        iv. The sinkhole in Bayou Choctaw, Louisiana, USA (1954) – references 10 and 12
        v. The crater that formed above an overfilled gas storage cavern in Petal, Mississippi, USA (1986) – references 10 and 13
        vi. Other published examples of sinkholes above caverns; see also reference 1.

After phase B, a series of theoretical, but realistic endmember models should be run to investigate the possible parameter space in the development and effects of sinkholes in the north of the Netherlands. Questions in this stage are:

3. If a sinkhole is developing due to the collapse of a typical cavern in the Northern Netherlands, what are the likely rates, possible pre-cursor effects, and potential tools to detect this sinkhole?
    a. Models should have the initiation of a catastrophic failure of the cavern roof (or side) as their starting point. As mentioned before, the cause of this failure is *not* in scope of this effect study.
    b. Precursor effects could include, but are not limited to:,(micro)-seismicity and subsidence. What other precursors events could be thought of?
    c. What sorts of uncertainty ranges can be expected? What is the fastest, and what is the slowest possible migration rate? Can collapse be aseismic?

4. If a sinkhole reaches the surface (i.e., the base of the unconsolidated sediments), what are the possible effects (given the weak nature of the near-surface sediments), and over what area can these be expected?

[7] Such as viscoplastic, Discrete Element Modelling (DEM), Finite Element Modelling (FEM) and the Material Point Method MPM.

a. These effects should include horizontal and vertical movement at points along a transect over the developing sinkhole, stresses, strains, and rates. After the situation has come to rest, what are the bearing capacities of the area surrounding the sinkhole.
b. It should be noted that the actual definition of potential damages, hazards and casualty numbers is *out of scope,* at this point. This project aims to first set (realistic) expectations of potential effects at ground level. The exact implications of these effects could be part of a future study, depending on the outcome.

As input for the realistic endmembers, the following parameter space should be investigated:

I. What are the expected differences, if a cavern is filled with gas or with brine?
II. Does the size, shape, and depth of the cavern have an influence?
III. What are realistic bulking factors?
IV. What are the expected differences if a cavern is operational (i.e. has open wells, relatively low internal pressures, and might be filled with a gas) or is abandoned (wells are plugged and abandoned, and the cavern is filled with brine under (near) geothermal equilibrium and (near) geostatic pressures?)
V. What are the sensitivities of these models to the input parameters?
VI. What is the uncertainty range in the resulting output?

SSM will help develop these scenarios when the project reaches this phase.

Deliverables expected

1) Phase A: Report giving an overview of the state-of-the-art and assessment of numerical tools to predict cavity collapse and sinkhole formation processes and effects at the surface (timing, dimensions, settlement rate, etc). This report should include a description of the proposed numerical approach(es) to move forward with.

2) Phase B: Report containing the results of the calibration of the approach(es) (models) by simulating typical cavity failure/collapse and sinkhole formation, based on published examples.

3) Phase C: Report containing the results of the realistic end-member modelling. The report should describe ranges of the development, rates, and surface effects of sinkholes in the north Netherlands, as well as possible pre-cursor events, and ways to identify these precursors. Recommendations for further work, including possible ways to mitigate cavern failure, quantify hazards and risks, and identify pre-cursor events, which can be used to help predict the onset of sinkhole formation.

4) Progress meetings (physical and/or via videoconferencing) during the three phases of the project.

Timeline

1,5 year for execution of the project with go-no-go moments between all phases.
Deliverable 1 after 3 month
Deliverable 2 after 9 month
Deliverable 3 after 18 month

Expected use

The results will be used (on the policy and licensing side by the ministry EZK, and regulator side by SSM) for guidelines for salt mining and gas storage in caverns during operation and after abandonment. Additionally, information can be used for emergency response plans. Information is used to answer questions from municipalities and citizens living in mining areas.

Expertise and tools preferred for the team

Analytical and numerical modelling expertise in sinkhole problems.
Geomechanical expertise, with speciality on post-failure geomechanical analysis (large deformations).
Salt geology and salt mechanics is highly recommended, but not a necessity.

Quality assurance, Organisational and communication requirements

Good project management, team with required expertise and track record, reviewing procedures in place.
Regular communication with client, SSM. Final presentation to SSM and scientific expert panel.

Remarks and Suggestions

Maximum 200 characters (extra information concerning the Innovation/Research question)

References

1. Bérest, P. (2017) Cases, causes and classifications of craters above salt caverns. International Journal of Rock Mechanics and Mining Sciences, Volume 100, Pages 318-329.
2. Beekendam, R. 2002, Analytical (spreadsheet) calculation using bulking factor, depth, roof thickness and material, etc. to assess sink hole hazard, SSM report?
3. Metcalfe, R., et al., 2012, Staged risk assessment of salt cavern stabilisation, Quintessa report.
4. Drost, G.I.A., 2012, Geomechanical properties of a backfill material suitable for stabilising salt caverns in Twenthe, TUDelft series AES/RE/12-22.
5. Shalev, E., and Lyakhovsky, V. 2012, Viscoelastic damage modeling of sinkhole formation, Journal of Structural Geology, Volume 42, Pages 163-170, https://doi.org/10.1016/j.jsg.2012.05.010.
6. Al-Halbouni, D., Holohan, E., Taheri, A., Schöpfer, M., Emam, S., and Dahm, T. (2018). Geomechanical modelling of sinkhole development using distinct elements: Model verification for a single void space and application to the Dead Sea area. Solid Earth. 9. 1341-1373. 10.5194/se-9-1341-2018.
7. Chen, X., Hu, Y., Zhang, L., and Liu, Y. 2023, 3D large-deformation modelling on face instability and sinkhole formation during tunnelling through non-uniform soils, Tunnelling and Underground Space Technology, Volume 134, https://doi.org/10.1016/j.tust.2023.105011.
8. Shiau, J., Chudal, B., and Keawsawasvong, S. Three-dimensional sinkhole stability of spherical cavity. Acta Geotech. 17, 3947–3958 (2022). https://doi.org/10.1007/s11440-022-01522-8
9. Jones, C.E., Blom, R.G.Bayou Corne, Louisiana, sinkhole: Precursory deformation measured by radar interferometry. Geology 2014;; 42 (2): 111–114. doi: https://doi.org/10.1130/G34972.1
10. Ford, S.R., and Dreger, D.S. Pre-Sinkhole Seismicity at the Napoleonville Salt Dome: Implications for Local Seismic Monitoring of Underground Caverns. Seismological Research Letters 2020; 91 (3): 1672–1678. doi: https://doi.org/10.1785/0220190224.
11. Eissing, J. Risk analysis of worldwide salt cavern storage and its implications for the Dutch cavern storage industry. MSc-hesis Vrije Univeristeit Amsterdam and State Supervision of Mines (2021) - https://www.sodm.nl/documenten/rapporten/2022/02/08/inventarisatie-opslag-in-zoutcavernes-resultaten-afstudeerstage
12. Horváth, P. L., Mirau, S., Schneider, G.-S., Bernhardt, H., Weiler, C., Bödeker, J., Wippich, M., Tangermann, T., & Ratigan, J. (2018). Update of SMRI's Compilation of Worldwide Salt Deposits and Salt Cavern Fields. 265.
13. Looff, K. (2017). The Impact of Anomalous Salt and Boundary Shear Zones on Salt Cavern Geometry, Cavern Operations, and Cavern Integrity. 31.
14. Réveillère, A., Bérest, P., Evans, D. J., Stöwer, M., Chabannes, C., Sandia, G., Koopmans, T., & Bolt, R. (2017). SMRI Research Report RR2017-2: Past Salt Caverns Incidents Database Part 1: Leakage, Overfilling and Blow-out. 121.
15. Bekendam, R., Oldenziel, C.E., and Paar, W. Subsidence potential of the Hengelo brine field (Part I)—physico-chemical deterioration and mechanical failure of salt-cavern roof layers. Proceedings of the SMRI fall meeting, San Antonio. 2000.