Cavern Field Maceió: Cavern Backfill for Long-Term Stability

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1 Introduction

Braskem operated a field of 35 solution mining caverns in the city of Maceió. Due to large and accelerating surface subsidence and a small tremor, solution mining was stopped in 2019. The field has experienced large deformations, cavern migration into the overburden, and the formation of a sinkhole.

Braskem has initiated an extensive geomechanical investigations, including seismic and deformation monitoring, rock-mechanical field and laboratory tests, and geological and geophysical exploration. Based on the results, a number of numerical investigations have been conducted, the stability of the field was assessed, and recommendations for additional measures were derived. Braskem is currently conducting a wide-ranging programme of plugging and remediation measures, specifically, the pressurisation of those caverns that are pressurisable and the backfilling with sand of those that are not.

The IfG has studied the Maceió field since 2019, see, e.g., (Institut für Gebirgsmechanik GmbH, 2021b, 2022, 2023, 2024). In (Institut für Gebirgsmechanik GmbH, 2021c), we discussed the abandonment process for solution mining caverns.

In this note, we review the possibility of abandoning caverns in the Maceió field and derive recommendations for achieving a stable and maintenance-free state for all 35 cavities that is suitable for final closure of the field[1]. Our main conclusion is that it is recommended to backfill all caverns in the Maceió field in the long run.

In Section 2, we present examples of sinkholes over caverns and conventional mines, with an emphasis on late formation. Then we discuss some pertinent aspects of the current situation in Section 3 and revisit our earlier memo on cavern abandonment (Institut für Gebirgsmechanik GmbH, 2021c) in Section 4. Based on these discussions, we assess the current and long-term behaviour of pressurised caverns in Section 5. Finally, we derive recommendations for future remediation measures in Section 6.

[1] The corresponding German term is *Entlassung aus der Bergaufsicht*, which translates to “release from mining supervision”.

2 Examples of Sinkholes over Mines and Cavern Fields

2.1 Outline of the Mechanism

Sinkhole formation has been discussed, e.g., in (Bérest, 2017; Minkley et al., 2022; Minkley & Lüdeling, 2020) and the reports (Institut für Gebirgsmechanik GmbH, 2021b, 2021a, 2024), where the process and examples are discussed in detail. Here we briefly mention some pertinent cases.

The basic sinkhole formation generically proceeds along the following failure sequence:

1. In the salt formation, cavities with sufficient volume and span are generated.
2. The salt back, i.e. the hydraulic barrier to the overburden, loses its integrity, gets dissolved or breaks into the cavity, or is not present at all.
3. The overburden cannot span the brine-filled cavity without fracturing anymore and starts to collapse into the cavity.

The further progress of the collapse process depends on the hydromechanical properties of the over-burden rocks. Bérest (2017) distinguishes two general mechanisms, the “piston” and the “hour-glass” model. In both cases, the cavern roof progresses upwards until it reaches a strong layer of rock (stoping). If that layer is breached, soft material above will flow into the cavern (the “hour-glass” model), while in jointed stronger rock, a larger chunk will slide as a single block (the “piston”).

The latter mechanism is particularly important for deep caverns because block sliding is not associated with significant bulking (i.e. volume increase of the fracturing and falling material), so that the cavern volume can more or less directly translate into sinkhole volume at the surface.

Given the structure of the Maceió overburden, the formation of a piston can possibly be detected in the seismic signal some weeks before sinkhole formation. However, the warning time is likely too short to take any preventive measures such as backfilling.

Since such rock blocks are supported by the lateral stress, sinkhole formation is aided by low lateral confinement (e.g. over mining edges or other extension zones) and low shear strength on vertical joints, faults, or weakness planes in the overburden.

We should stress the crucial rôle of fluids, in particular for brine-filled caverns:

- If the cavern is contained in intact rock salt, which is impermeable to fluids, brine pressure close to the lithostatic stress will support the salt back and overburden, and sinkholes cannot form. On the other hand, if the integrity of the cavern is lost, fluids can migrate into porous or jointed overburden.

- If the brine is in contact with overburden joints and their joint water, brine pressure will propagate along the joints and lower the effective stress. The brine can also move along joint by pressure-driven percolation.
- This effect will be particularly pronounced if initial fracture processes generate dynamic over-pressures that can rupture rock bridges similar to a hydrofrac.

2.2 Cavern Field in 1200 m

In a cavern field in a depth of 1200 m (Institut für Gebirgsmechanik GmbH, 2021a; Minkley & Lüdeling, 2020), solution mining was conducted. Pillars between caverns were insufficiently dimensioned, and a soluble potash seam was present in the thin salt back. As a consequence, several caverns coalesced, and the salt back was dissolved over a number of caverns; plausibly, these processes already occurred during the operational life of the field.

Consequently, the caverns were now hydraulically connected to the jointed overburden rocks (sandstones and other sedimentary rocks). Due to the large subsidence, the horizontal stress was lowered, in particular over the edges of the field. Ground water form overlying aquifers and brine squeezes out form converging caverns could infiltrate the overburden joints, lowering the effective stress and hence the shear resistance. Once a continuous fluid-filled joint system is created over a cavern of sufficient span, a rock column can slide into the cavern and leave a sinkhole at the surface, which is what happened in this field.

The formation of the sinkhole in 2018 occurred 34 years after the cavern was plugged. An accumulation of diesel in the resulting crater, which was used as a blanket during leaching, clearly confirmed the deep cavern as the cause of the sinkhole (Minkley et al., 2022).

2.3 Solvayhall

The conventional potash mine Solvayhall (Friedenshall), parts of the mining horizon had no overlying salt barrier. In the early 1960s, fluid inflows were detected here, and the mine had to be abandoned in 1967. Three sinkholes appeared in the next five years over the field without salt back. A fourth one opened up in 2012 – almost 40 years after the mine was flooded (Landesamt für Geologie und Bergwesen Sachsen-Anhalt, 2012).

2.4 Neustaßfurt

During the controlled flooding of the Neustaßfurt potash mine, a major sinkhole occurred in 1975 (Institut für Gebirgsmechanik GmbH, 2021b). In 1998, 23 years later, two further, much smaller sinkholes formed.

2.5 Haoud Berkaoui

The Haoud Berkaoui sinkhole (Morisseau, 2000) was formed due to an oil well drilled through a salt layer that was not properly abandoned following some technical difficulties 1978. The well created a hydraulic connection between two aquifers, the lower of which had an Artesian overpressure. The upward-flowing water leached a cavity into salt, which later collapsed and formed a crater at the surface. In this case, the sinkhole formed eight years after the start of leaching.

3 Some Aspects of the Status of the Field

3.1 Current Cavern Closure Categories

The cavities in the Maceió field can be categorized according to their closure status:

- Cavities M05, M06, M08, M14, and M24 are naturally backfilled, i.e., they have moved into the overburden and are filled with debris from roof falls. Due to the bulking of the rock mass, the initial cavity volume has been consumed.
  This category also includes cavity M18, which is backfilled by sinkhole formation.
- Cavities M01, M02, M10, M13, M22/M23, M26, M28, M30, M31, M32, M33, and M35 are in the salt and pressurised (the pressurisation still needs to be confirmed for cavities M22/M23, M26, and M33): The wells are closed at the wellhead, and the pressure, which is monitored, has increased above halmostatic pressure. Note, however, that the pressures are generally constant at values between 60% and 70% of the lithostatic pressure.
- Cavities M04, M07, M11, M17, M19, and M25 have been backfilled with sand. Braskem has generally achieved backfill ratios above 90%.
- Cavities M03, M09/M12, M15, M16, M20/M21, M27, M29, and M34 are currently being backfilled or are scheduled to be backfilled in the next two years. (After the sinkhole

occurred at cavity 18, the former “monitoring” category was changed to “backfilling” in agreement with IfG’s recommendations.) Note that the backfilling category includes several cavities for which the sonar surveys indicate the presence of a salt back, but which nevertheless cannot be pressurised.

3.2 Rock Mechanics of the Salt Stratum

The Paripueira salt formation, i.e. the leaching horizon, is characterised by an intercalation of rock salt and shale. The strength of the rock salt is similar to that of other salt deposits worldwide (uniaxial compressive strength approx. 20 MPa). However, the shale intercalations are significantly weaker: The uniaxial compressive strength of the interbedded shale at 7 MPa is only 35 % of that of rock salt, and the triaxial strength is around 50 % below that of rock salt under the stress conditions present at depth (Figure 1). The shale of the Tabuleiro dos Martins (TMS) formation overlying the salt formation is about twice as strong as the shale layers in the salt deposit at low stresses; note, however, that direct tensile tests showed low tensile strength (around 0.1 MPa) orthogonal to the lamination (see also Institut für Gebirgsmechanik GmbH, 2022).

Fractured shale layers also possible fluid pathways for brine to move between caverns, possibly forming hydraulic connections to the overburden.

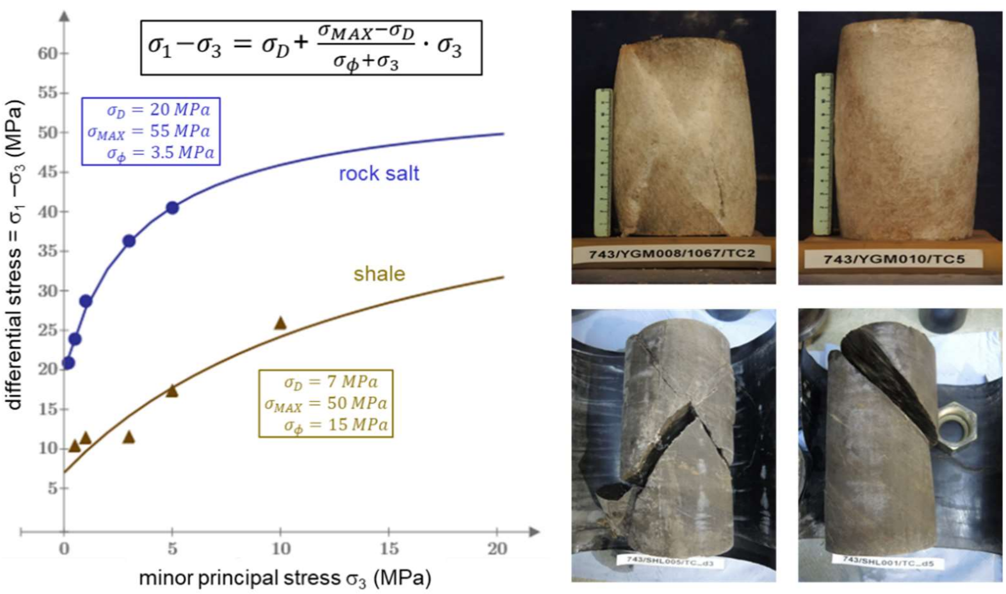

Figure 1: Strength of the Paripueira salt and the shale interbedding. The salt behaviour is comparable to other salt deposits, but the shales are significantly weaker.

3.3 Observed Cavern Behaviour

The pressurised caverns, i.e., caverns within salt layer that develop a pressure above halmostatic when closed at the wellhead, reach pressures in the range of 60% – 70% of lithostatic stress. This is in contrast to the usual pressure of closed salt caverns which rises towards the minor principal stress, which generally is close to the lithostatic stress. Since the cavern pressure is thus significantly below the rock stress, the caverns continue to convergence. Since the observed cavern pressures are constant to good approximation, brine is squeezed out from the caverns. It is currently not known whether the brine moves along permeable zones in the salt, along the shales, or both.

Some caverns are in the salt layer but cannot be pressurised. This indicates a hydraulic connection to the overburden, plausibly via a damaged salt back or along fractured shale layers and neighbouring cavities.

In general, the caverns in the field tend to move upwards, including M18, which had only the lower component in 2018.

Due to Braskem’s pressurisation and backfilling measures, surface subsidence rates above the field are reduced from accelerating rates in the 2010s but are still significant. Large-scale modelling of the cavern field (Institut für Gebirgsmechanik GmbH, 2023) indicates residual rates can stay at of few cm/a after backfilling and pressurising a significant number of caverns. The main reason is that the pressurised cavities do not reach lithostatic pressures but stay significantly below.

4 Abandonment Conditions

In the memo (Institut für Gebirgsmechanik GmbH, 2021c), written with less data and experience with the specific situation in Maceió, we have sketched the basic abandonment procedure: Abandonment means plugging the well close to the cavern roof, with the aim of reaching a maintenance-free and long-term stable state. The geomechanical basis was that salt is tight, so pressure in cavern approaches lithostatic stress. Hence, convergence (and surface subsidence) will essentially stop. Over very long timescales (thousands of years), caverns will continue to converge, and brine will very slowly move into salt by pressure-driven percolation.

We should point out that abandonment requires a hydraulically tight cavern. Raising the pressure on a cavern with hydraulic connection to the overburden risks an increase in the joint fluid pressure, reducing field stability.

In the memo, the following prerequisites for abandonment were stated:

- The well should be intact and not ruptured or strongly deformed by overburden movement.
- At least 50 m of salt back to ensure integrity of the hydraulic barrier. However, experience in Maceió shows that salt back reduces over time, for many caverns quite quickly (several metres per year).
- To demonstrate tightness, a mechanical integrity tests (MIT) should be performed at 90% of lithostatic stress.
  However, it seems clear that the caverns in the Maceió field will not be able to withstand such a pressure, since their equilibrium brine pressures are significantly lower. Hence, no MITs have been performed on cavities in Maceió to avoid accidental hydraulic fractures in the rock mass. (MITS have been done on wells in the Maceió field.)

We thus conclude that it is **very** likely not possible to abandon the pressurised Maceió caverns to reach a long-term stable maintenance-free state that would allow for final closure of the field.

5 Assessment of Long-Term Cavern Stability

Based on the preceding summary of geomechanics and field data, we can draw some conclusions regarding the long-term stability of the caverns in the Maceió field.

Cavities that are inside the salt stratum and are pressurised do not present a sinkhole risk. However, since their brine pressure is around 60% – 70% of the lithostatic stress, they will continue to converge, inducing deformations in the rock mass and surface subsidence.

Due to the structure of the deposit, in particular the shale intercalations and the interplay of brine pressure and low shear strength, it is likely that there will be no long-term stable roofs. The migration of caverns that are currently pressurised and in the salt into the overburden cannot be excluded. The examples in Section 2 show that sinkholes can form decades after the hydraulic barrier has been lost.

Hence, long-term monitoring, and possibly more remediation measures, are required. The pressurised caverns are not in a maintenance-free state.

We should point out that a due to a comparatively small size or isolated position, several cavities are very unlikely to form a sinkhole even if they migrate into the overburden.

6 Recommendations

From the assessment in the previous section, we derive the following recommendations:

- The current backfilling schedule (cavities M03, M09/M12, M15, M16, M20/21, M27, M29, M34) should be continued, as the formation of a sinkhole cannot be excluded for the cavities that are outside the salt stratum, or inside the salt but hydraulically connected to the overburden.
- While the current backfilling plan (cavities M03, M09/M12, M15, M16, M20/21, M27, M29, M34) is in operation, the pressurised cavities should be kept pressurised, because the pressurisation reduces convergence, rock deformation and surface subsidence.
- The monitoring system should stay active.
- In the long term, i.e., several years to decades, and after the current backfilling plan is completed, it is recommended to also backfill the currently pressurised cavities to achieve, for all 35 cavities, a maintenance-free situation that is suitable for final closure of the field, without significant open cavities.
- The specific backfill schedule for the presently-pressurised cavities should be decided based on a more detailed analysis. It is not recommended to depressurise many cavities at the same time.
- If the monitoring shows significant phenomena (in particular, loss of salt back, loss of cavern pressure, well rupture, or significant seismic events), a specific new assessment is required.

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