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LONG-TERM SAFETY ASSESSMENT AND BACKFILL STRATEGY EVALUATION FOR ABANDONMENT OF A BRINE PRODUCTION CAVERN

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Abstract

This paper presents the investigation results with regard to the long-term safety and closure strategy for a brine production cavern. The primary objective was to assess the geomechanical behavior of the cavern during the abandonment phase and to recommend a suitable backfill concept for its safe and sustainable closure.

The studied cavern was originally drilled in early 19th century and leached within the rock salt formation, however, extending partially into the overburden composed of salt clay. It was used for brine production for about 90 years and has since remained filled with brine. Based on a recent echometric survey, the cavern has a total volume of about 90,000 m³ (117,716 yd³) and a maximum diameter of 95 m (312 ft). The shape of the cavern can be described as a shallow, inverted cone.

A numerical model based on the Distinct Element Method (DEM) was developed using UDEC software to simulate the operational history and post-closure evolution of the cavern. This model incorporates geological layers from the cavern to the surface, including local topography. A history-matching approach was used to calibrate the model, allowing for the estimation of the in-situ creep behavior of the salt and pre-closure stress conditions.

Assuming a 100-year operational phase during which the cavern remains brine-filled, simulations were conducted to evaluate its long-term structural stability. Upon closure, it was assumed that 95% of the cavern volume would be filled with backfill material, with the remaining 5% forming a residual brine zone. The study considered the potential for brine percolation into the rock salt due to pressure-induced secondary permeability in the rock salt or adjacent salt clay formations. Two closure strategies were analyzed: filling with a single dense backfill material (slurry) and a two-phase system consisting of granulate followed by slurry. Both approaches were evaluated with respect to geomechanical implications, including cavern stability, tightness, and brine percolation potential. The compaction behavior of the backfill materials was incorporated into the model using stress-strain relationships derived from laboratory data. An analytical method was applied to estimate the pressure buildup in the residual brine zone after complete closure.

According to the results, cavern convergence is expected to stabilize within 400 years post-closure. During this time, surface subsidence is predicted to be minimal, suggesting no risk to surface infrastructure or safety. Brine percolation to shallow subsurface layers is not expected, and the integrity of overlying strata is anticipated to remain intact. In conclusion, both backfill scenarios, monolithic dense backfill and two-phase granulate-dense backfill, are considered equally suitable for ensuring the long-term tightness and stability of the cavern. The cavern is expected to remain sealed and structurally stable under both approaches, with negligible environmental impact or surface deformation over the 400-year evaluation period. The results provide a robust foundation for the safe and effective abandonment of a brine production cavern.

Key words: Cavern Abandonment, Long-term Stability, Backfill Materials, DEM Simulation, Percolation

Introduction

The abandonment of underground salt caverns requires careful engineering and environmental consideration to ensure long-term safety and containment. Salt formations exhibit visco-plastic behavior, allowing them to creep and self-heal over time, which makes them favorable for storage but also introduces complexities when closing a cavern (Bérest, et al., 2001) & (Lux, 2009). Primary concerns during abandonment include fluid migration, wellbore integrity, and surface subsidence. As salt caverns are often connected to overlying aquifers or other formations, improper integrity can lead to groundwater contamination or environmental damage (API RP 1170, 2015).

Abandonment typically involves a combination of methods such as backfilling with brine or engineered materials, sealing the wellbore with cement plugs, and installing mechanical barriers to isolate the cavern from surrounding formations (API RP 1170, 2015). Cement plugs are strategically placed at various depths to ensure zonal isolation, often with testing such as pressure logging to verify seal integrity (Lux, 2009). In some cases, granular fill or engineered materials are used.

This study investigates the long-term geomechanical stability of a brine production cavern slated for backfilling as part of its abandonment to ensure structural integrity and environmental safety. To identify the most effective backfilling strategy, a geomechanical simulation was conducted to compare two scenarios: backfilling with slurry alone, and backfilling with granulate and slurry.

The study addresses key concerns, including long-term stability of the cavern, the potential for brine percolation through the cavern roof into surrounding rock mass and groundwater aquifers, and anticipated surface subsidence after closure. A coupled hydromechanical model based on the Distinct Element Method (DEM) was employed to assess both structural and hydrogeological impacts. By comparing the two backfilling scenarios, the study identifies the option that best mitigates long-term geomechanical and environmental risks and based thereon, ultimately the recommended backfilling approach.

A four-step investigative framework guided the analysis: (1) development and calibration of a geomechanical model, (2) simulation of the two backfilling scenarios, (3) subsidence prediction, and (4) evaluation of the results and recommendations.

Basic Data and Assumptions

The cavern parameters used in the modeling are summarized in Table 1. These values served as input for the numerical simulation to evaluate the initial stress distribution within the surrounding rock mass.

Above the rock salt formation, the stratigraphic units from the overburden sequence were included in the model. These overburden layers were assumed to behave as ideally elastic materials, with their mechanical behavior governed by Hooke's Law.

Table 1: Basic cavern data applied to numerical modeling

Parameter	Value
Assumed cavern geometry	
maximum cavern diameter	95 m (312 ft)
depth of the last cemented casing shoe	491 m TVD (1,611 ft TVD)
depth of the cavern roof	515 m TVD (1,690 ft TVD)
depth of the cavern bottom	544 m TVD (1,785 ft TVD)
depth of the model bottom	650 m TVD (2,133 ft TVD)
Assumed geological data	
pressure gradient of overburden (average)	0.246 bar/m (1.087 psi/ft)
pressure gradient of rock salt	0.212 bar/m (0.937 psi/ft)

The creep behavior of salt was represented using the viscoelastic Waste Isolation Pilot Plant (WIPP) constitutive model, as described by Equation 1. A detailed formulation of the WIPP model in UDEC can be found in (Itasca Consulting Group, 2018).

$$\dot{\varepsilon_p} = \begin{cases} \left(A - B\varepsilon_p\right)\dot{\varepsilon}_s & if\ \dot{\varepsilon}_s \geq \dot{\varepsilon}_{ss}^* \\ \left\{A - B(\dot{\varepsilon}_{ss}^*/\dot{\varepsilon}_s)\varepsilon_p\right\}\dot{\varepsilon}_s & if\ \dot{\varepsilon}_s < \dot{\varepsilon}_{ss}^* \end{cases} \qquad \text{Equation 1}$$

$$\dot{\varepsilon}_s = D\bar{\sigma}^n e^{(-Q/RT)}$$

with

$\dot{\varepsilon_p}$	Primary creep rate
$\dot{\varepsilon_s}$	Secondary creep rate
$\bar{\sigma}$	*Von Mises* stress
A	Material constant (typical value = 4.56)
B	Material constant (typical value = 127)
n	Material constant, stress exponent
D	Material constant
$\dot{\varepsilon}_{ss}^*$	Material constant, critical steady-state creep rate
R	Universal gas constant
Q	Activation energy
T	Temperature

The von Mises equivalent stress, is calculated as a function of the principal stress components σ_1, σ_2, and σ_3 of the stress tensor, as follows:

$$\bar{\sigma} = \sqrt{\frac{3\sigma_{ij}^d\sigma_{ij}^d}{2}} = \sqrt{\frac{1}{2}\left[(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2)\right]}$$

The applied creep parameters based on WIPP model are listed in Table 2.

Table 2: Creep parameters according to WIPP material law applied to numerical modeling

Parameter	**Value**
Activation Energy, Q	40 kJ/mol (47.39 BTU/mol)
Universal Gas Factor, R	8.314e-03 kJ/mol.K (4.378e-3 BTU/mol·°R)
Material constant stress exponent, n	2.5
Material constant, D	0.18
Temperature, T	303.15 K (86 °F)

Model Development and Calibration

The numerical model was developed using UDEC software by Itasca Consultants. The adopted model with geological units is presented in Figure 1. The model includes the overburden, idealized as a series of inclined stratigraphic layers extending from the ground surface to the top of the salt formation. The salt formation was explicitly modeled to a depth of approximately 610 m TVD (2,001 ft TVD) along the vertical axis of the cavern. The bottom layer was extended to the model base at depth of 650 m TVD (2,133 ft TVD).

Boundary conditions were applied as follows: all lateral boundaries were constrained in the horizontal direction, while the model base was fixed in the vertical direction to simulate mechanical confinement. The cavern geometry was derived from the most recent available survey data conducted in 2014. The maximum cavern diameter was determined from the cross-section exhibiting the largest area. The sump region, known to be filled with insoluble material, was excluded from the model due to the absence of reliable geometric and material property data.

To simulate potential brine percolation through the rock mass, a Voronoi-based discretization was applied to the model domain surrounding the cavern. A preliminary sensitivity analysis was conducted to evaluate the influence of discretization scale, specifically, block size, on brine migration velocity. A series of uncoupled fluid flow simulations (i.e., excluding mechanical interactions) were performed using various Voronoi discretization (e.g. block sizes from 0.25 m to 4 m). In these simulations, fluid was introduced along one of the lateral boundaries of the model, and the temporal evolution of fluid distribution was monitored.

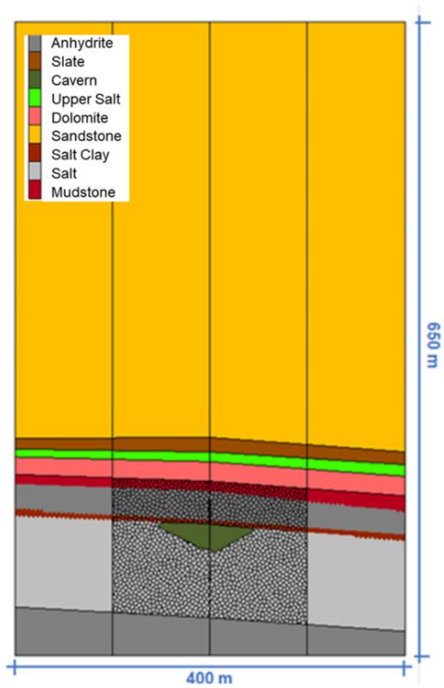

Figure 1: Considered numerical model using DEM method with geological units

The objective was to assess the extent to which the discretization geometry influences fluid migration behavior and to determine an appropriate discretization scale for subsequent hydro-mechanically coupled simulations. The results indicate that, from a purely geometrical standpoint, a coarser Voronoi discretization with block sizes up to 3 m (9.8 ft) does not significantly impact brine migration dynamics. Therefore, this level of discretization is considered sufficiently accurate for coupled simulations, even though it does not explicitly capture the natural microstructural features of the salt rock.

Assessment of Cavern Stability during Operation and Post-Operational Phase

The operational and post-operational phases of the cavern were modeled and assessed in terms of long-term integrity over a 100-year period, during which the cavern was assumed to be filled with brine under atmospheric well head pressure. This approach served two main purposes: first, to evaluate the current integrity of the cavern; and second, to validate the simulation model assumptions against actual observations. Following this, future closure scenarios were assessed based on the defined backfilling strategies.

To assess the long-term integrity of the cavern, the stresses in the surrounding rock mass should remain below the long-term strength of the salt. While short-term stress peak above this threshold may be tolerated, they must be limited in both magnitude and duration, and must be followed by prolonged periods during which the stress state remains below the threshold limit. In addition to stress criteria, the deformation behavior at the cavern boundary is assessed based on the effective strain and strain rate developed over time, which serve as indicators of potential long-term damage or creep-induced instability.

For assessment of the stress condition of the rock mass at the cavern contour, the ultimate stress intensity, η, defined with respect to the short-term strength of the salt and calculated from the current stress state is employed. In parallel, the dilatancy-based stress intensity, η_{Dil}, defined relative to the dilatancy strength of the rock salt, is used to assess the potential for time-dependent instability (see Equation 2).

$$\eta = \frac{\sqrt{calculated\ 2J_2^D}}{\beta^S} \quad \& \quad \eta_{Dil} = \frac{\sqrt{calculated\ 2J_2^D}}{\beta^{Dil}} \qquad \text{Equation 2}$$

where

$\sqrt{2J_2^D}$ existing deviatoric stress

J_2^D second invariant of the deviator of the stress tensor

β^S ultimate short-term strength

β^{Dil} dilatancy strength

The deformation state at the cavern contour is assessed using the effective strain based on the von Mises criterion, calculated from the principal strains ε_1, ε_2, ε_3 according to Equation 3.

$$\varepsilon_{eff} = \sqrt{\frac{1}{2}[(\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_1 - \varepsilon_3)^2 + (\varepsilon_2 - \varepsilon_3)^2)]} \qquad \text{Equation 3}$$

Furthermore, the global support system of the cavern is defined by the salt roof above and the salt bottom below the cavity, which act as the primary load-bearing components. These zones must retain sufficient thickness throughout the entire operational period and remain in a stress state below the long-term strength limit of the salt. Additionally, no overstressing is permitted in the overburden.

To verify the long-term structural stability, the following limit values shall apply (Staudtmeister & Struck, 1990) & (Hasanpour & Zander-Schiebemhöfer, 2023):

- Maximum ultimate and dilatancy stress intensities: $\eta < 30\%$ and $\eta_{Dil} < 70\%$
- Maximum increase in effective strain within one year: < 3%.

For safety verification of the global support system, the ultimate stress intensity, η, must remain below 30%, and the dilatancy stress intensity, η_{Dil}, must be less or equal than 70% within the salt roof over a vertical extent of at least 50 m (164 ft) above the cavern. Similarly, these conditions must be satisfied in the salt bottom, beginning no later than 25 m (82 ft) below the lowest point of the cavern.

The assessment results indicate that, except for instability zones along the cavern edge, the ultimate and dilatancy stress intensities in the rock mass remain below critical thresholds, with η_{max} calculated at 22% at $\eta_{Dil,max}$ with 31% (see Figure 2). The instabilities along the cavern edge were also documented during monitoring activities in the post-operational phase. These instabilities typically present as localized detachments and salt degradation with a roof expansion of approximately 3 to 8 m (9.8 to 26.2 ft) and a radial growth of 10 to 20 m (32.8 to 65.6 ft) were observed. This emphasizes the necessity of implementing a robust and effective abandonment strategy to mitigate further structural degradation.

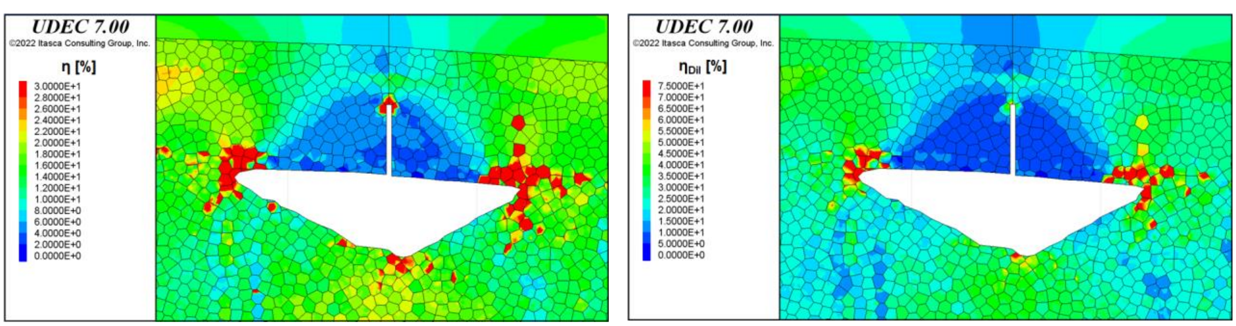

Figure 2: Stress intensity factors in the rock mass after 100 years of brine filling under atmospheric well head pressure

Additionally, the effective strain increases at a rate of only 0.2% per year, significantly lower than the critical limit of 3%/a, indicating very slow deformation rates and no critical strain accumulation. Moreover, the global load-bearing system during operation and post-operational phase is also confirmed to be stable. The analysis identifies a structurally sound salt beam both above (hanging wall) and below (footwall) the cavern, each with acceptable stress intensity levels and sufficient lateral continuity, particularly, the hanging salt beam extends over 50 m (164 ft). These observations validate that the cavern remains supported by mechanically competent geological units even under long-term loading, satisfying the criteria for global structural stability.

Assessment of Cavern Integrity during Abandonment Phase

Building on the results of the history-matching process, including simulations over a 100-year operational period, the condition of the surrounding rock mass was evaluated in the context of the proposed abandonment concept. Two backfilling scenarios were considered:

- Monolithic backfill: Complete filling of the cavern with a slurry backfill material, and
- Two-stage backfill: Sequential filling, beginning with granular material followed by slurry backfill.

It was assumed that approximately 95% of the cavern volume could be filled with backfill material. The remaining 5%, located in the upper section just below the cavern roof, would remain filled with brine. Since brine is retained in both backfilling scenarios, migration of brine into the surrounding rock mass is expected during the abandonment phase.

To model this phenomenon, a Discrete Element Method (DEM) approach was employed. In this framework, the rock salt was discretized into Voronoi blocks, randomly generated convex polyhedra that approximate the granular structure of natural salt, albeit at a coarser computational scale (typically on the order of decimeters to meters). Each block was assigned a visco-elasto-plastic material model to represent both creep behavior and plastic deformation. The interfaces between the blocks were modeled using an adhesive shear constitutive law to capture the potential for delamination or fracturing.

Rock salt is virtually impermeable under natural conditions unless it is mechanically damaged or subjected to fluid pressures exceeding the in-situ stress within the rock matrix. Under such conditions, pressure-driven percolation may occur, enabling the formation of flow paths along grain boundaries. In the hydro-mechanically coupled simulations, potential fluid migration along these boundaries was analyzed using two distinct criteria for brine percolation (Zill, et al., 2021):

- Criterion I: Shear or tensile failure has already occurred along the interfaces between Voronoi blocks.
- Criterion II: The brine pressure exceeds the minimum principal in-situ stress in the rock matrix (i.e., $p_f > \sigma_{min}$).

In this study, Criterion II was applied in the simulations to identify potential brine percolation zones around the cavern and to visualize the resulting pore pressure distribution. Under Criterion II, the surrounding geological units are initially assumed to be impermeable. Brine percolation is considered to occur only through induced secondary permeability, which is activated when the fluid pressure exceeds the local minimum principal stress. For comparison, simulation results based on both percolation criteria are presented in the following sections to illustrate the potential for brine migration and the corresponding pore pressure distribution around the cavern.

To simulate pressure build-up during cavern closure, an analytical approach developed by (Bérest, et al., 2006) was applied to calculate the pressure evolution during the abandonment phase. As both backfilling scenarios assume that 5% of the cavern volume remains unfilled, this residual brine-filled space was used as the basis for the pressure evolution calculations. The resulting pressure-time data from this analysis as illustrated in Figure 3a were subsequently used as input for the DEM simulations to model the pressure conditions in the brine-filled region of the cavern.

To define the appropriate simulation time frame for assessing long-term structural stability, the expected convergence behavior of the cavern was analyzed. Numerical simulations showed that convergence occurs rapidly in the early years and gradually slows, approaching zero over several decades (see Figure 3b). By approximately 400 years, and under the internal pressures derived from the pressure build-up analysis, the convergence rate was effectively 0.0% per year. Therefore, the convergence process was considered nearly complete, and the time frame for subsequent evaluations, such as brine percolation analysis, was set to 400 years.

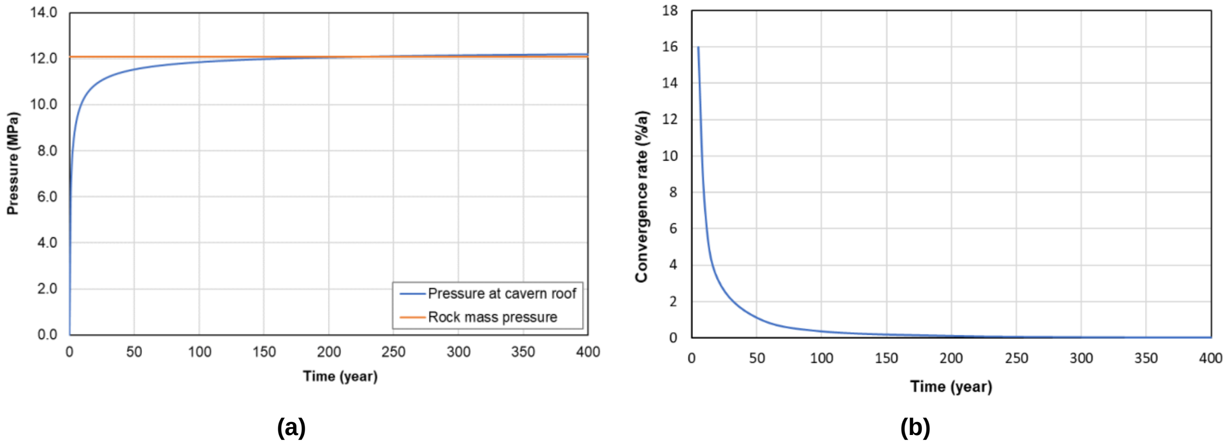

Figure 3: a) Pressure build-up over time in the brine-filled section of cavern **b)** Convergence rate over time during backfilling with viscous backfill materials

Assessment of Numerical Simulations Results for Monolithic Backfilling

To characterize the mechanical behavior of the slurry considered for backfilling, a series of laboratory tests were conducted. The stress–strain relationship obtained from these tests served as the basis for geomechanical modeling, particularly for simulating the compaction phase using the Double-Yield material model in UDEC. A 28-day simulation was performed, assuming that the slurry backfill would reach its maximum uniaxial compressive strength within this period.

The resulting horizontal and vertical displacements of the backfill and surrounding rock mass after 28 days are shown in Figure 4. The results also show that deformation extends significantly into the surrounding rock salt and partially into the overlying strata.

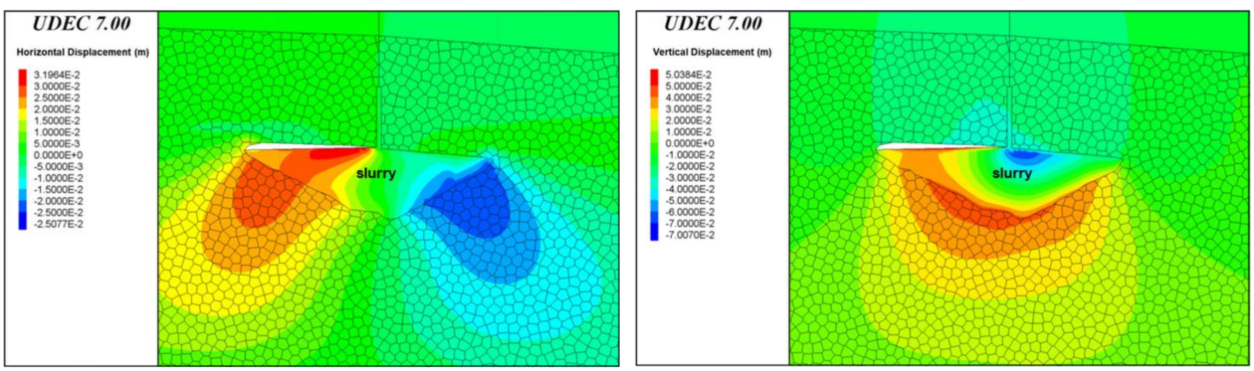

Figure 4: Simulation of the compaction phase of the slurry backfilling, horizonal and vertical displacements after 28 days

Following the compaction phase, the numerical simulation was extended for additional 400 years to account for the abandonment period. Figure 5 presents the pore pressure distribution within the salt formation and the immediately overlying layers at four different time points after cavern closure. As brine pressure increases within the cavern, the pore pressure propagates vertically above the cavern over the first 100 years. Subsequently, the pore pressure spreads horizontally within the clay salt, and the distribution stabilizes. Due to continued pressure buildup from salt creep, a more pronounced brine percolation is observed in the horizontal direction over time, especially at the cavern flanks. However, brine does not reach the overlying main strata.

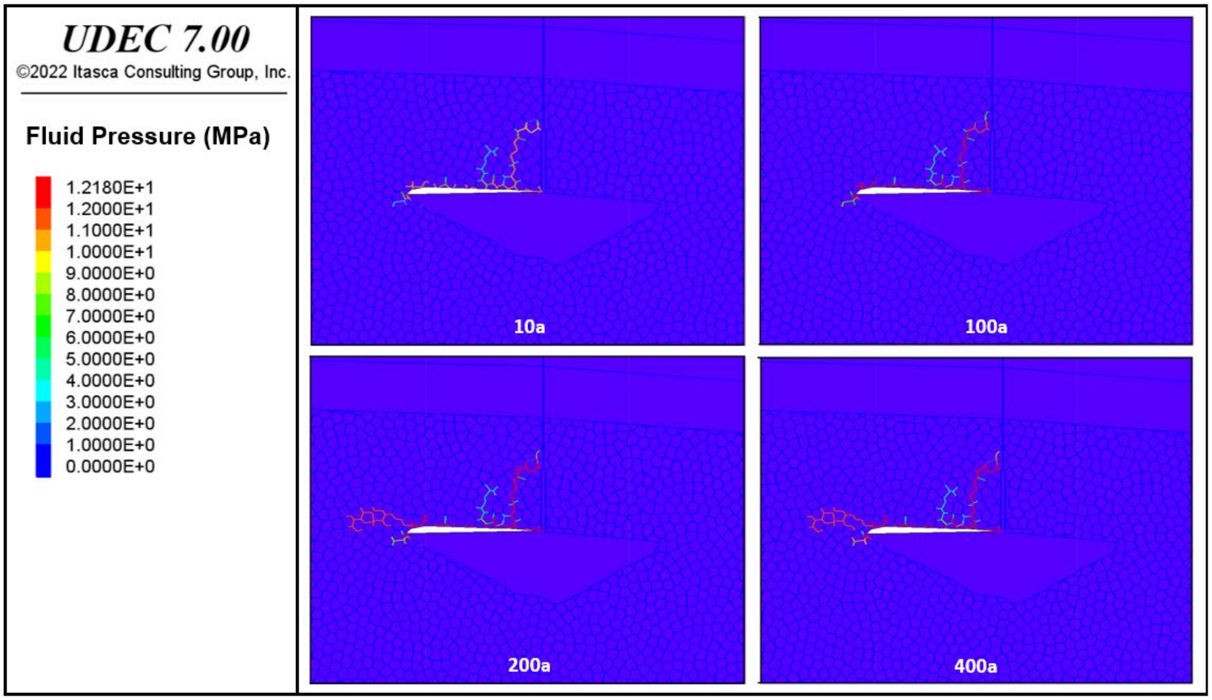

Figure 5: Temporal development of brine percolation into the surrounding salt formation after cavern closure for backfilling Scenario 1 (filling with slurry)

Assessment of Numerical Simulations Results for Two-stage Backfilling

In the absence of laboratory tests to determine the properties and mechanical behavior of a mixed slurry–granulate backfill, it was assumed that the addition of granulate would result in lower volumetric deformations compared to pure slurry. To account for this in the compaction phase of the scenario, a conservative stress–strain response was adopted by setting the volumetric deformation to 50% of that observed for pure slurry. This assumption served as the basis for defining the input parameters used in the geomechanical modeling.

Based on the numerical simulation results for the compaction phase, the horizontal and vertical deformations in the rock mass and backfill after 28 days are shown in Figure 6. Due to the presence of granulate and the resulting lower volumetric deformation, the overall deformations are slightly reduced compared to those observed with backfilling using pure viscous slurry.

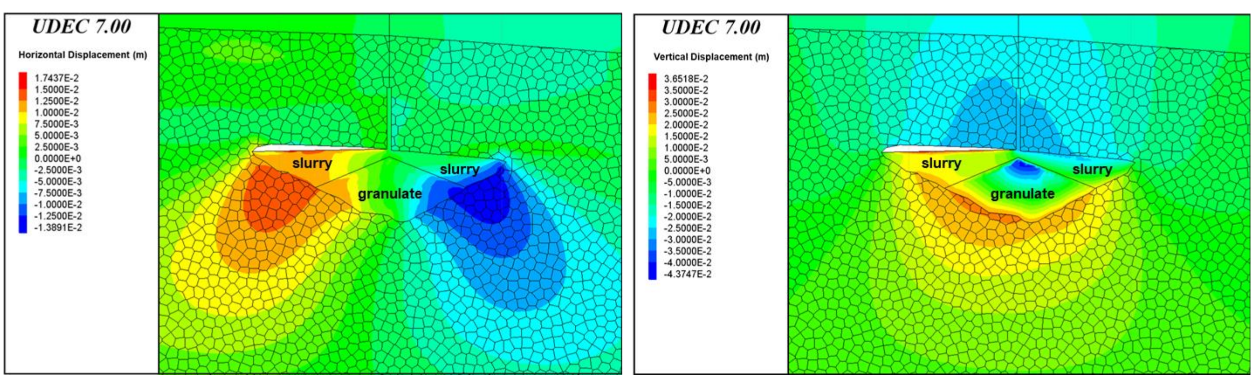

Figure 6: Simulation of the compaction phase of the granulate + slurry backfilling, horizonal and vertical displacements after 28 days

The numerical simulation was then extended for 400 years following the compaction phase. Figure 7 shows the distribution of brine pore pressure within the salt formation and the immediately overlying strata at four time points: 10, 100, 200, and 400 years. As brine pressure increases within the cavern, pore pressure initially propagates vertically above the cavern during the first 100 years after backfilling. Subsequently, pore pressure spreads horizontally within the clay-rich salt, with only minor changes observed thereafter. At the earliest time point (10 years), vertical brine intrusion into the cavern boundary zone occurs only in limited areas above the cavern roof. As pressure continues to build due to salt creep, more pronounced horizontal brine percolation is observed over time. A comparison between the influence zones at 200 and 400 years indicates negligible further expansion. Importantly, brine does not reach the main overburden layers.

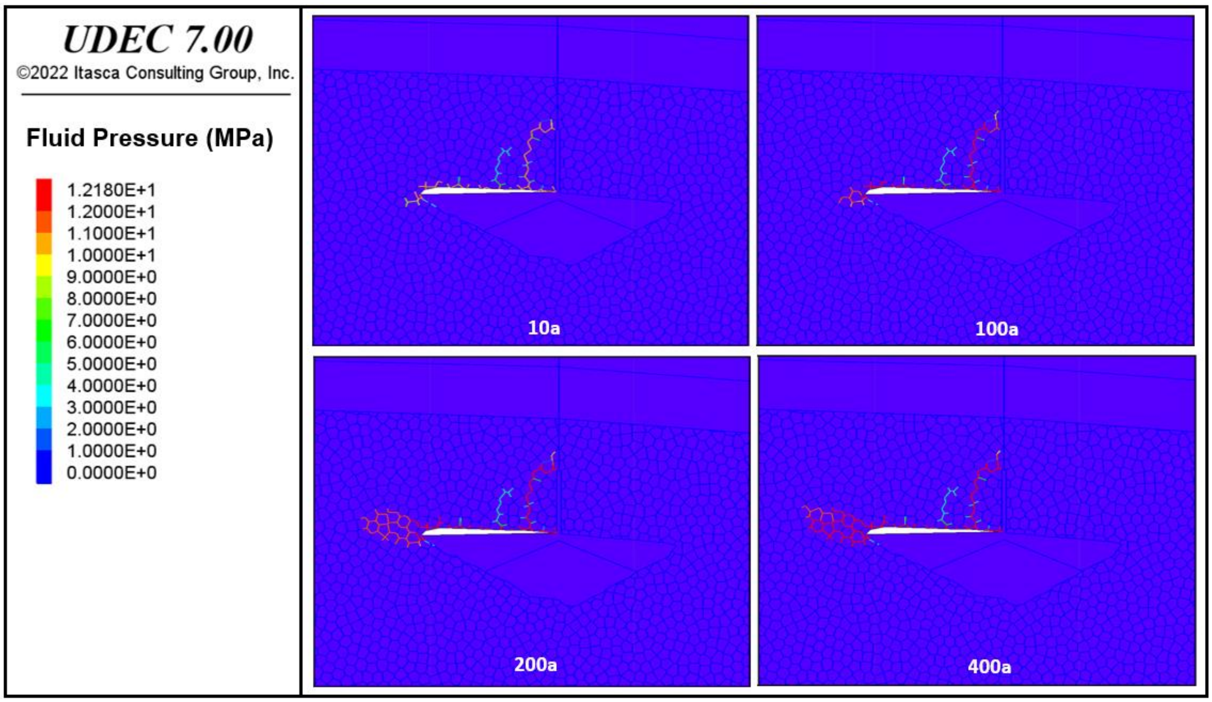

Figure 7: Temporal development of brine percolation into the surrounding salt formation after cavern closure for two-stage backfilling with granulate and slurry

Comparative Analysis of Brine Percolation and Cavern Stability for Two Backfilling Scenarios

The simulation results, extending up to 400 years after cavern backfilling, indicate that for both examined backfilling scenarios, no brine percolation from the cavern into the near-surface geological units above the clayey salt is expected within the analyzed timeframe.

Between 200- and 400-years cavern closure, only minor changes occur in the extent of brine percolation under the specified conditions and assumptions. Additionally, the fluid percolation rate decreases over time as brine pore pressure stabilizes, exhibiting little to no further evolution.

The calculation results confirm the tightness and structural stability of the rock mass surrounding the cavern for both backfilling approaches. Furthermore, negligible differences are observed in the fluid percolation patterns when comparing the monolithic slurry fill to the combined granulate-slurry fill. Therefore, both backfilling scenarios can be considered equally suitable for the long-term safe closure of the cavern.

Subsidence Prediction

An estimation of surface subsidence was conducted for a 400-year period following the backfilling of the cavern. The subsidence prediction model was created using Salt Subsid software, developed by the Solution Mining Research Institute (SMRI). The model encompasses three life-cycle phases: the production phase, a subsequent idle phase (modeled as a brine-filled cavern) between the end of production and the start of abandonment, and the abandonment phase itself.

Unlike the solution mining and idle phases, the abandonment phase was modeled with an effective cavern volume reduced to 5% of the total volume assuming that 95% of the cavern is backfilled. This remaining volume continues to undergo convergence, contributing to long-term subsidence.

Subsidence leveling measurements recorded a maximum subsidence of 65 mm (2.56 in) above the cavern over the 50-year operational period. During the 10-year idle phase, a maximum subsidence of 10 mm (0.39 in) was observed. These measurements were used in a history-matching process to estimate the in-situ convergence rates throughout the survey period. The resulting convergence rates were 0.65% per year for the production phase, 0.30% per year during the idle phase, and a conservative estimate of 0.25% per year for the abandonment phase.

Using these convergence rates, the volume loss due to salt creep and the corresponding surface subsidence were calculated with Salt Subsid software. The model predicts a maximum surface subsidence of 27 mm (1.06 in) at 400 years after cavern backfilling, as illustrated in the isoline map shown in Figure 8.

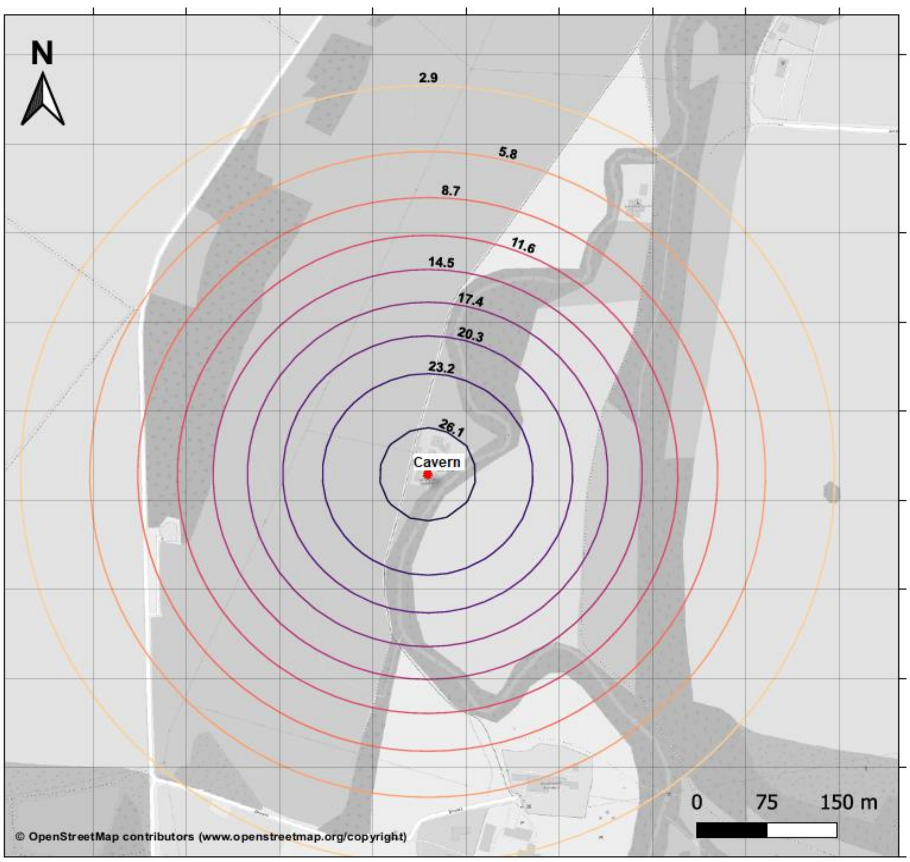

Figure 8: Subsidence forecast at 400 years after the start of the abandonment phase (values in mm)

Conclusion

This study addresses the long-term safety assessment of a brine production cavern during the abandonment phase using two backfilling methods. A DEM simulation model was developed to simulate the operational history of the cavern and investigate its future abandonment phase. The simulation model was calibrated through history matching to determine the in-situ creep behavior of the surrounding salt and to accurately represent the stress state in the rock mass prior to cavern closure.

The evaluation initially focused on the operational phase, assuming a 100-year period with the cavern brine-filled. Based on the history-matching results, the rock mass condition for the closure phase was predicted and assessed.

Two backfilling scenarios were analyzed: a single-stage slurry backfill, and a two-stage backfill combining granulate and slurry. Both the short- and long-term effects of the backfill materials on cavern stability and tightness were investigated. It was assumed that 95% of the cavern volume would be filled with backfill material, while the remaining 5% would remain as a brine-filled residual cavity, located between the cavern roof near the neck and the cavern crown adjacent to the residual brine pocket. The compaction behavior of the backfill materials was incorporated into the model using a pressure-deformation relationship derived from laboratory test data.

An analytical method was applied to estimate pressure buildup in the remaining brine, enabling prediction of pressure increases in the brine-filled zone of the cavern.

The development of volume loss after backfilling was studied based on expected convergence rates to define an appropriate calculation period. After 400 years, the convergence process was considered nearly complete, making this time frame suitable for numerical analysis.

Potential brine percolation into the surrounding rock was simulated under the condition that pressure buildup inside the cavern might exceed the rock pressure, enabling brine migration through originally impermeable rock salt and salt clay. The extent of possible brine percolation and the pore pressure distribution in the rock salt and overburden during closure were analyzed. Results indicate that brine is unlikely to reach the near-surface layers to any significant extent within 400 years; thus, no weakening of the overburden layers above the claystone is expected.

Settlement analysis up to 400 years post-backfilling shows very minor surface settlements, indicating no anticipated stability or safety concerns at the surface.

In summary, the calculation results confirm that cavern integrity is maintained under both backfill scenarios and respective assumptions regarding brine percolation. Furthermore, minimal differences were observed between the slurry-only and two-stage granulate/slurry backfill concepts concerning the extent of the percolation zone. Therefore, both backfill methods are deemed equally suitable for the long-term secure backfilling of the cavern.

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