TU Clausthal
Clausthal University of Technology

Numerical Simulations in the Framework of Cavern Abandonment – a Look into our Toolbox including some Updates since 2019

Workshop “Proceedings in salt cavern uses and abandonment: Bridging the technical and social perspectives”

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TNO, Utrecht, Netherlands

1. Cavern Abandonment – Background and Demands
2. Some Historical Highlights
3. Some Basics with Respect to Physical Modelling and Numerical Simulation
4. Some Basic Findings regarding Examples from Practice
5. Some recent Extensions of our Modelling Approach and Simulation Software
6. Concluding Remarks

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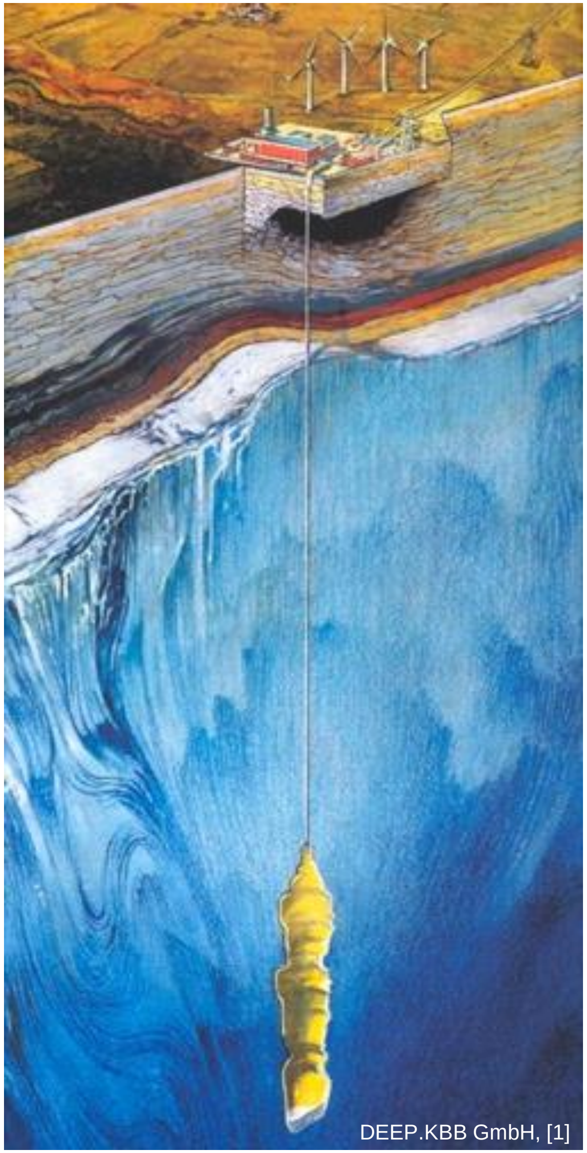
Cavern Abandonment – Background and Demands


DEEP.KBB GmbH, [1]

- A lot of large cavities have been created all over the world in salt rock mass since decades (solution mining, storage of liquids and gases, waste disposal).
  - ⇒ cavern design and approval
  - ⇒ cavern operation for decades

  } ***basically well experienced***

but …

- ***How to safely, economically, and maintenance-free as well as reliably abandon these special kind of geotechnical constructions?***
- Main aspects of safe as well as maintenance-free cavern abandonment ⇒
  - long-term stability →
    no sinkholes at surface, no failure at salt dome flanks, no unacceptable seismic events, …
  - long-term agreeability → limited surface subsidence
  - long-term environmental protection →
    no or agreeable release of contaminants into groundwater
- Preconditions
  - availability of experienced design and construction techniques?
  - acceptability by mining authorities / public?

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Expectations

Two basic theories in the 1980s

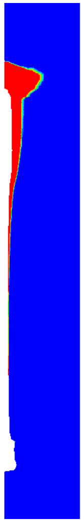
- Macro-fracturization
  ⇒ instantaneous creation of large hydrofracs

↕ ?

- Micro-fracturization
  ⇒ time-dependent pressure-driven infiltration / permeation / percolation

2012: Numerical Simulation ⇒

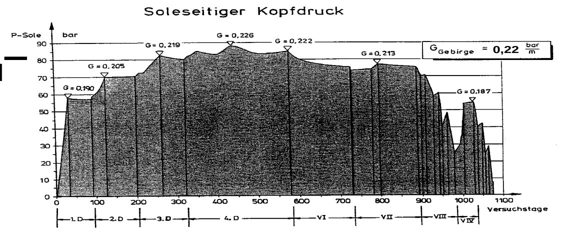
Wolters (2014), [5]



Observations

Etzel Field Test 1991-1994

p_{RM}



Konsortium „Druckaufbautest“, [4]

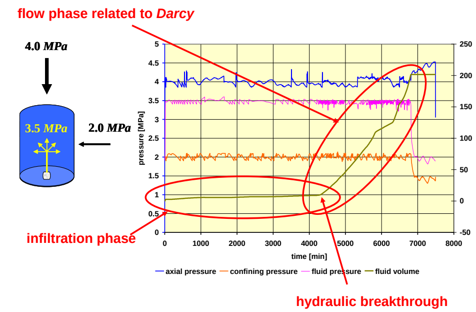
- No macro-fracturization at $p_{FI} \rightarrow p_{RM}$ / p_{RM} *unknown* (geophones, hydrophones)
- Infiltration starts at $p_{FI} \approx p_{RM}$
- Brine infiltration proceeds at elevated pressures

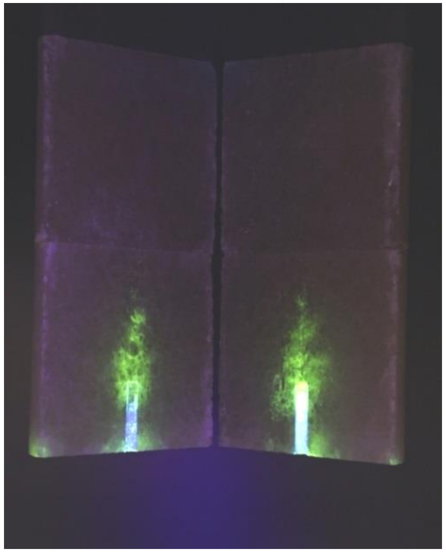
⇒ Abandonment of brine-filled cavities basically possible

- Extending infiltration zone?

Experiences

Lab Tests after 2000





SMRI

1996 Onset of Cavern Sealing and Abandonment Program

2000 Ratigan, J. – Status Report

2006 Crotogino et al. ⇒

Cavern Well Abandonment Techniques – Guidelines Manual

Boundary conditions: - homogeneous rock salt mass
- sufficient temperature equilibrium

→ brine-filled cavity can be sealed for an unlimited period of time without leading to uncontrolled fracturing of the surrounding rock mass

→ no uncontrolled brine expulsion is expected to take place into the covering rock mass, into drinking water aquifers or at the surface

…. several field tests, lab tests, and retrospective analyses in the following years

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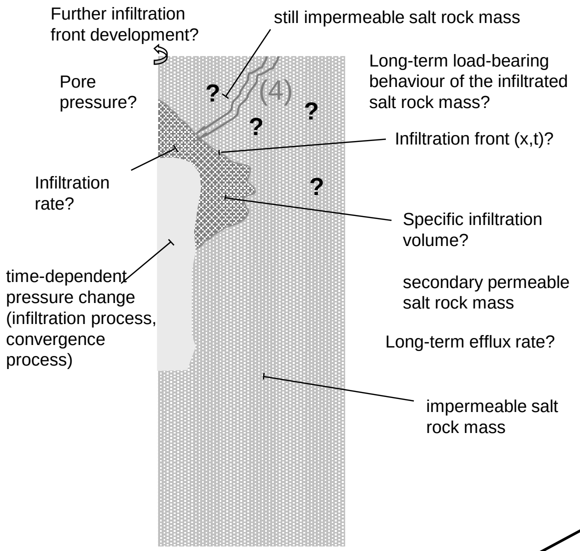
Main Questions Related to Load-bearing Behaviour of Sealed Brine-filled Cavities



Processes influencing fluid pressure / Ratigan (2000), [6]:

- salt rock mass creep / convergence (low deviatoric stresses) $p_i \uparrow$
- salt rock mass / cavern fluid heat transfer $p_i \uparrow$
- salt dissolution / cavern fluid saturation $p_i \downarrow$
- cavern fluid transportation into formation → perhaps most controversal issue $p_i \downarrow$
- cavern fluid transport through sealing plug / cementation $p_i \downarrow$

Key issues of uncertainties:

(1) Permeability of salt rock mass at complex stress states

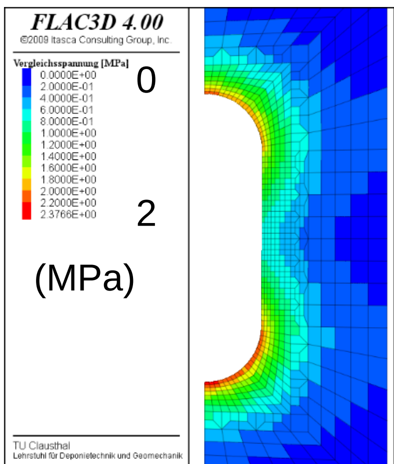
(2) Hydraulic and mechanical integrity of well casing shoe

(3) Geomechanical modelling of fluid/salt hydraulic and mechanical interaction after sealing

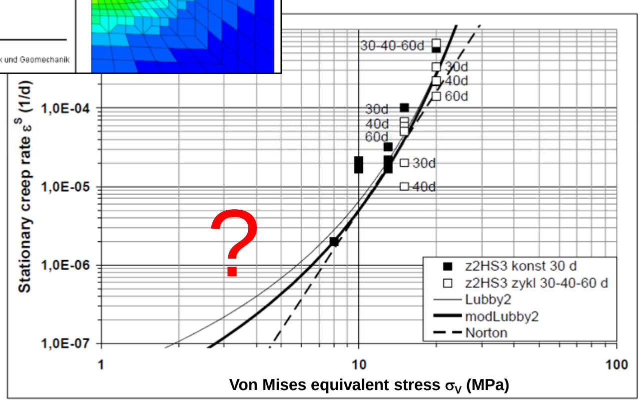
(4) Influence of heterogeneous salt rock mass (texture, impurities, fault zones) – supplement by Urai

Two Main Processes and Approaches for Physical Modelling

- **Creep Properties of Rock Salt at Small Deviatoric Stresses**



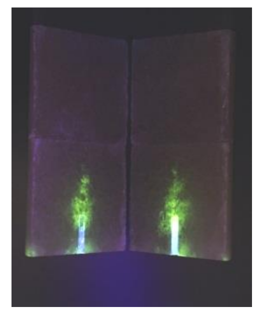
closed cavity – deviatoric stresses

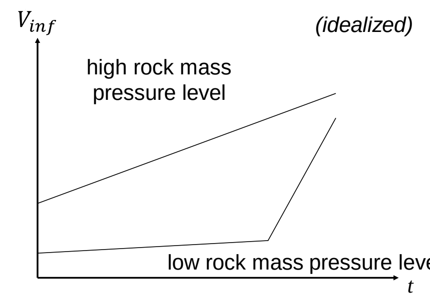


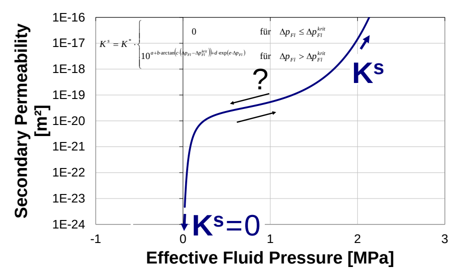
- **Basic assumption, Ratigan (2000):**

  Salt rock mass underlying primary rock mass stress field is impermeable

- **Pressure-driven Infiltration**







transient Darcy-flow with
- K^s irreversible, if p_{Fl} ↓
- K^s reversible, if p_{Fl} ↓ ?

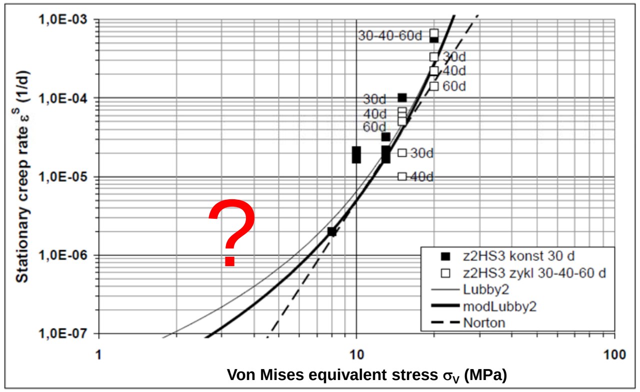
Modelling of Creep Process

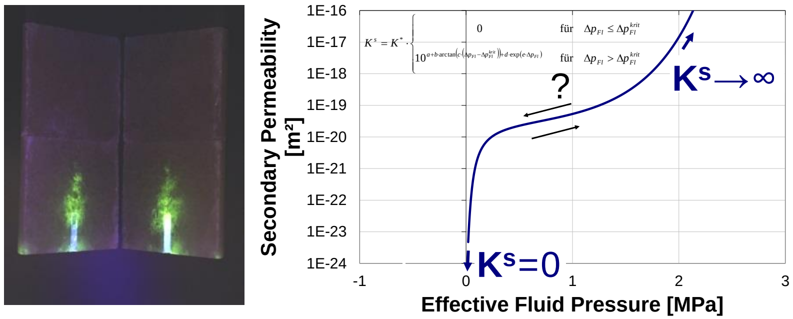
Modelling of Thermohydraulic Process

FLAC^{3D} ↔ **TOUGH3**

communicating by using

FTK-subroutines





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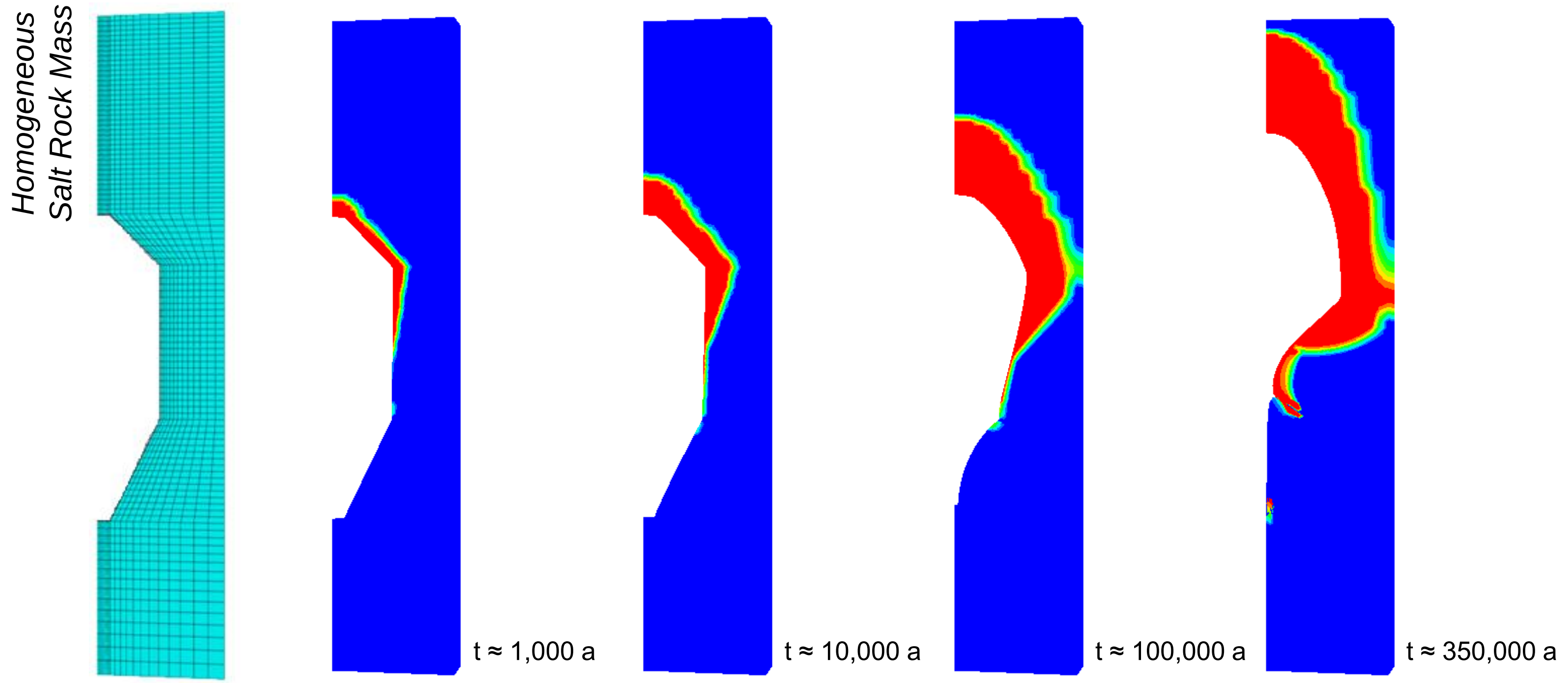
(4/1) Brine-filled Sealed Cavity – Limited Height / Shallow Depth

Infiltration process / transient Darcy flow ($K^s\uparrow\downarrow$)

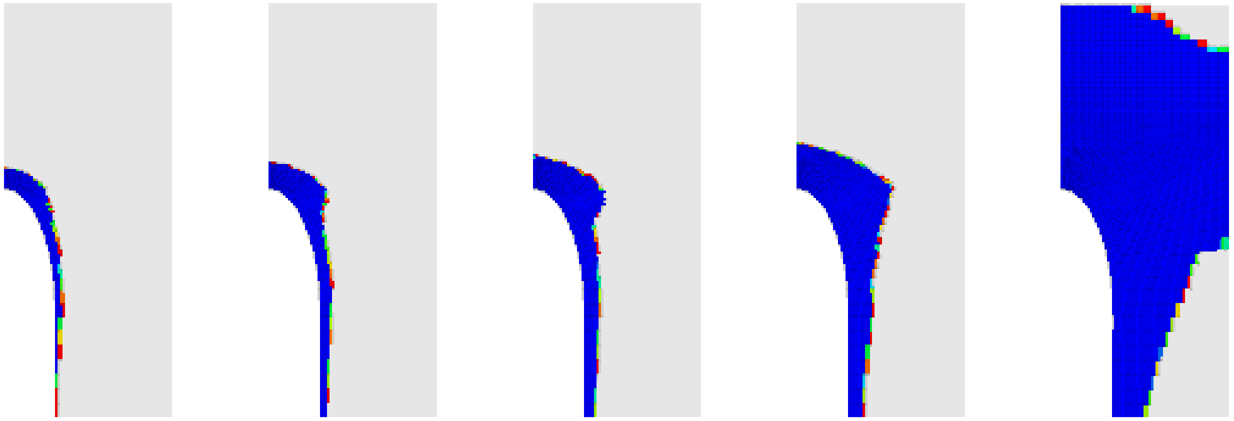


infiltration rate:	approx. 0.2 m³/a after 1,000 a and decreasing over time
hydraulic connection:	after approx. 350,000 a
exfiltration rate:	approx. 2-3·10^{-4} m³/a
convergence rate:	approx. 1.5·10^{-5} %/a after 1,000 a and decreasing to approx. 3·10^{-8} %/a after hydraulic connection

(?)

(4/2) Brine-filled Sealed Cavity – Large Height / Large Depth

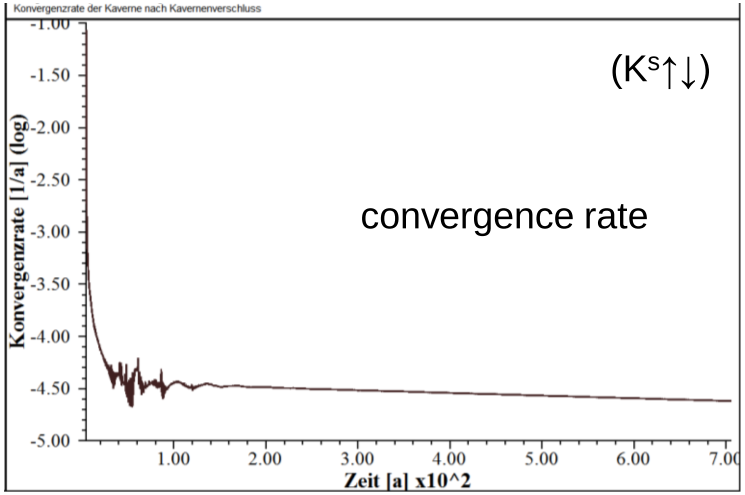
Infiltration process / transient Darcy flow ($K^s\uparrow\downarrow$)

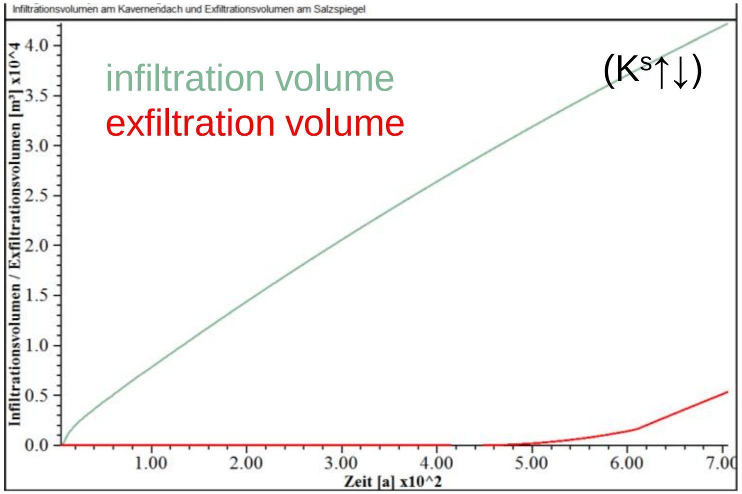


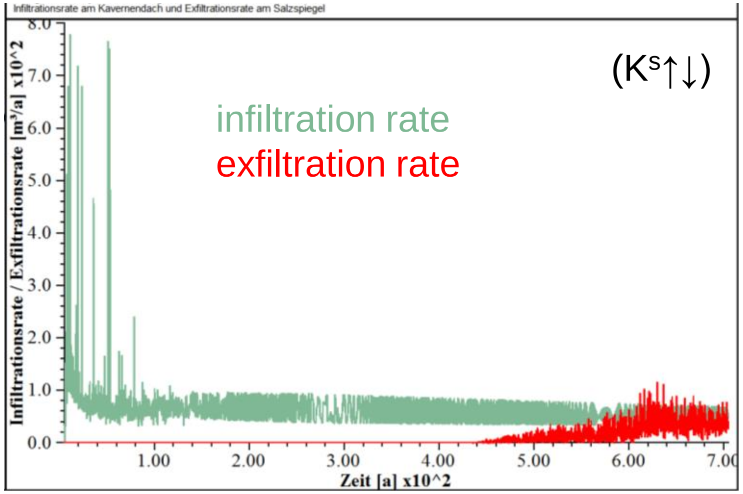
Main parameters related to safety aspects:

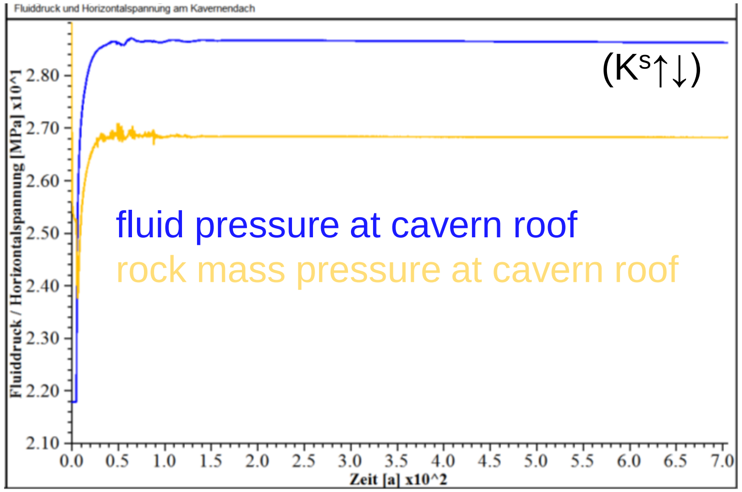
infiltration rate:	approx. 75 m³/a
hydraulic connection:	after approx. 500 a (?)
exfiltration rate:	approx. 60 m³/a
convergence rate:	approx. 0.003 %/a

(4/2) Brine-filled Sealed Cavity – Large Height – some state variables

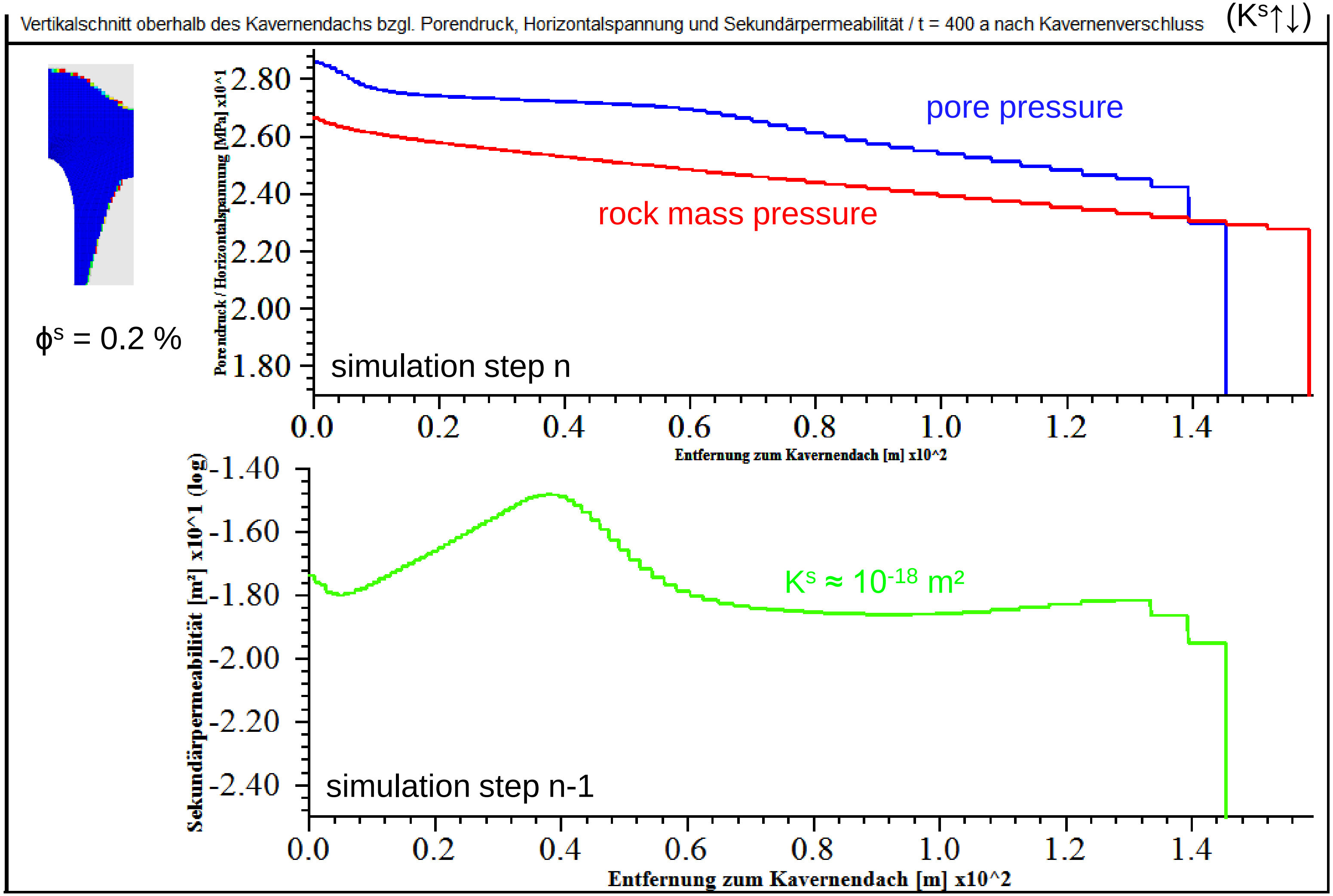




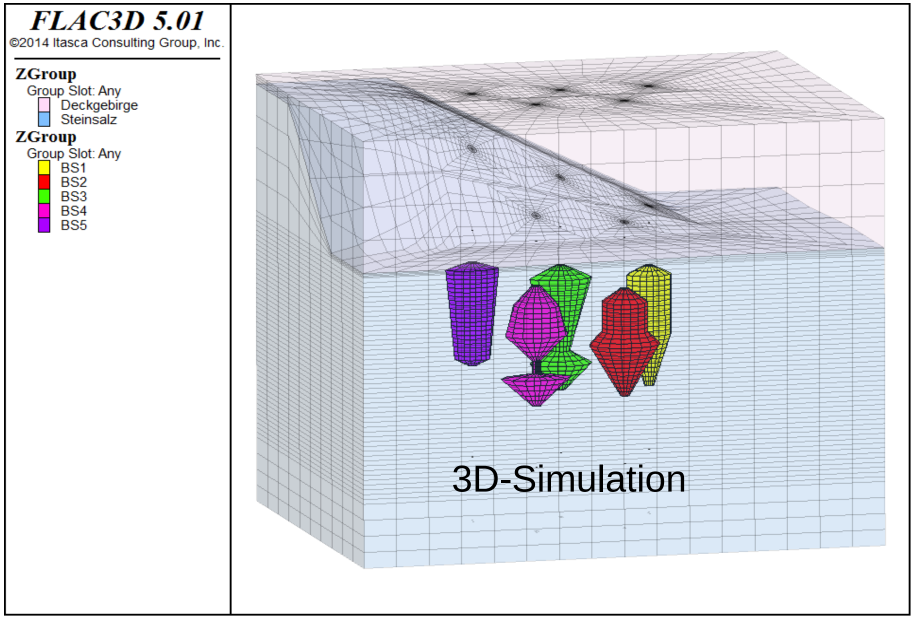


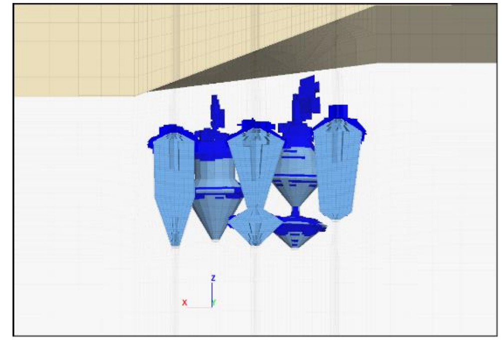


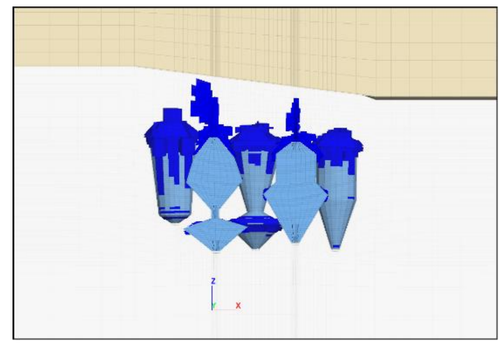
(4/2) Brine-filled Sealed Cavity – Large Height – some state variables

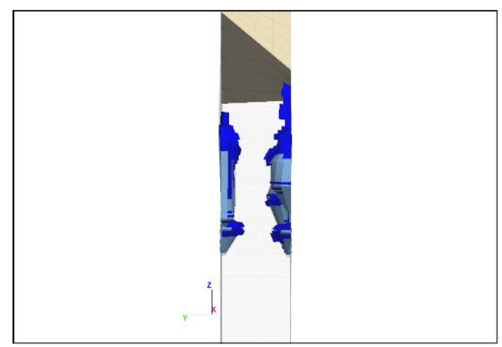


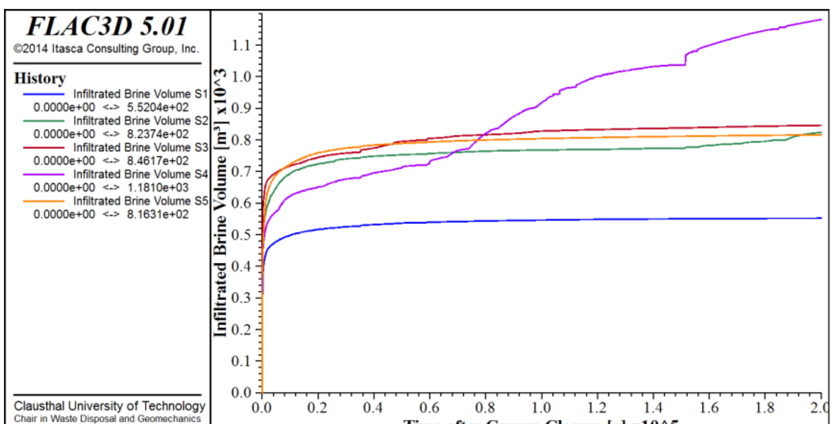
(4/3) Brine-filled Cavern System – Shallow Depth / t = 200,000 a



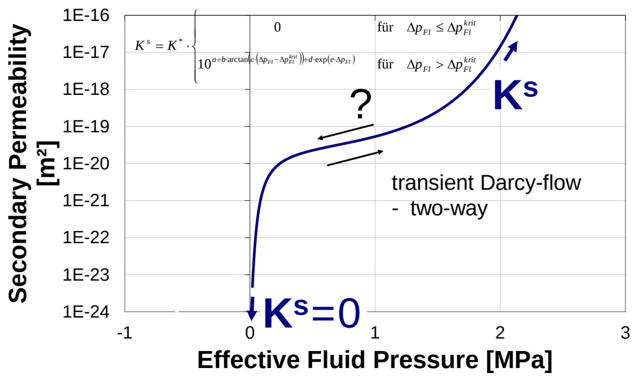








(4/4) Solid-filled Sealed Cavity – Shallow Depth / Backfilled



Laboratory at
Chair for Geomechanics and multiphysics Systems of
Clausthal University of Technology

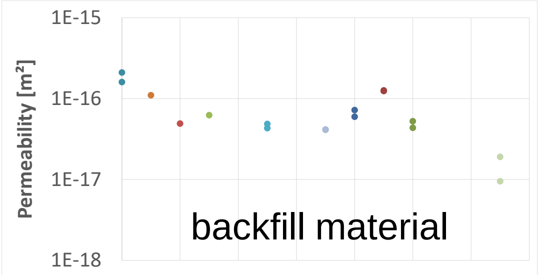
before consolidation
(slurry)

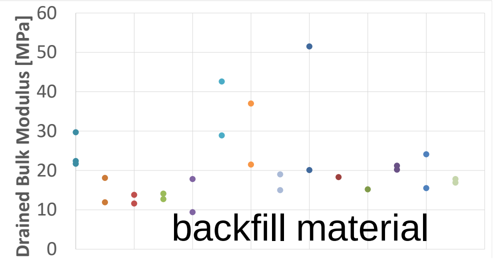
after consolidation

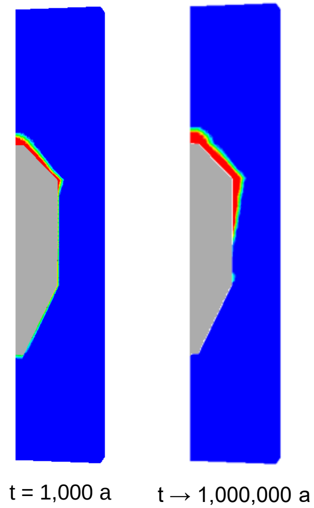
waste sample

(compacted material with residual pore fluid)

≈ 30% of pore fluid is squeezed out under consolidation pressure conditions !!!







finally protection of intact geologic rock salt mass barrier with sufficient thickness!

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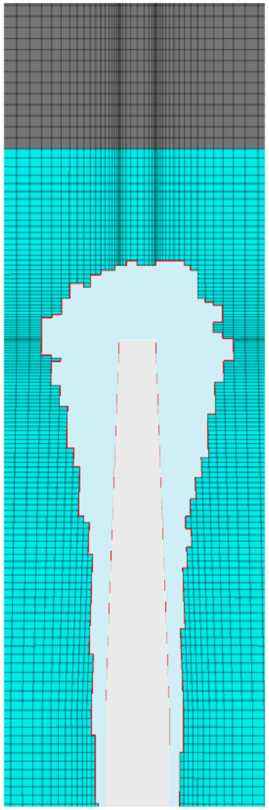
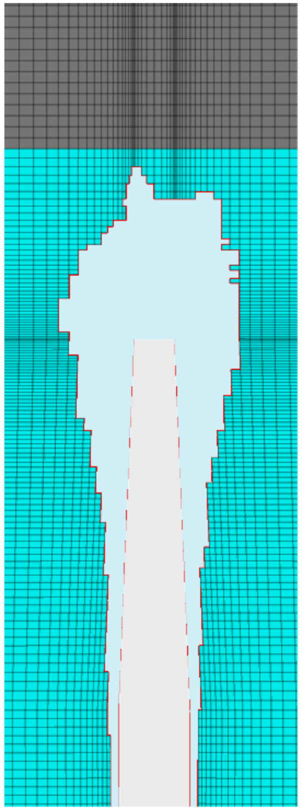
Hydraulic anisotropy

hydraulically isotropic salt rock mass ↔ hydraulically anisotropic salt rock mass



500 a



500 a

Assumptions:

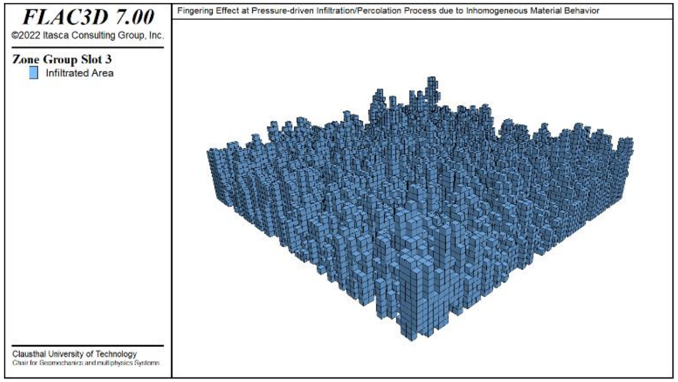
- steeply layered arrangement of salt crystal structure
- pressure-driven infiltration leads to bigger opening of grain boundaries and thus to hydraulically anisotropic material behaviour (secondary permeability in infiltration zone)
- secondary permeability in infiltration zone parallel to layering direction is 10 times higher than normal to layering direction

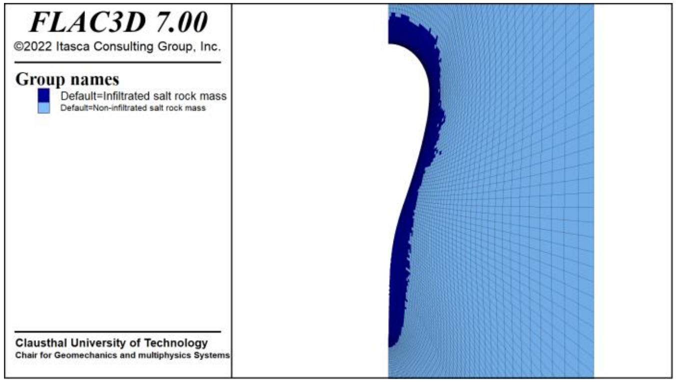
↓

upwards movement of infiltration front is faster

Fabric heterogeneity

micro-scale ↔ cavern-scale





Scenario (micro-scale):

– Rock salt block (1m x 1m x 1m) gets infiltrated from the bottom due to an slowly increasing fluid pressure.

– Infiltration threshold limit for each zone of the discretized model varies randomly between -1 MPa and 1 MPa due to fabric heterogeneities within the salt block.

→ **Fingering effect at infiltration front induced by fabric heterogeneities in the rock salt is clearly visible in the simulation results!**

Scenario (cavern-scale):

– Rock salt mass surrounding a sealed brine-filled cavern gets infiltrated.

– Fabric heterogeneities are considered in the numerical simulation by randomly varying infiltration threshold limit.

→ **Infiltration zone does not show relevant fingering effects exept for some non-infiltrated isolated zones with very high infiltration threshold limits!**

Outline

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Concluding Remarks

(a) State of the art – some aspects - 2024

(a/1) Large progress in understanding of basic mechanisms, physical modelling, numerical simulation techniques, as well as understanding of load-bearing system during past decades

(a/2) - Simulation of brine-filled sealed cavities / cavern fields
- Simulation of slurry-filled sealed cavities / cavern fields

} basically possible

How to consider / handle heterogeneities? How to handle imponderabilities?

(a/3) Quantification of safety-relevant state variables regarding long-term behaviour
→ convergence rate → subsidence rate
→ hydraulic connection → time of intact salt rock mass
→ exfiltration rate → rate of released fluids into environment

→ period under observation?
→ maximum permissible value?

(b) Further improvement of reliability (reduction of uncertainties) ⇒

Enhanced validation of relevant physical processes:
- creep properties at low deviatoric stresses / cavern convergence
- development / recreation of secondary permeability in salt rock mass?
- influence of inhomogeneities → hydraulic anisotropy
→ fabric heterogeneity

… some more?

References and additional literature:

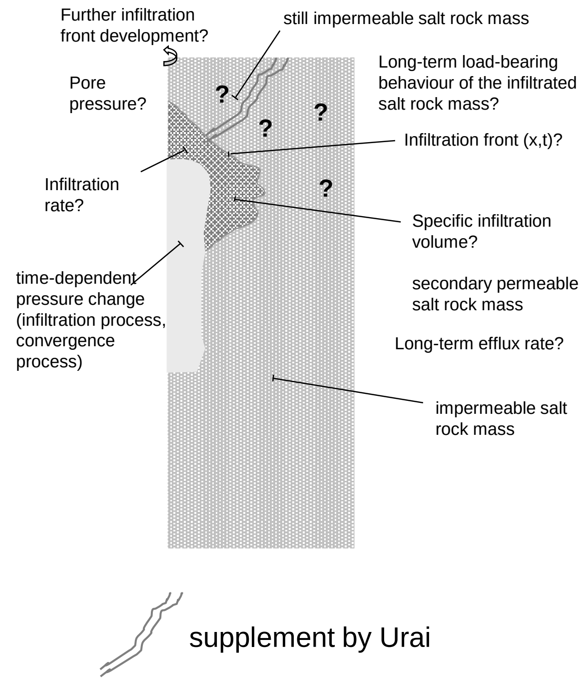
[1-3] *DEEP.KBB GmbH*

[4] *Konsortium „Druckaufbautest“ (1994)*:
Pressure Build-up Test at Etzel K102. Final Report.

[5] *Wolters, R. (2014)*:
Thermisch-hydraulisch-mechanisch gekoppelte Analysen zum Tragverhalten von Kavernen im Salinargebirge vor dem Hintergrund der Energieträgerspeicherung und der Abfallentsorgung. PhD thesis, TU Clausthal (Germany).

[6] *Ratigan, J.L. (2000)*:
A Status Report on the SMRI Cavern Sealing and Abandonment Program. SMRI Fall 2000 Meeting.

[7] *Lux, K.-H., Wolters, R., Sun-Kurczinski, J.Q. & Herchen, K. (2022)*:
Verbundprojekt: Weiterentwicklung und Qualifizierung der gebirgsmechanischen Modellierung für HAW-Endlagerung im Steinsalz (WEIMOS) (Teilprojekt E: TUC). Einzelbericht zum BMWi-geförderten Forschungsprojekt mit dem Förderkennzeichen 02E11446.



[8] *Lux, K.-H., Wolters-Zhao, R., Pan, T.J. & Feierabend, J. (2024)*:
Computer- und laborgestützte Analysen zur Bewertung der mechanisch-hydraulischen Bohrungsintegrität im Rohrschuhbereich von Salzkavernenbohrungen im Hinblick auf die langzeitsichere Speicherung von Wasserstoff und Druckluft. Abschlussbericht zum BMWi-geförderten Forschungsprojekt mit dem Förderkennzeichen 03EI3006.

[9] *Lux, K.-H., Wolters, R. & Düsterloh, U. (2015)*:
Konsistente TH2M-gekoppelte multi-physikalische Simulationen zum Tragverhalten von Speicherkavernen im Steinsalzgebirge während der Aussol-, der Betriebs- und der Stilllegungsphase sowie in der Nachverschlussphase. Erdöl-Erdgas-Kohle, 11/2015.

Thank you for your attention!