BUNDESGESELLSCHAFT
FÜR ENDLAGERUNG

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Treatment of uncertainties with respect to geomechanical modelling for proof of structural stability and integrity of the geological barrier of a radioactive waste repository in rock salt

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Background – integrity criteria

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Integrity-relevant processes

leading to damage and loss of initial tightness of the rock salt

(1) generation and growth of (inter-connected) cracks due to deviatoric loading; shear stress-induced damage

and/or

(2) fluid-pressure-driven opening of grain boundaries, if p exceeds the normal stress and adhesive forces at the boundaries

Criteria to assess integrity and tightness of rock salt

↳ *Dilatancy criterion*

i.e. boundary for microstructural damage, after *Hunsche & Cristescu*

$$\frac{\tau}{\sigma^*} \le -0.1697 \cdot \left(\frac{\sigma_0}{\sigma^*}\right)^2 + 0.8996 \frac{\sigma_0}{\sigma^*} \quad \rightarrow \quad \tau_{oct} / \tau_{dil} > 0$$

↳ *Fluid-pressure criterion*

(„Minimum principal stress criterion" or „hydrofrac-criterion") i.e. conservative approach using σ_3 and theoretical brine-pressure by neglecting tensile strength

$$\sigma_{min} > p_{fl} \quad \rightarrow \quad \Delta p = \sigma_{min} - p_{fl} > 0$$

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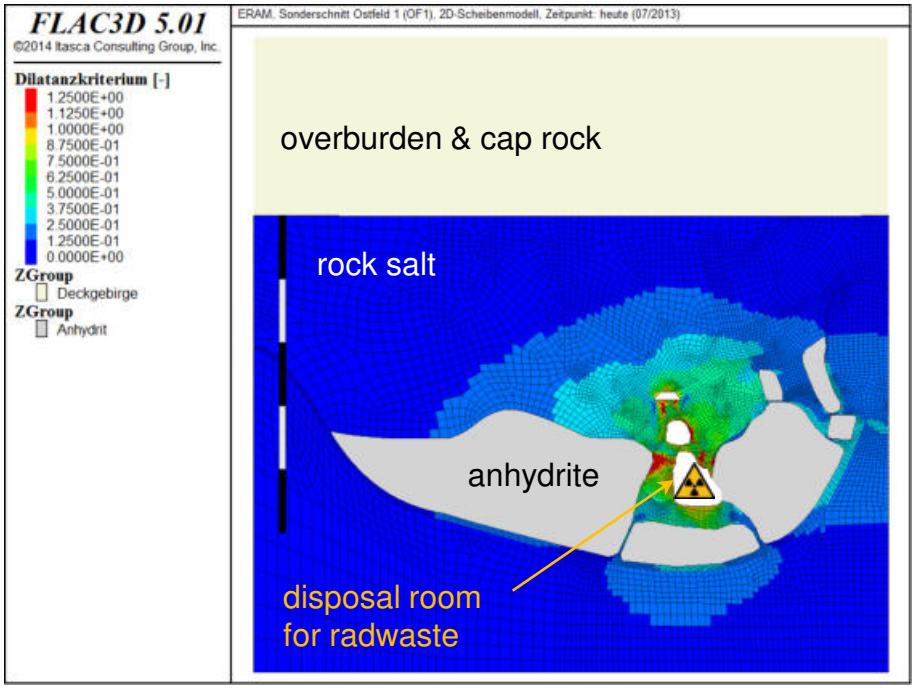
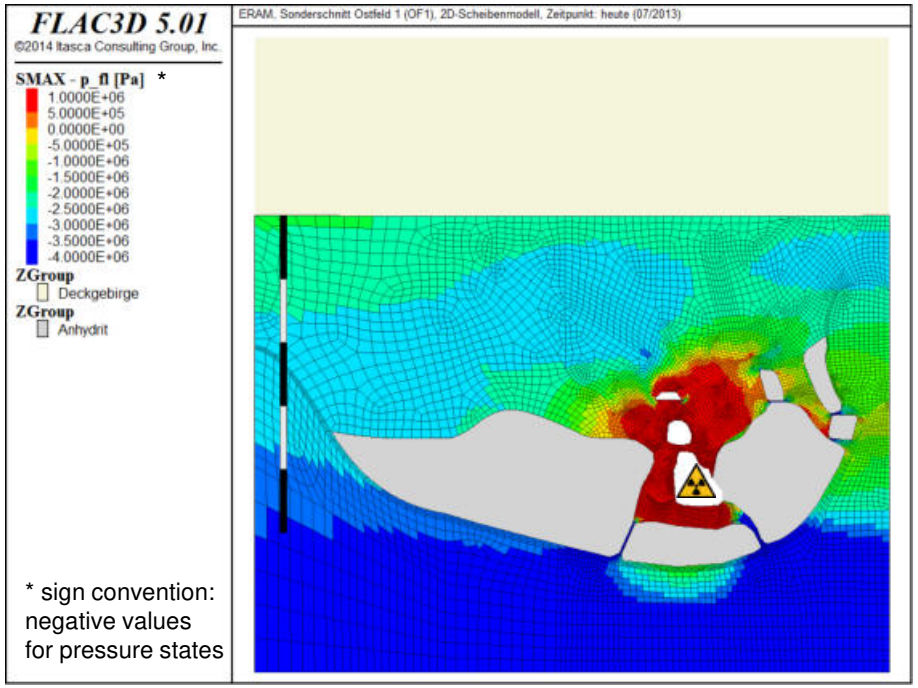
Geomechanical modelling – exemplary results

State: „today"

Dilatancy criterion τ_{oct} / τ_{dil}



Fluid-pressure criterion $\sigma_3 - p_{fluid}$



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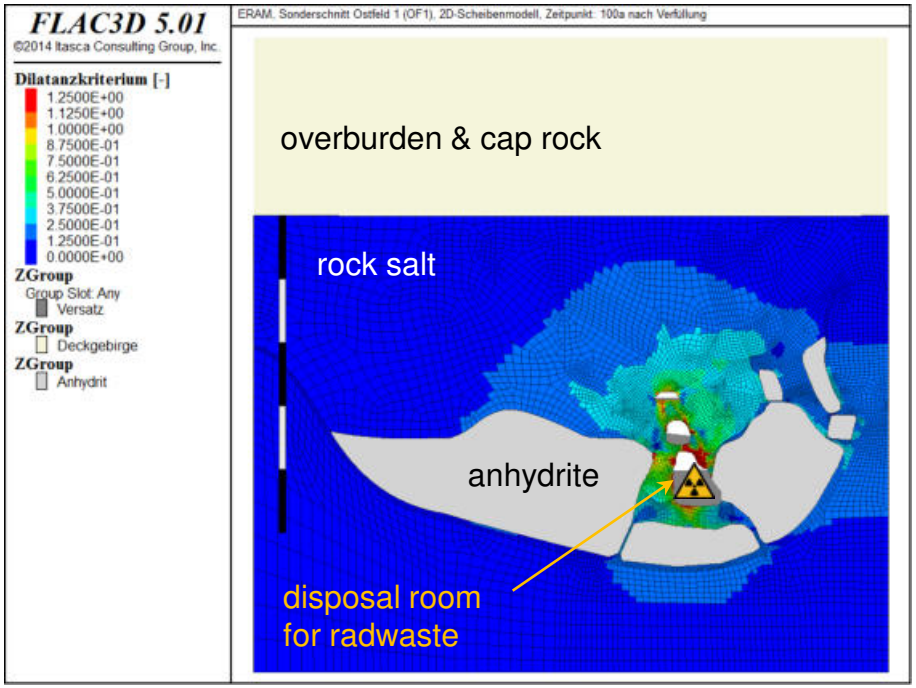
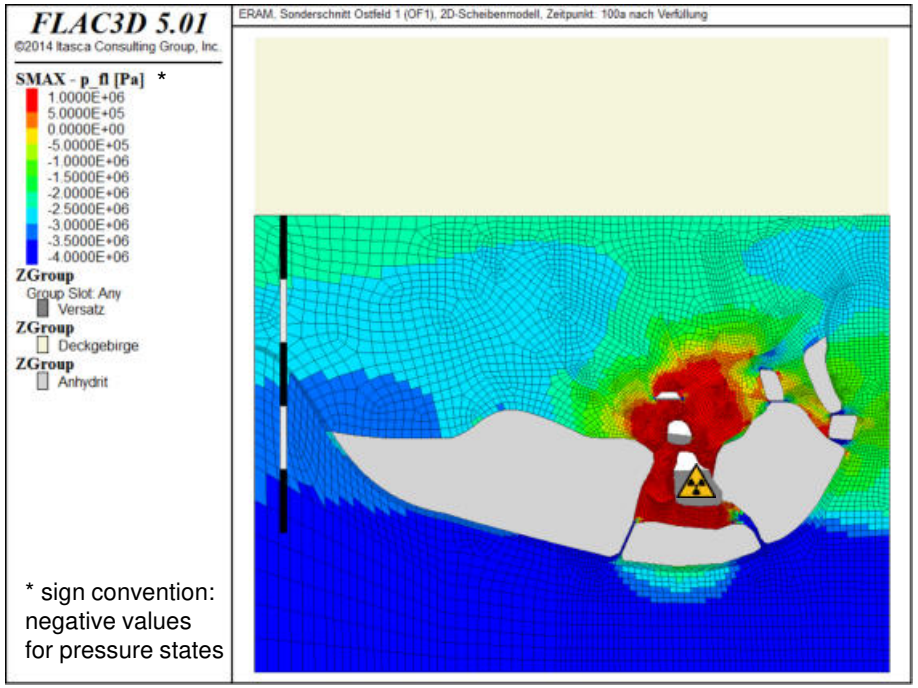
Geomechanical modelling – exemplary results

State: 100 years after emplacement and backfilling

Dilatancy criterion τ_{oct} / τ_{dil}

Fluid-pressure criterion $\sigma_3 - p_{fluid}$





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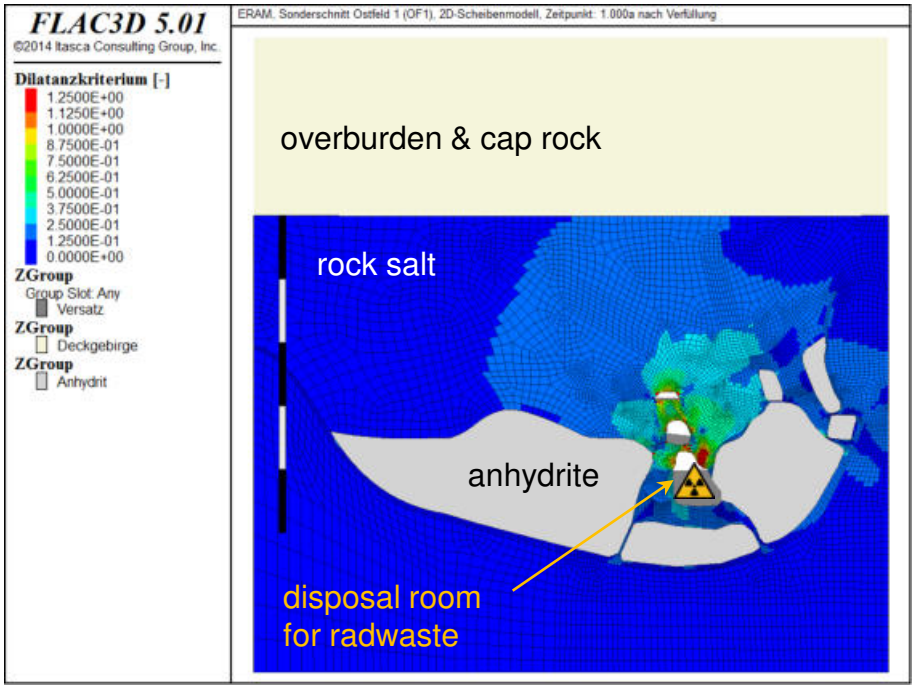
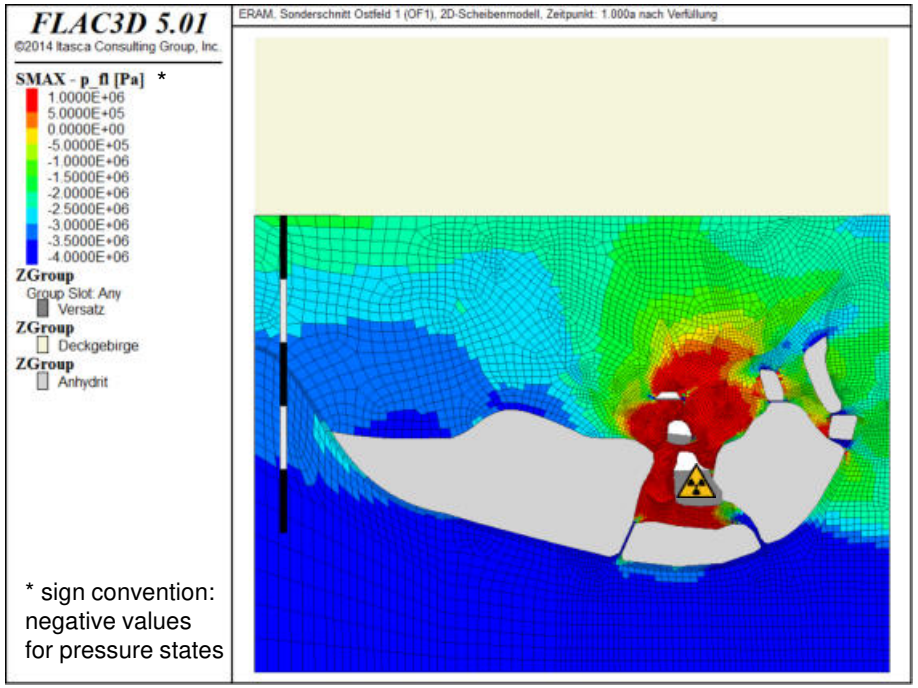
Geomechanical modelling – exemplary results

State: 1.000 years after emplacement and backfilling

Dilatancy criterion τ_{oct} / τ_{dil}

Fluid-pressure criterion $\sigma_3 - p_{fluid}$





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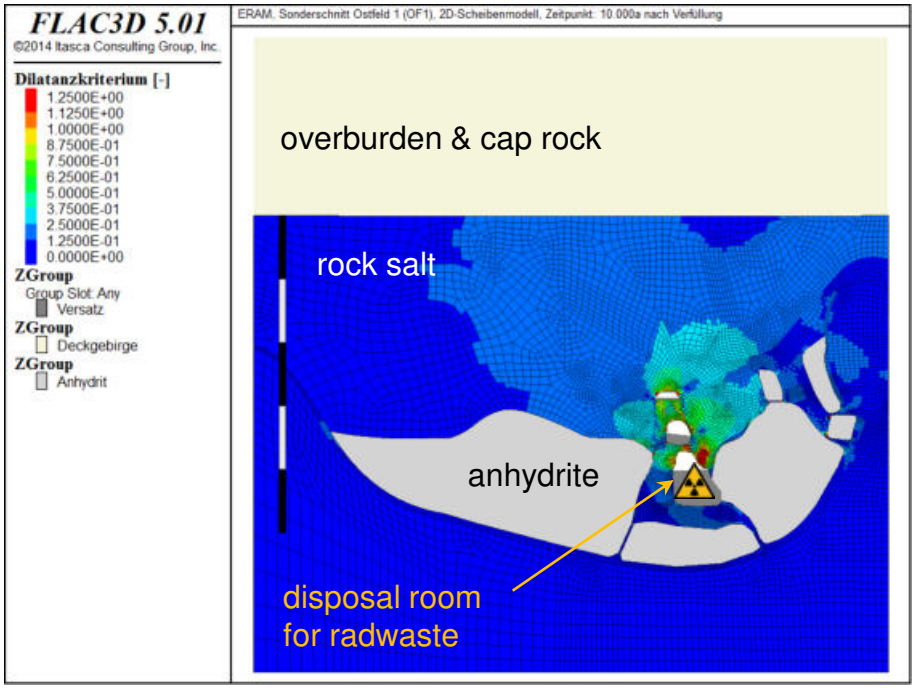
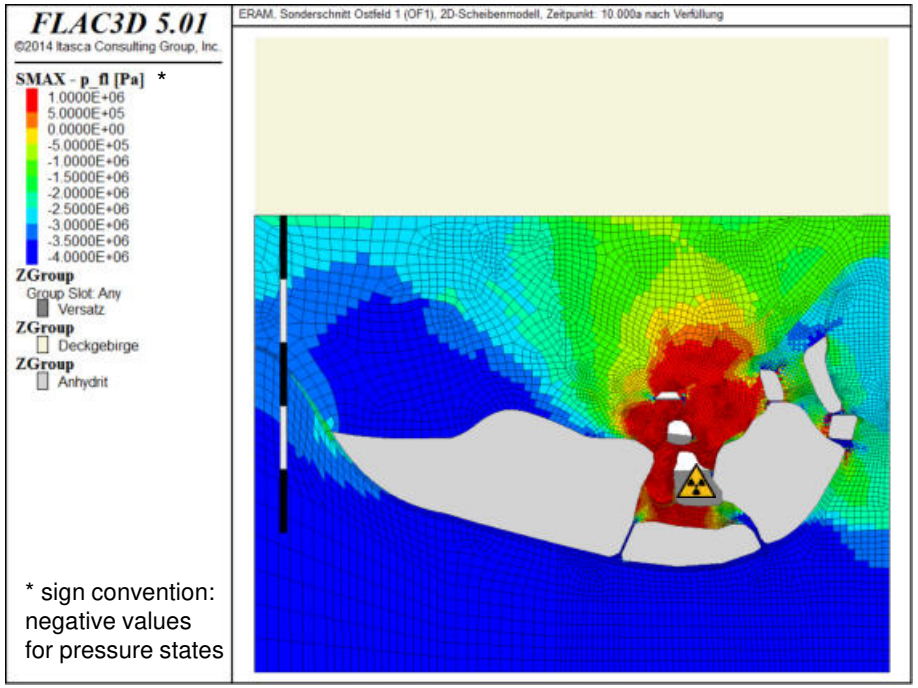
Geomechanical modelling – exemplary results

State: 10.000 years after emplacement and backfilling

Dilatancy criterion τ_{oct} / τ_{dil}

Fluid-pressure criterion $\sigma_3 - p_{fluid}$





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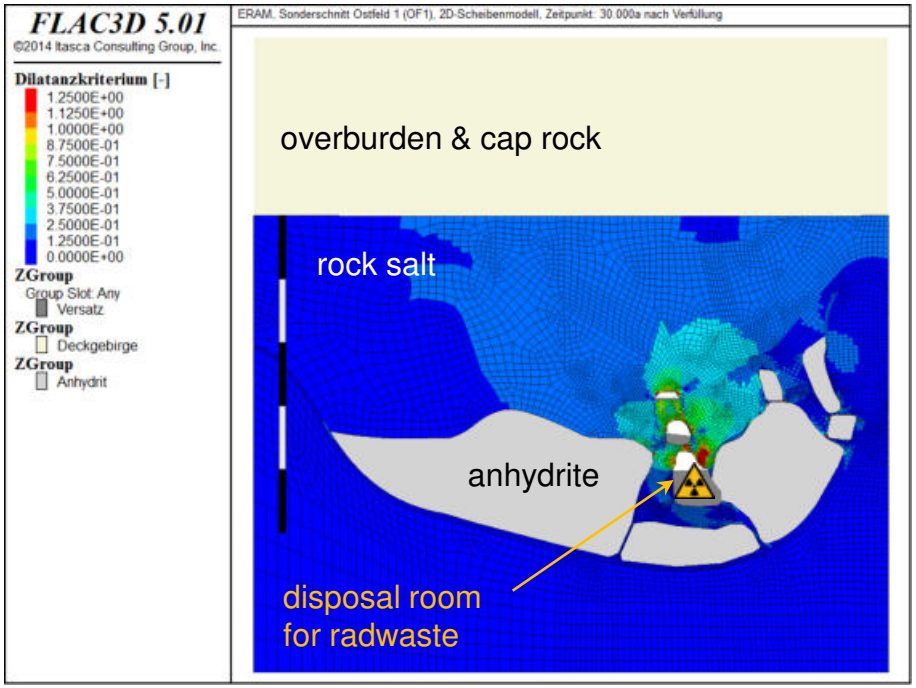
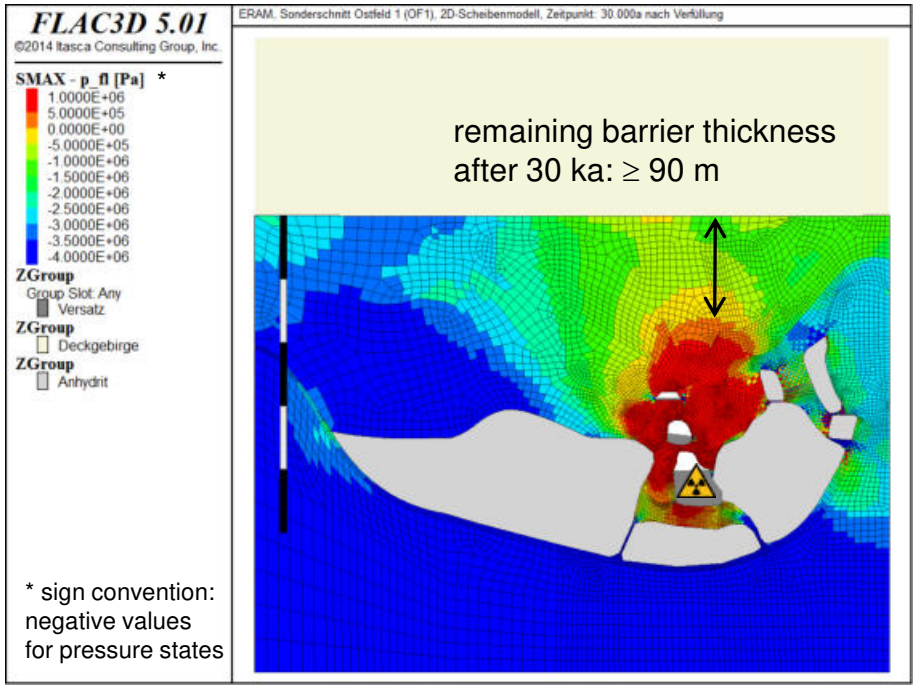
Geomechanical modelling – exemplary results

State: 30.000 years after emplacement and backfilling

Dilatancy criterion τ_{oct} / τ_{dil}

Fluid-pressure criterion $\sigma_3 - p_{fluid}$





Background – safety analyses

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Geomechanical modelling – exemplary results

State: 30.0

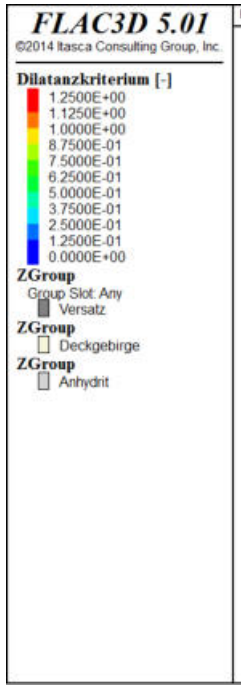
Dilatancy cr

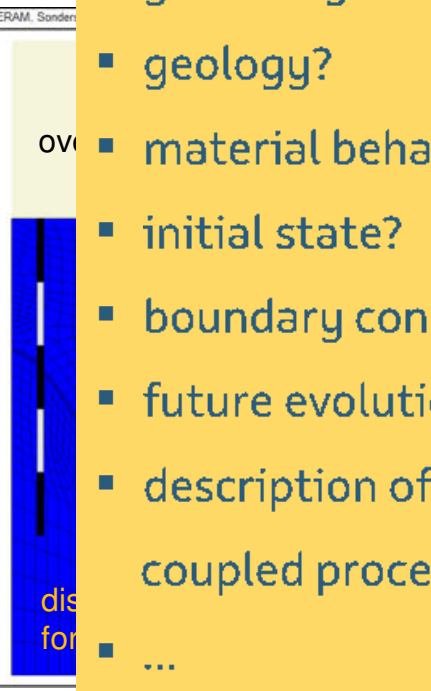
iterion $\sigma_3 - p_{fluid}$

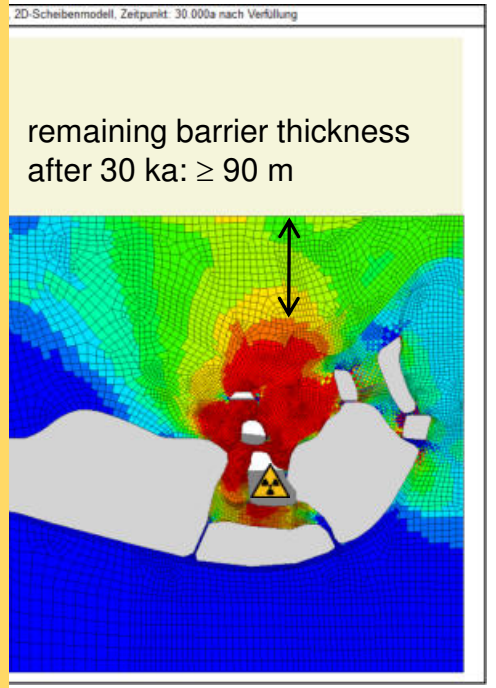
***BUT:* influence of data uncertainties and modelling approaches and assumptions**

- geometry?
- geology?
- material behaviour?
- initial state?
- boundary conditions?
- future evolution?
- description of coupled processes
- ...

robustness of analyses and results?







Background – legal requirements

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Requirement for numerical calculations of long-term-evolution

due to regulatory guidelines (*Sicherheitsanforderungen /BMU, 2010/*)

- Uncertainty and sensitivity analyses aiming at data, parameter, and model-uncertainties
  - ➢ showing possible bandwidth of solutions
  - ➢ showing influence of uncertainties

- Compliance with numerical criteria has to be shown with sufficient reliability – even taking into account uncertainties

Course of action – stepwise approach

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1. Systematic screening of the whole modeling sequence from input data to output
   - → *compiling catalogue of uncertainties and possible relevant issues*
   - → *determining responsibilies for assessment*

2. Quantifying uncertainties and assigning bandwidths, if possible
   - → *expert's assessment, literature studies, other evidence, ...)*

3. Analyzing and quantifying impacts of individual uncertainties on the safety function (= barrier integrity) through sensitivity- and bandwidth-studies
   - → *using generic models (if necessary several representative models)*
   - → *evaluating the long-term evolution of the geomechanical state within the rock salt barrier; i.e., violation of fluid-pressure and dilatancy criteria as well as barrier thickness*
   - → *quantifying the impact of each uncertainty on the barrier integrity*
   - → *identifying uncertainties with relevant impact*

Course of action – stepwise approach

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4. Additional safety analyses for sensitive issues identified

   → *checking the relevance of these issues on more realistic, comprehensive location-specific models*

↓

Relevant impact of uncertainties on safety function?

YES ↓

↓ NO

✓

5. Assessment regarding reduction / avoidance or acceptance of uncertainties

   → *if necessary taking measures to narrow down bandwidths until uncertainty range becomes acceptable or has to be accepted (iterative approach)*

Step (1) – catalogue of uncertainties

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Categories*:

1. Mine-opening model
2. Geological/geotechnical model
3. Backfill planning
4. Code used (computational model)
5. Numerical model
6. Open void (modeling of non-backfilled cavity volume)
7. Constitutive models and parameter

* In the present case, limitation regarding data, parameter, and model uncertainties with respect to demonstration of integrity of the rock salt barrier (no scenario uncertainties).

Step (1) – catalogue of uncertainties

BGE BUNDESGESELLSCHAFT FÜR ENDLAGERUNG

Categories*:

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* In the present case, limitation regarding data
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Issues (data uncertainties, etc.), i.e.:

- geometry of rooms
  - deviation/variation of location
  - deviation/variation of dimensions
  - idealization: scanned surface vs. plain contour (modelling assumption)
- excavation history
  - point of time (shorter/longer open period)
  - stepwise vs. instantaneous excavation (modelling assumption)
- backfill (debris)
  - point of time
  - degree of backfilling / open voids
  - stepwise vs. instantaneous backfilling (modelling assumption)

Step (1) – catalogue of uncertainties

BGE BUNDESGESELLSCHAFT FÜR ENDLAGERUNG

Categories*:

1. Mine-opening model
2. **Geological/geotechnical model** ⇨
3. Backfill planning
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5. Numerical model
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7. Constitutive models and parameter

Issues (data uncertainties, etc.), i.e.:

- position & setting of geologic structures
  - position of stratigraphic boundaries
  - position and thickness of anhydrite
  - position of top of salt dome
  - segmentation of anhydrite (thickness of blocks, distance and material between individual blocks)
- geotechnical description of homogeneous units & their properties
  - creep ability
  - transition zone between units (impact of different modelling approaches)

* In the present case, limitation regarding data

respect to demonstration of integrity of the rock salt barrier (no "scenario uncertainties).

Step (1) – catalogue of uncertainties

BGE BUNDESGESELLSCHAFT FÜR ENDLAGERUNG

Categories*:

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3. **Backfill planning**
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5. Numerical model
6. Open void (modeling of non-backfilled
7. Constitutive models and parameter

Issues (data uncertainties, etc.), i.e.:

- backfill-planning (salt concrete)
  - influence of time-delay for backfilling
  - influence of sequence for backfilling (several rooms)
- backfilled volume / ratio
  - backfilling ratio / open void
  - additional rooms to be backfilled
- backfilling process
  - stepwise vs. instantaneous backfilling (modelling assumption)

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Step (1) – catalogue of uncertainties

BGE BUNDESGESELLSCHAFT FÜR ENDLAGERUNG

Categories*:

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5. Numerical model
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7. Constitutive models and parameter

Issues (model assumptions, etc.), i.e.:

- code used for modelling
  - continuum-based codes (FDM vs. FEM)
  - continuum-based vs. DEM ("glued joints")
- influence of non-linear behaviour
  - geometrical non-linear behaviour (geometry update due to convergence)
  - geometrical & structural non-linear behaviour (form and force closure, contact)

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Step (1) – catalogue of uncertainties

BGE BUNDESGESELLSCHAFT FÜR ENDLAGERUNG

Categories*:

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7. Constitutive models and parameter

Issues (model assumptions, etc.), i.e.:

- influence of model boundaries
  - position / model dimensions
  - mechanical boundary conditions
  - thermal boundary conditions
  - kinematic restrictions (2D vs. 2,5D)
- influence of initial state
  - mechanical initial state
  - thermal initial state
- influence of discretization
  - influence of grid refinement
  - time increment
  - solution scheme (explicit vs. implicit)
- evaluation of results
  - interpolation algorithm

* In the present case, limitation regarding data
respect to demonstration of integrity of the rock salt barrier (no scenario uncertainties).

Step (1) – catalogue of uncertainties

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Categories*:

1. Mine-opening model
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4. Code used (computational model)
5. Numerical model
6. **Open void (modeling of non-backf...**
7. Constitutive models and parameter

Issues (model assumptions, etc.), i.e.:

- creep-failure; different modelling approaches
  - ➢ reduced system stiffness (→ stress re-distribution)
  - ➢ downfall leading to filling of open voids (self-stabilization of system)
- creep-failure; assumptions
  - ➢ depth of rooms
  - ➢ downfall sequence (instantaneous vs. successive) / duration
  - ➢ properties of filling material

* In the present case, limitation regarding data, parameter, and model uncertainties with respect to demonstration of integrity of the rock salt barrier (no scenario uncertainties).

Step (1) – catalogue of uncertainties

BGE BUNDESGESELLSCHAFT FÜR ENDLAGERUNG

Categories*:

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4. Code used (computational model)
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7. **Constitutive models and parameter**

Issues (data uncertainties, etc.), i.e.:

- rock salt
  - material behaviour (additional consideration of primary & tertiary creep)
  - constitutive models
  - model parameters
- cap rock & overburden
  - constitutive model & parameters
- backfill material (salt concrete and debris)
  - constitutive model & parameters
- anhydrite
  - constitutive model & parameters

* In the present case, limitation regarding data, parameter, and model uncertainties with respect to demonstration of integrity of the rock salt barrier (no scenario uncertainties).

Step (3) – generic models

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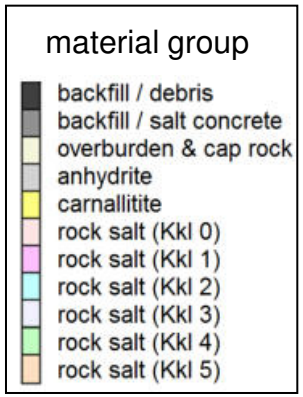
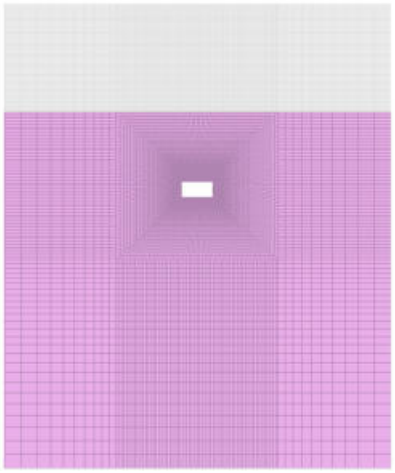
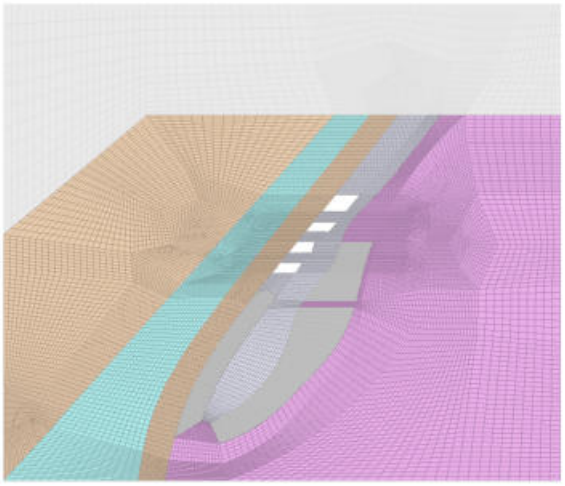
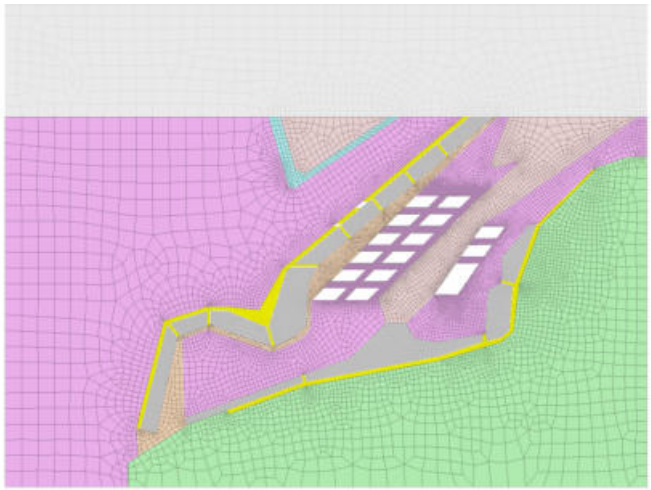
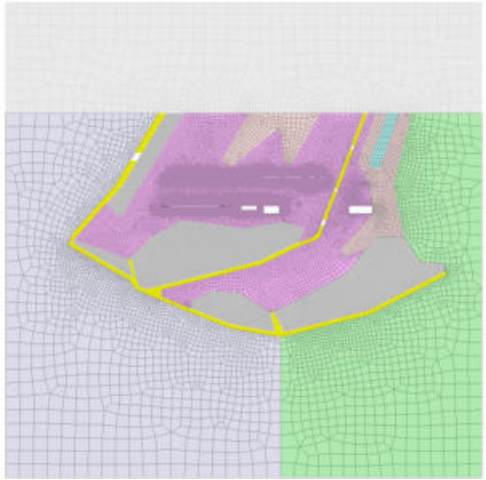
- Use of 4 generic models with representative setup of geology & mine lay-out
- Easy to adapt to specific issues (geometry, geology, discretization, etc.)
- Not every issue handled in/by each model)











Step (3) – generic models
Example: single room model – reference case

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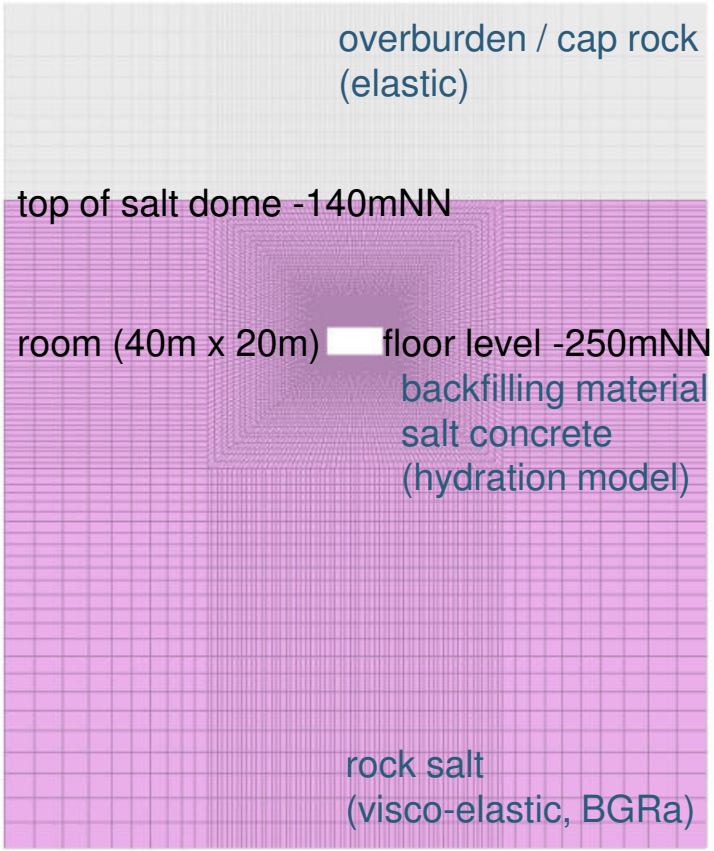
- Defining reference case in terms of
  - model approaches (in this case: 2D, plane strain)
  - model dimensions
  - constitutive models and parameters
  - boundary & initial conditions
  - calculation sequence
  - ...
- simulation of excavation and backfilling, time-dependent, TM-coupled (in this case instantaneous excavation 100 years before backfilling with a ratio of 65%)
- creep calculation until end of calculation at 100.000 years; defined interim states for result evaluation



Step (3) – generic models
Result evaluation

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- Quantifying the impacts of individual uncertainties on the safety function (= barrier integrity)

- Result evaluation with respect to time– and location–dependent variability
  - at defined time t = „today", 10^1a/ 10^2a / 10^3a / 10^4a / 10^5a
  - at definded levels z = top of salt dome / 50m below top of salt dome

- Result recording of:
  - min σ_3 (t, z) and $\sigma_3 - p_{fluid}$ → *Fluid–pressure criterion*
  - max τ_{oct}/τ_{dil} (t, z) → *Dilatancy criterion*
  - barrier thickness

- identifying relevant issues / differences to reference case

Step (3) – generic models
Single room model: exemplary results

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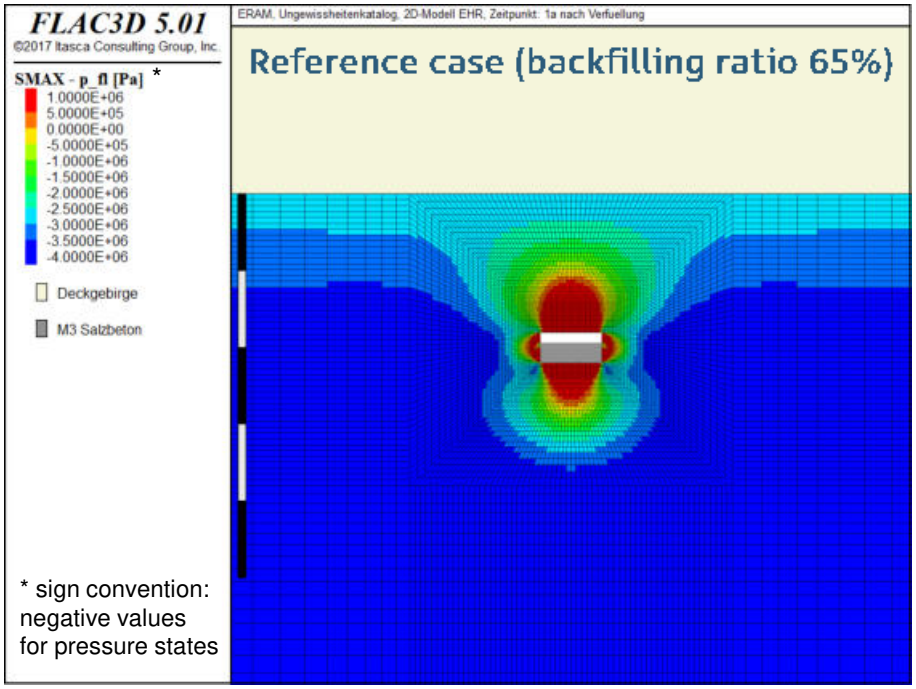
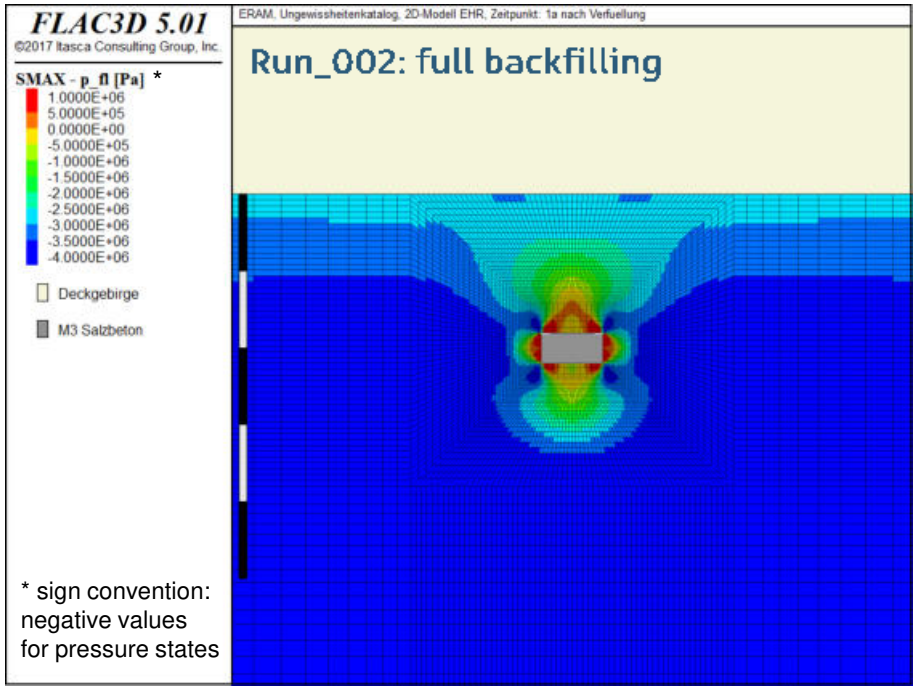
Fluid-pressure criterion $\Delta p = \sigma_3 - p_{fluid,\ theoretical}$

State: 1 year after backfilling





Step (3) – generic models
Single room model: exemplary results

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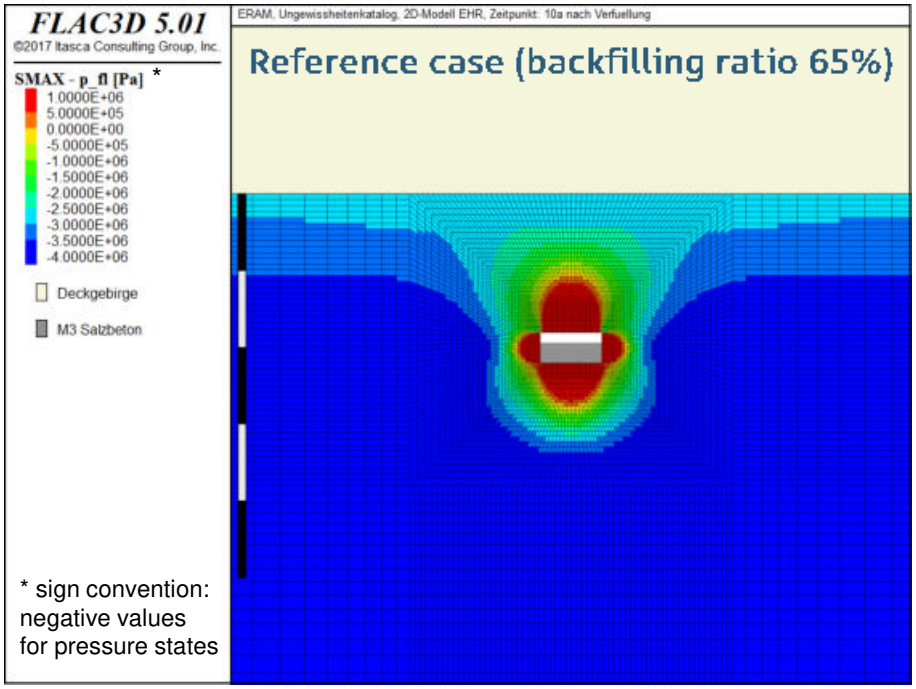
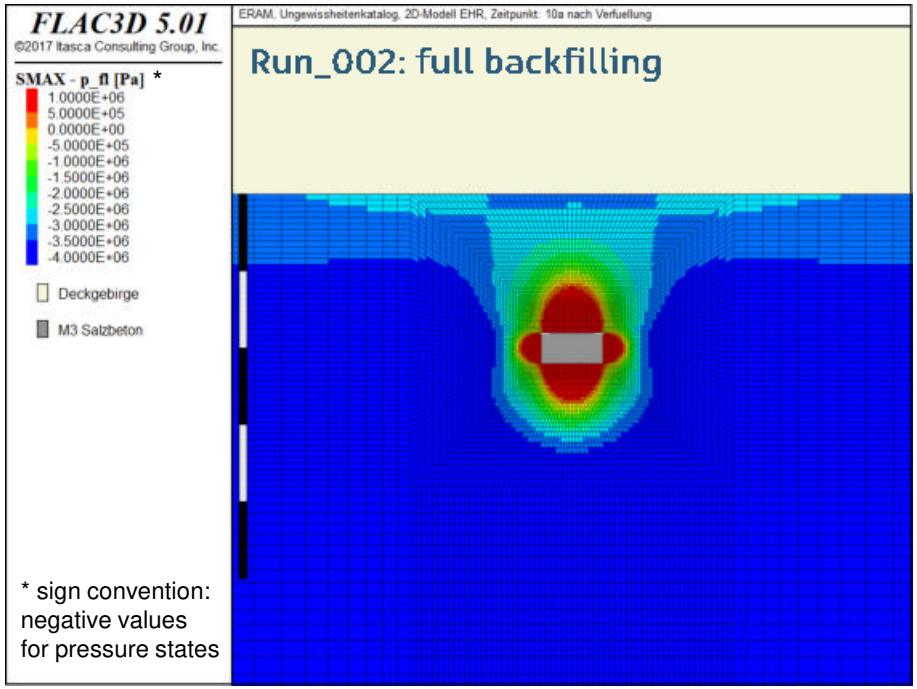
Fluid-pressure criterion $\Delta p = \sigma_3 - p_{fluid,\ theoretical}$

State: 10 years after backfilling





Step (3) – generic models
Single room model: exemplary results

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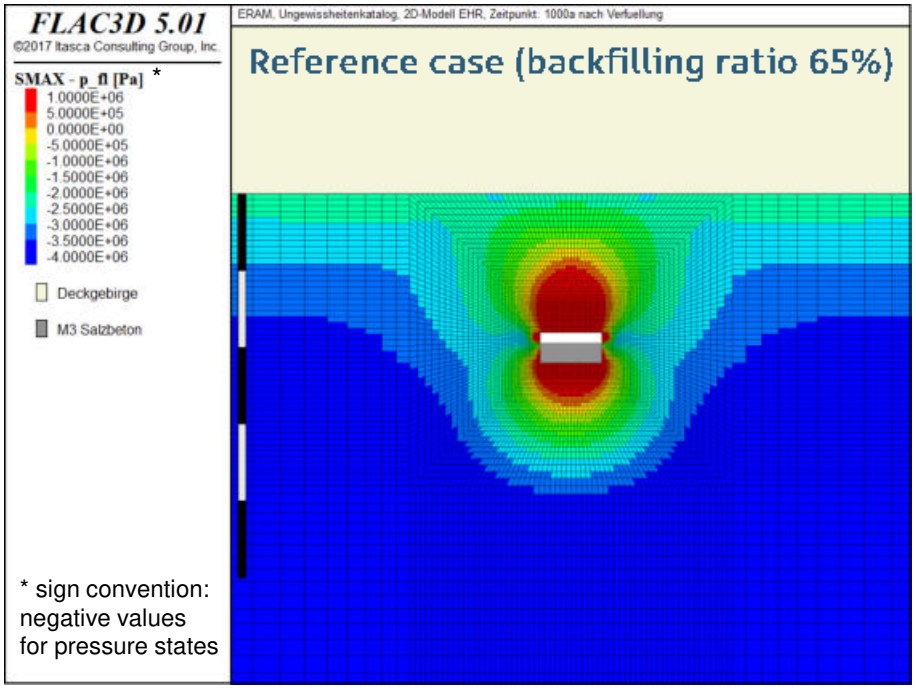
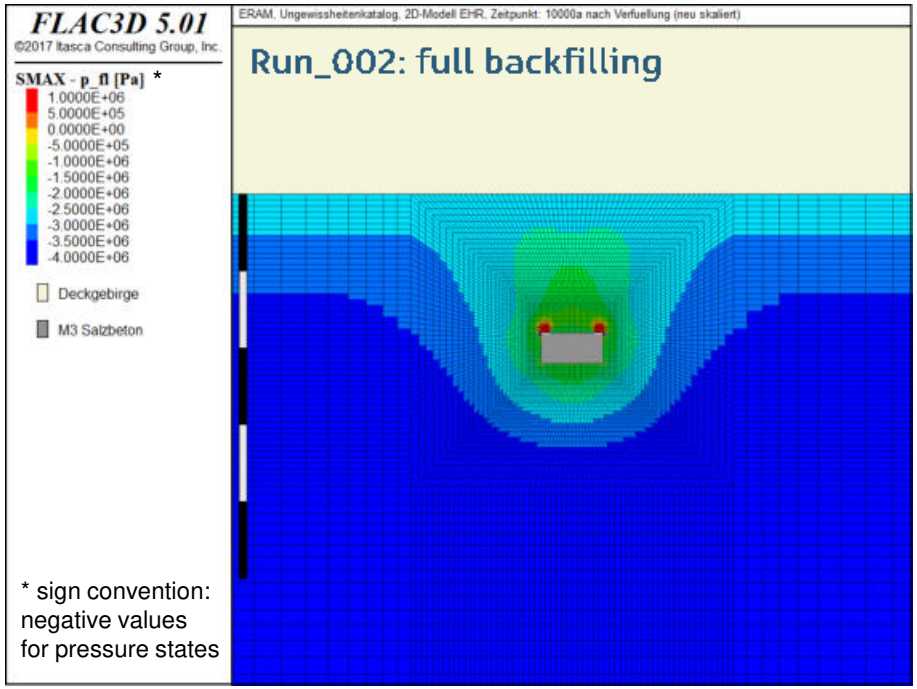
Fluid-pressure criterion $\Delta p = \sigma_3 - p_{fluid,\ theoretical}$

State: 1.000 years after backfilling





Step (3) – generic models
Single room model: exemplary results

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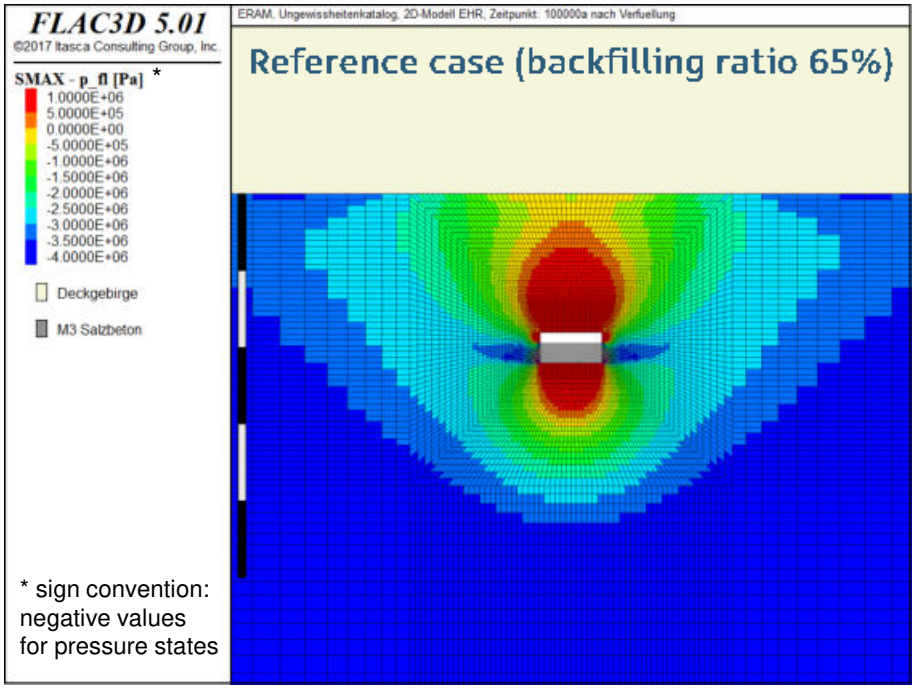
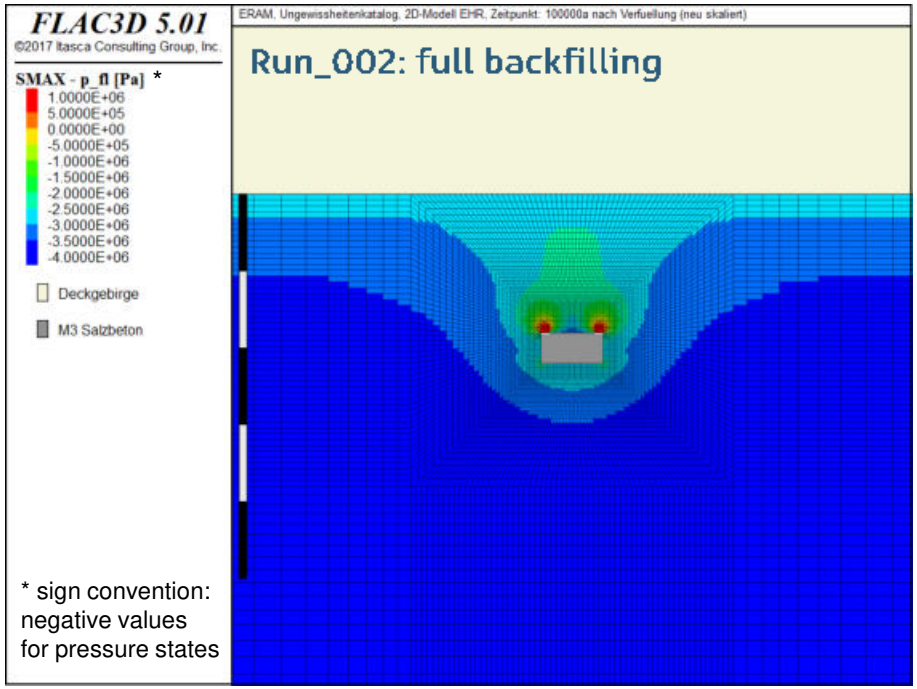
Fluid-pressure criterion $\Delta p = \sigma_3 - p_{fluid,\ theoretical}$

State: 100.000 years after backfilling





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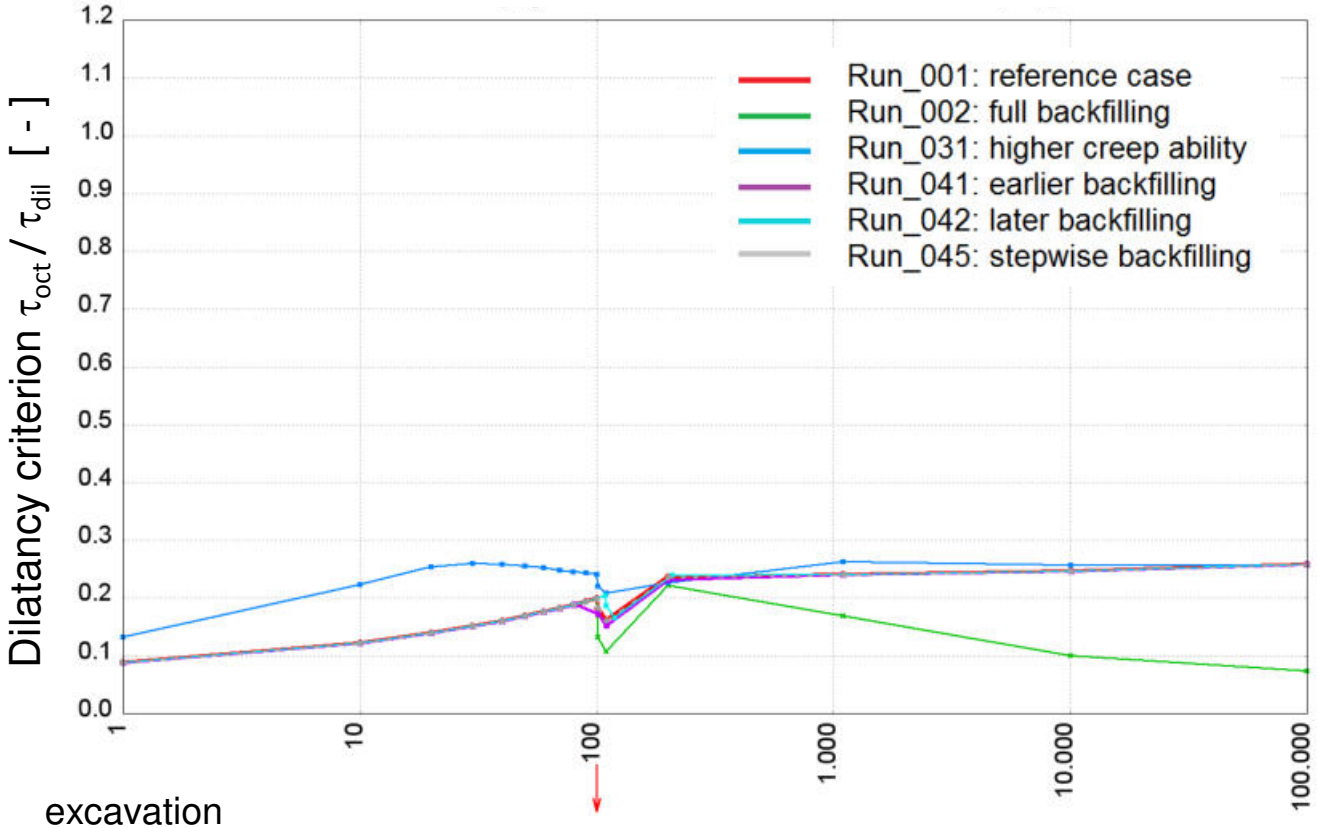
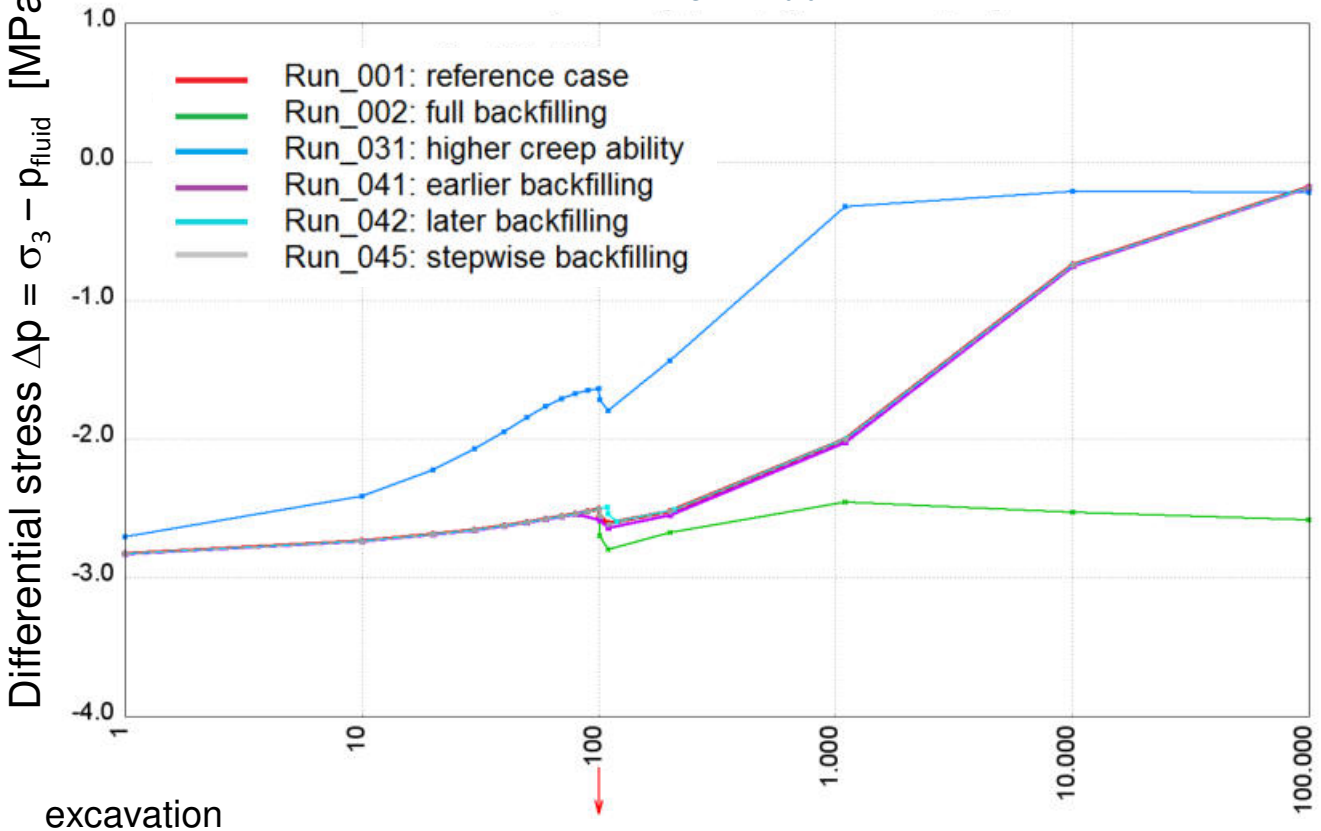
Dilatancy criterion τ_{oct} / τ_{dil} at the top of salt dome



BGE BUNDESGESELLSCHAFT FÜR ENDLAGERUNG

Fluid-pressure criterion $\sigma_3 - p_{fluid}$ at the top of salt dome



Step (3) – generic models
Single room model: exemplary results

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Thickness of rock salt barrier