Hydro-Mechanical Modeling of a Shaft Seal in a Deep Geological Repository

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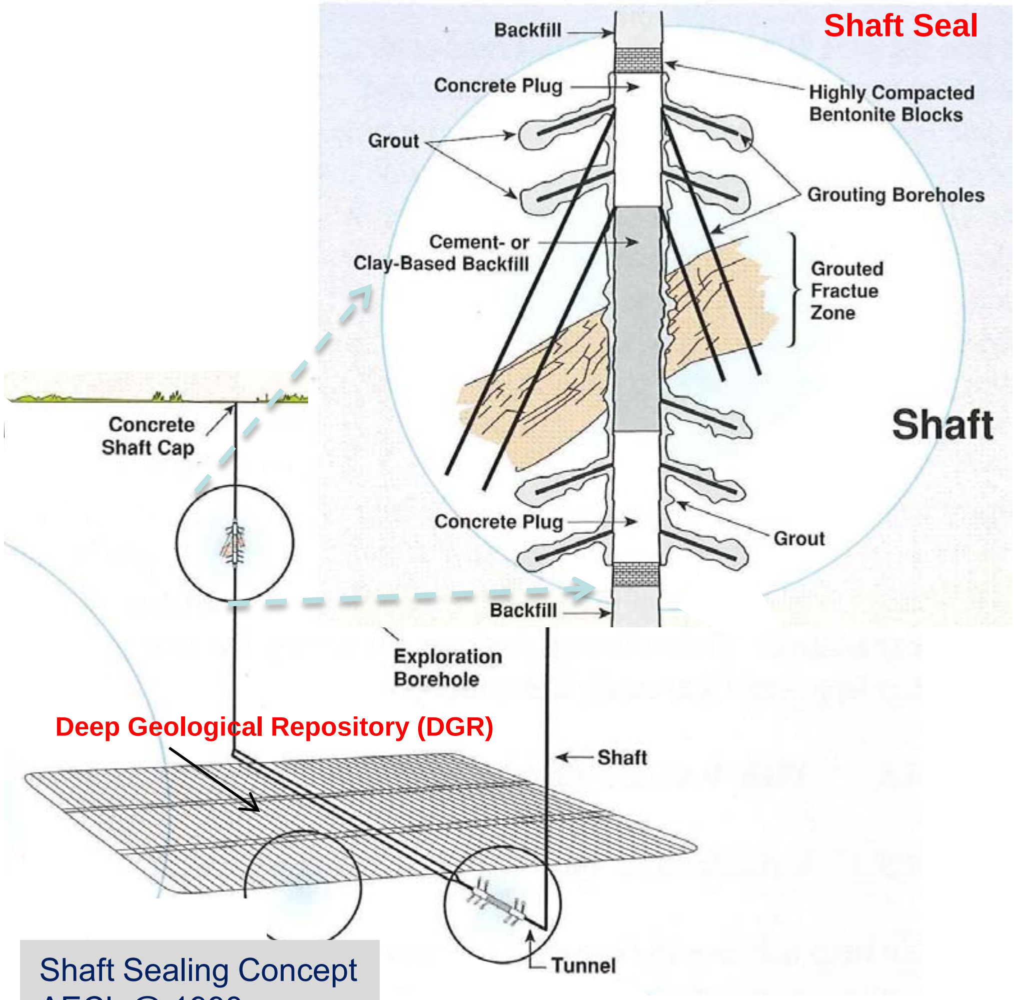
Background

- The Nuclear Waste Management Organization's (NWMO) Adaptive Phased Management (APM) approach to nuclear fuel waste management includes the isolation and containment of used nuclear fuel in a Deep Geological Repository (DGR).

- A shaft seal is one of the engineered barriers considered in isolating and containing used nuclear fuel in a Deep Geological Repository (DGR).

Shaft Sealing Concept



Shaft Sealing Concept
AECL @ 1993

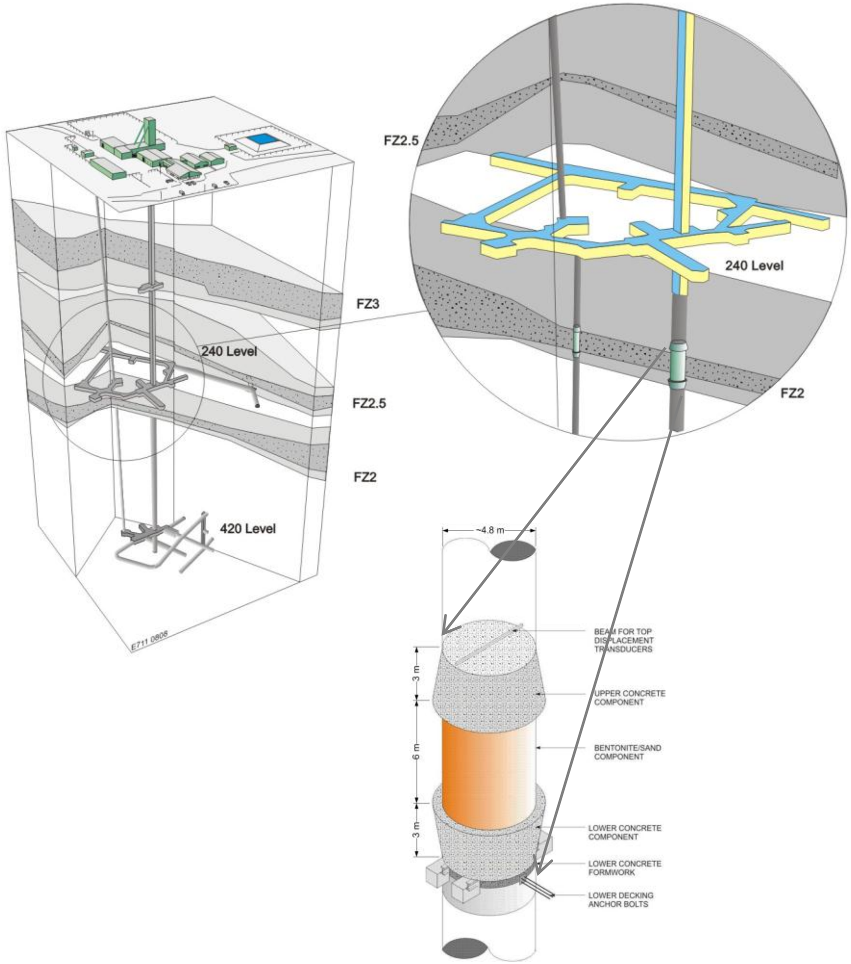
A shaft seal

•would be installed at strategic locations, such as significant fracture zone.

•to limit the potential for fast movement of groundwater from repository level to the surface via the shaft.

Full-Scale Shaft Seal at AECL's URL

(Dixon, Martino & Onagi 2009)



Seals at the AECL's Underground Research Laboratory (Martino et al. 2010)

The objective of the seals at URL is to limit the mixing of groundwater with higher salinity below the FZ with lower salinity above the FZ.

•The seal construction is funded by Natural Resources Canada (NRCan) under the Nuclear Legacies Liability Program (NLLP).

•Monitoring is funded by Enhanced Sealing Project (ESP) (NWMO, Posiva Oy, SKB and ANDRA).

• THM responses being monitored include: temperatures, displacements, strains, pore pressures, & total pressures at selected location.

Objective

The objective of this presentation is:

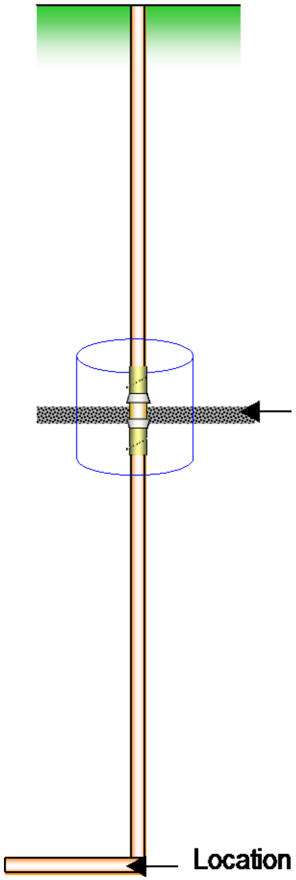
• to evaluate the capability of COMSOL to simulate the **hydraulic & mechanical (H-M)** processes of a shaft seal installed at a fracture zone in a **hypothetical** geosphere.

The final objective:

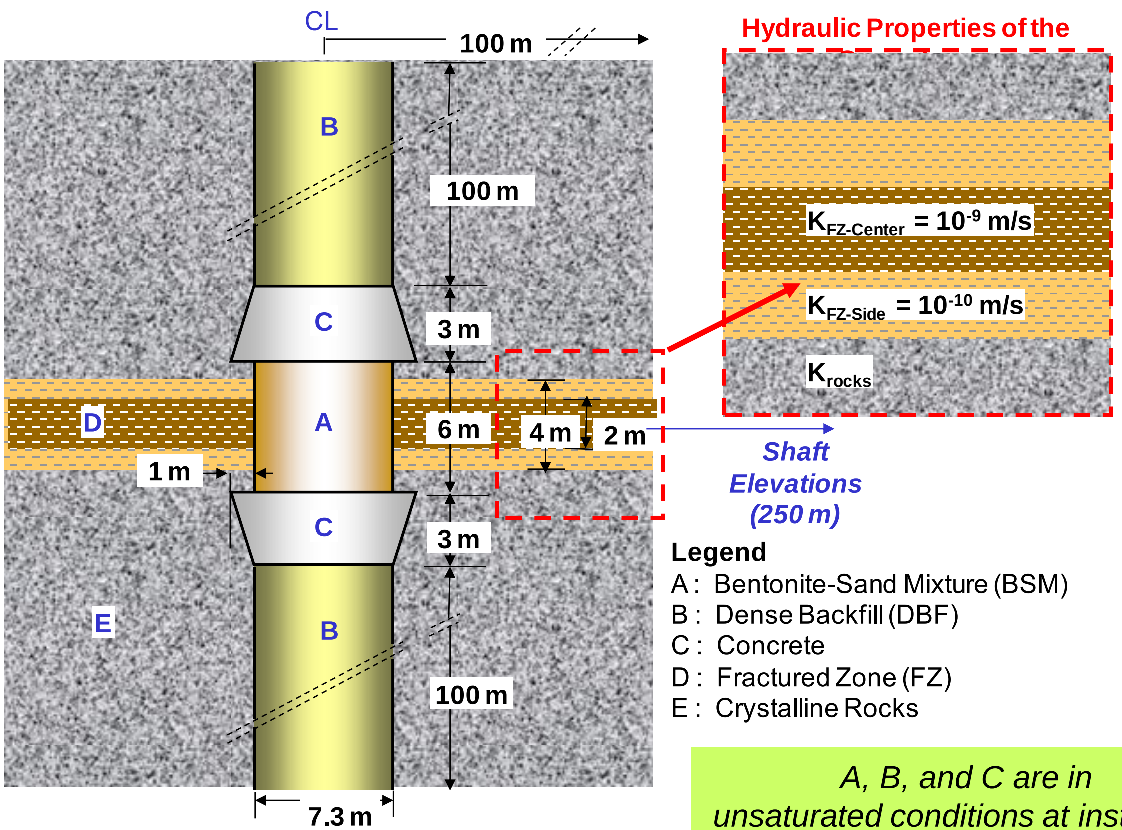
• to simulate **all required processes** of an **actual shaft seal**.
(e.g., coupling H, M, T, Mass transfer)

Hypothetical Shaft Seal Geometry

Major Fracture Zone at 250 m



2D-axisymetrical geometry



Legend

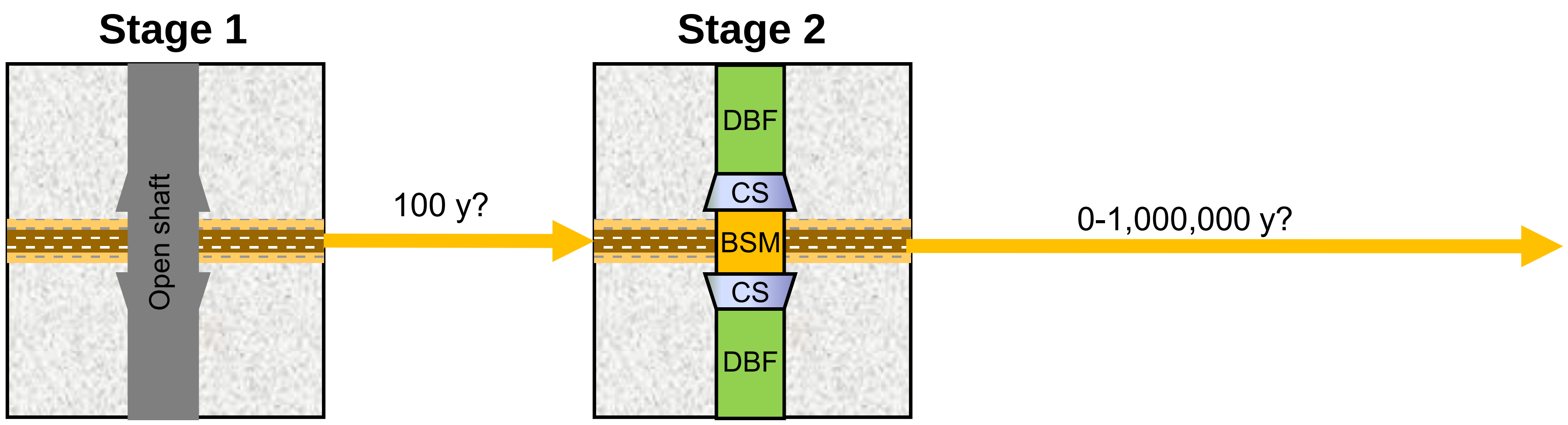
A : Bentonite-Sand Mixture (BSM)
B : Dense Backfill (DBF)
C : Concrete
D : Fractured Zone (FZ)
E : Crystalline Rocks

A, B, and C are in unsaturated conditions at installation

Stages of Numerical Modeling

1. **Stage 1** simulates groundwater flow into open shaft and stress condition prior to seal installation.
   Duration: time between excavation and shaft seal installation (100 y?)

2. **Stage 2** simulates groundwater flow after shaft seal installation.
   Duration: depending the half life of the nuclear waste (0 – 1,000,000 y?)



Challenges

Challenge 1

- Sealing components are initially unsaturated,
- Clay-based sealing components have large volume change
  ➔coupling of the unsaturated flow with structural mechanics

Challenge 2

- Properties and conditions at the seal location change abruptly between Stages 1 and 2.

Challenge 3

- The durations of Stages 1 and 2 considered in this study are anticipated to be in order of 100 years to 1,000, 000 years.
  ➔ reasonable solution time

Coupling of HM Formulation for Unsaturated Soil

Detailed formulations are provided in (Priyanto 2010)

$$[C + S_e S]\frac{\partial H_p}{\partial t} + \nabla \cdot \left[-K\nabla\left(H_p + D\right)\right] = Q_s$$

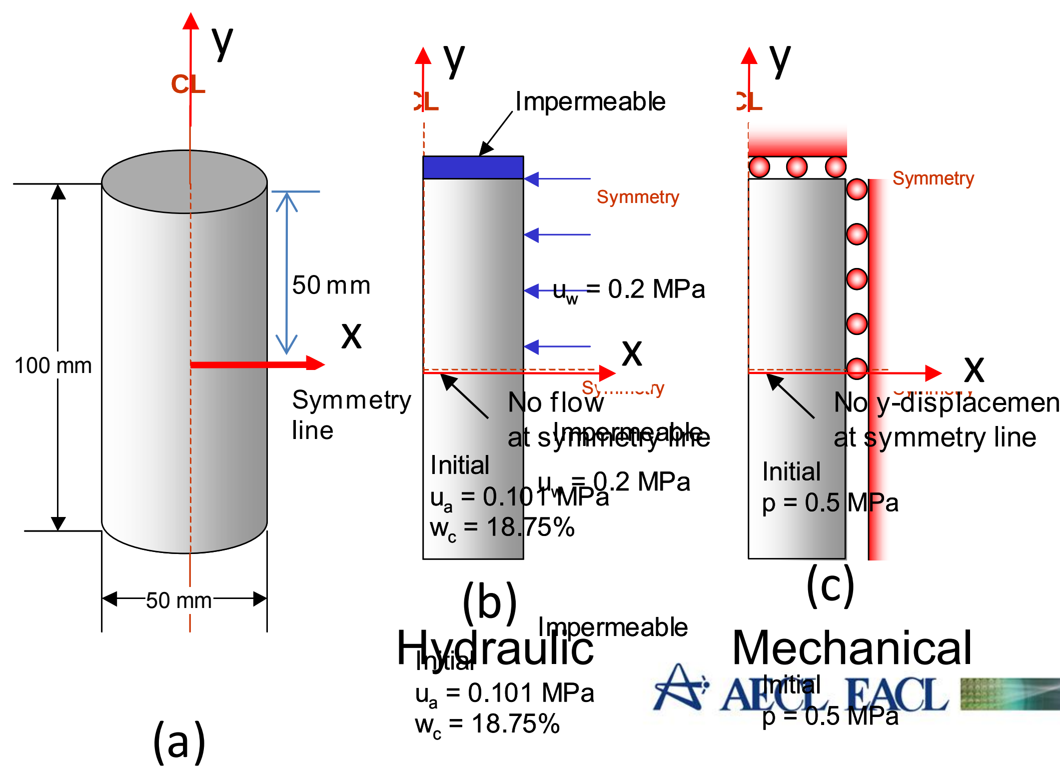
$$S = \rho_f\, g\, (\chi_p + \theta\chi_f) \qquad K = k_w^{sat} \cdot k_r$$

$$k_w^{sat} = k_0 \frac{\theta^3}{(1-\theta)^2} \frac{(1-\theta_0)^2}{\theta_0^{\ 3}}$$

$$S_e = \begin{cases} \dfrac{1}{\left[1 + \left|\alpha H_p\right|^n\right]^m} & \text{for } H_p < 0 \\ 1 & \text{for } H_p \geq 0 \end{cases}$$

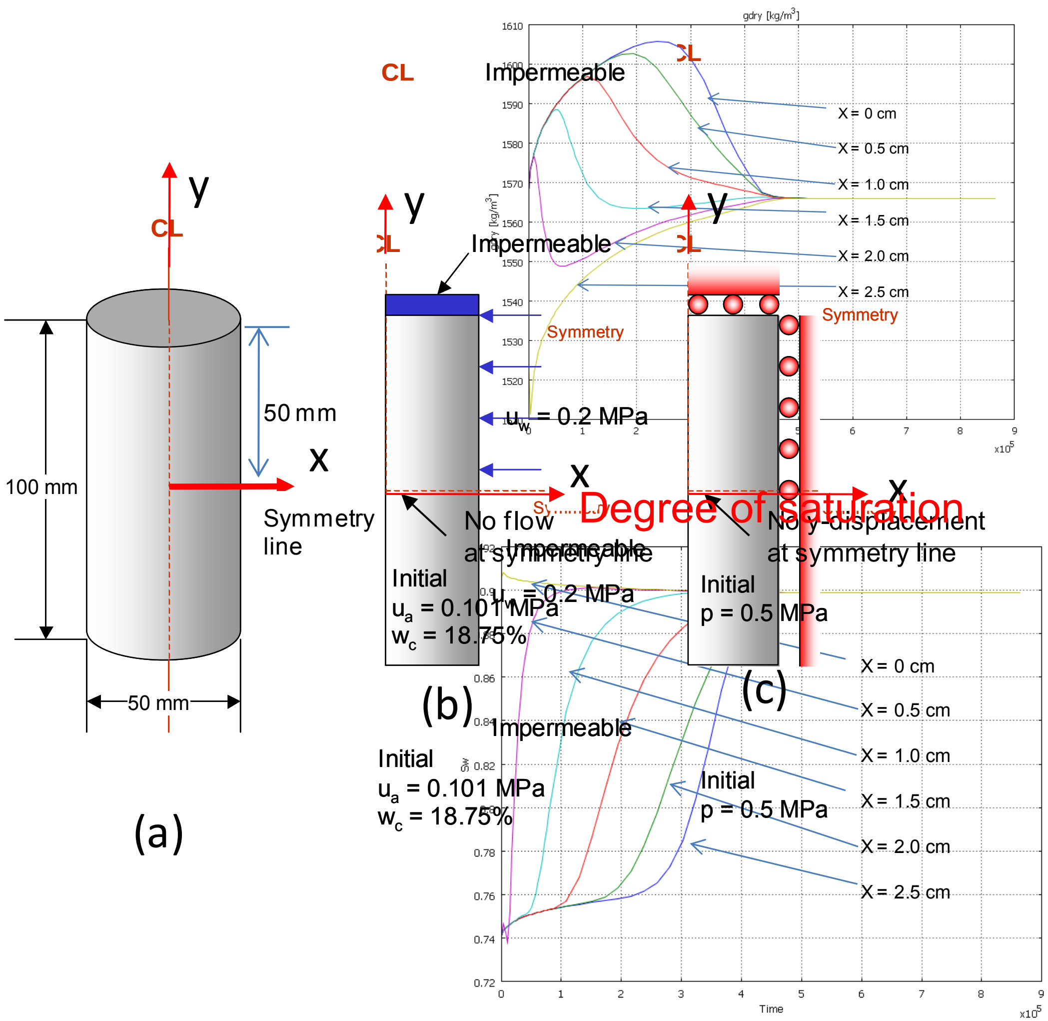
$$C = \begin{cases} \dfrac{\alpha m}{1-m}(\theta_s - \theta_r) S_e^{\frac{1}{m}} \left(1 - S_e^{\frac{1}{m}}\right)^m & \text{for } H_p < 0 \\ 0 & \text{for } H_p \geq 0 \end{cases}$$

- Unsaturated flow = Richard's equation with vanGenuchten's SWCC and permeability models.
- Mechanical = Linear elastic model
- Compare with laboratory triaxial test of the Bentonite-Sand Mixture (BSM)

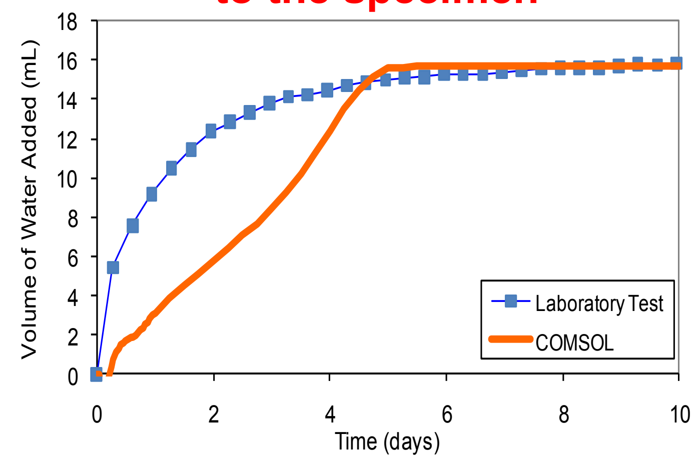


Results of HM Numerical Modeling of Unsaturated BSM Specimen

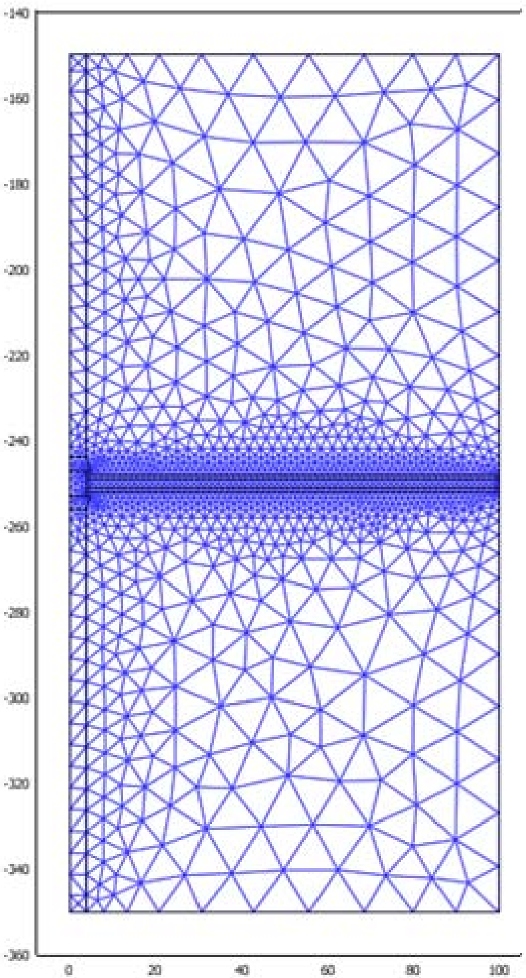
Dry density

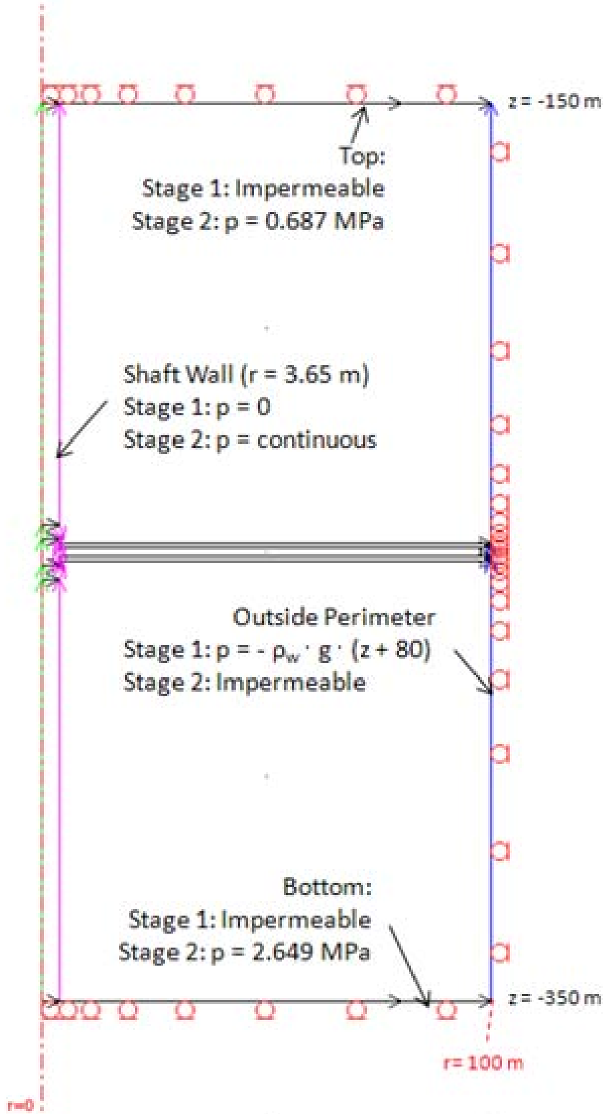


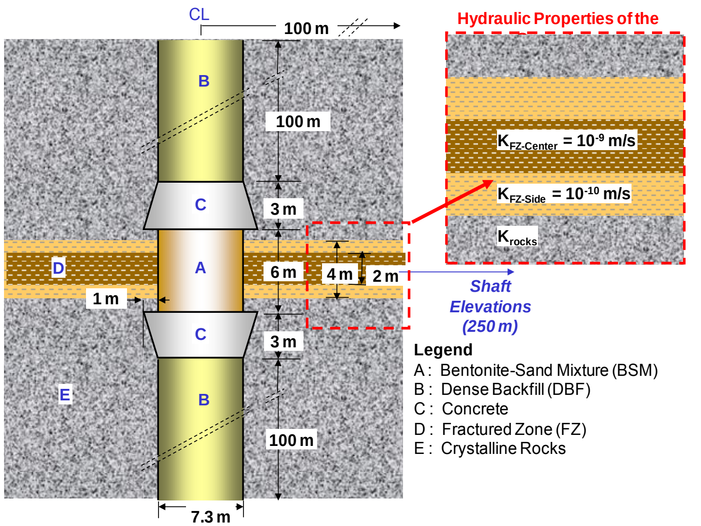
Volume of water added to the specimen

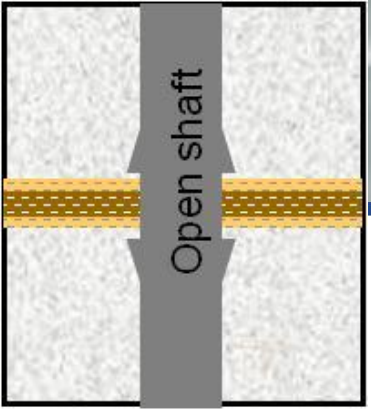


H-M Modeling of Shaft Seal



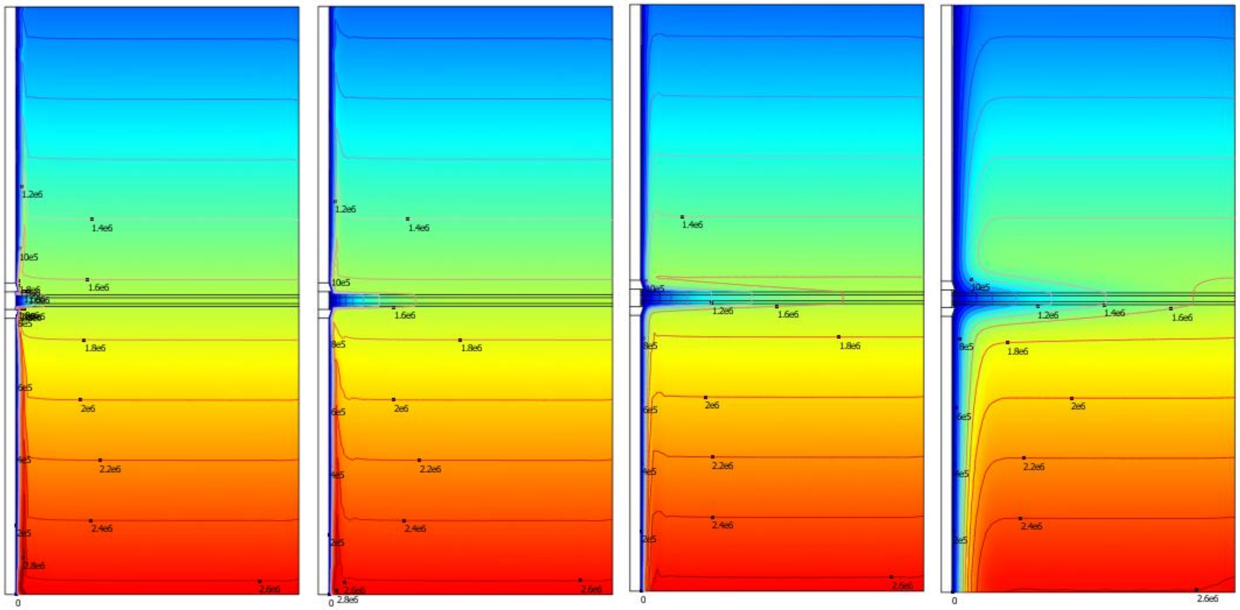


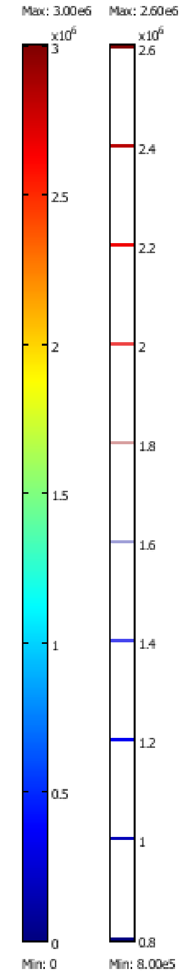




Porewater Pressure, Stage 1

Stage 1, groundwater flow into open shaft

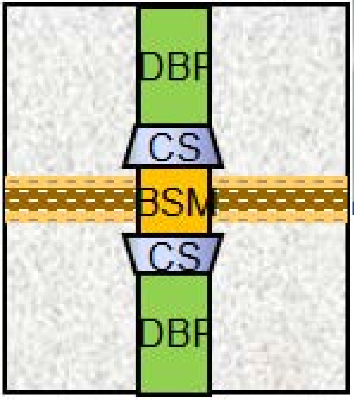




0 1 10 100

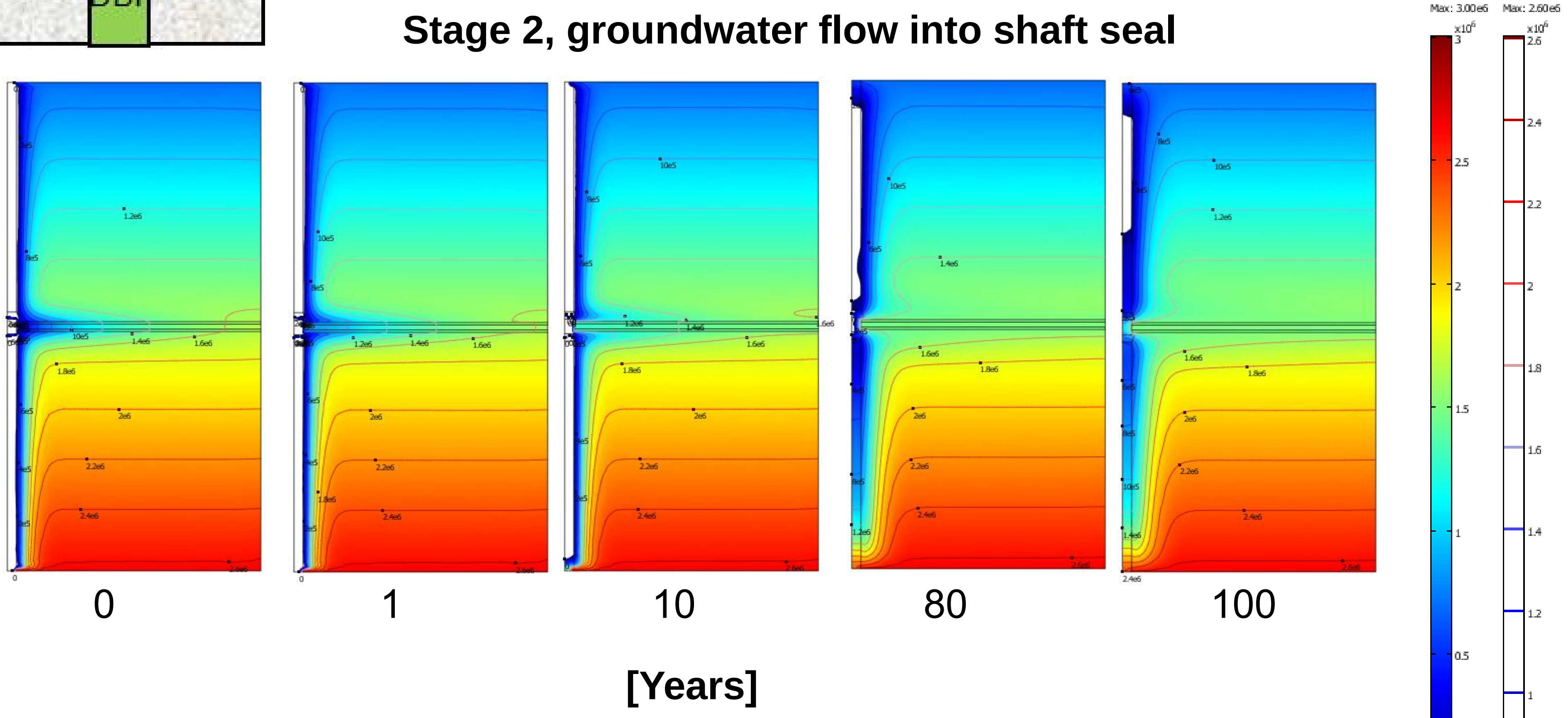
[Years]

Note that this results is only valid for the hypothetical assumptions and properties used in this study.



Porewater Pressure, Stage 2 (0-100 years)

Stage 2, groundwater flow into shaft seal



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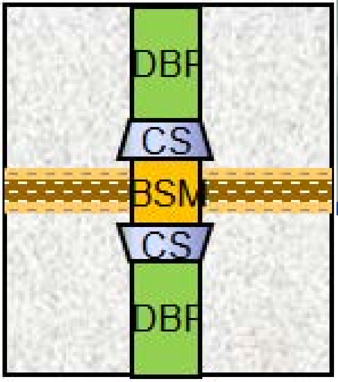
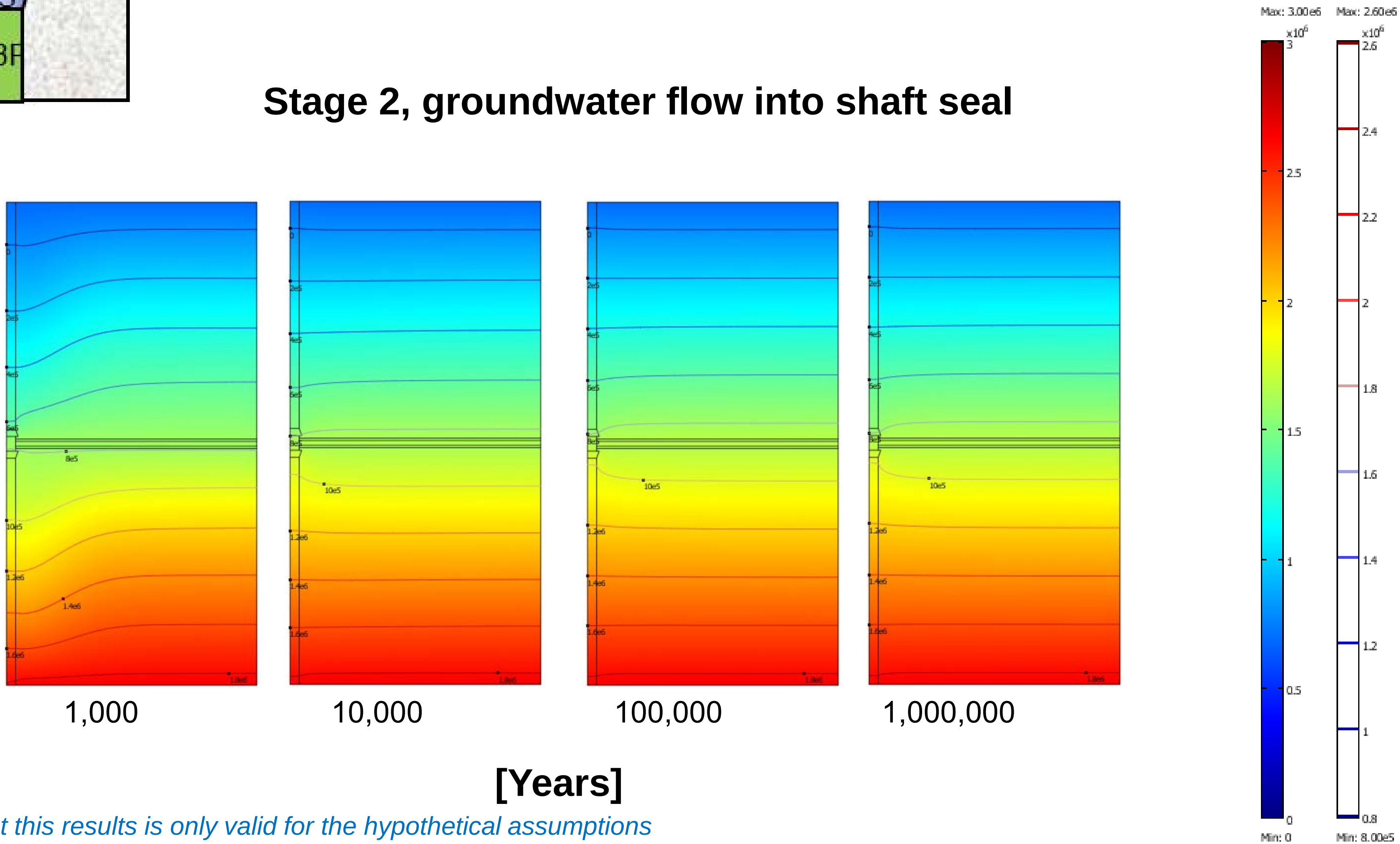


Porewater Pressure, Stage 2 (1e3-1e6 years)

Stage 2, groundwater flow into shaft seal



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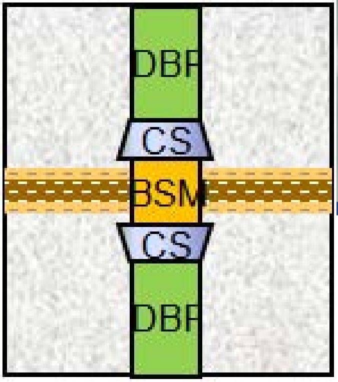
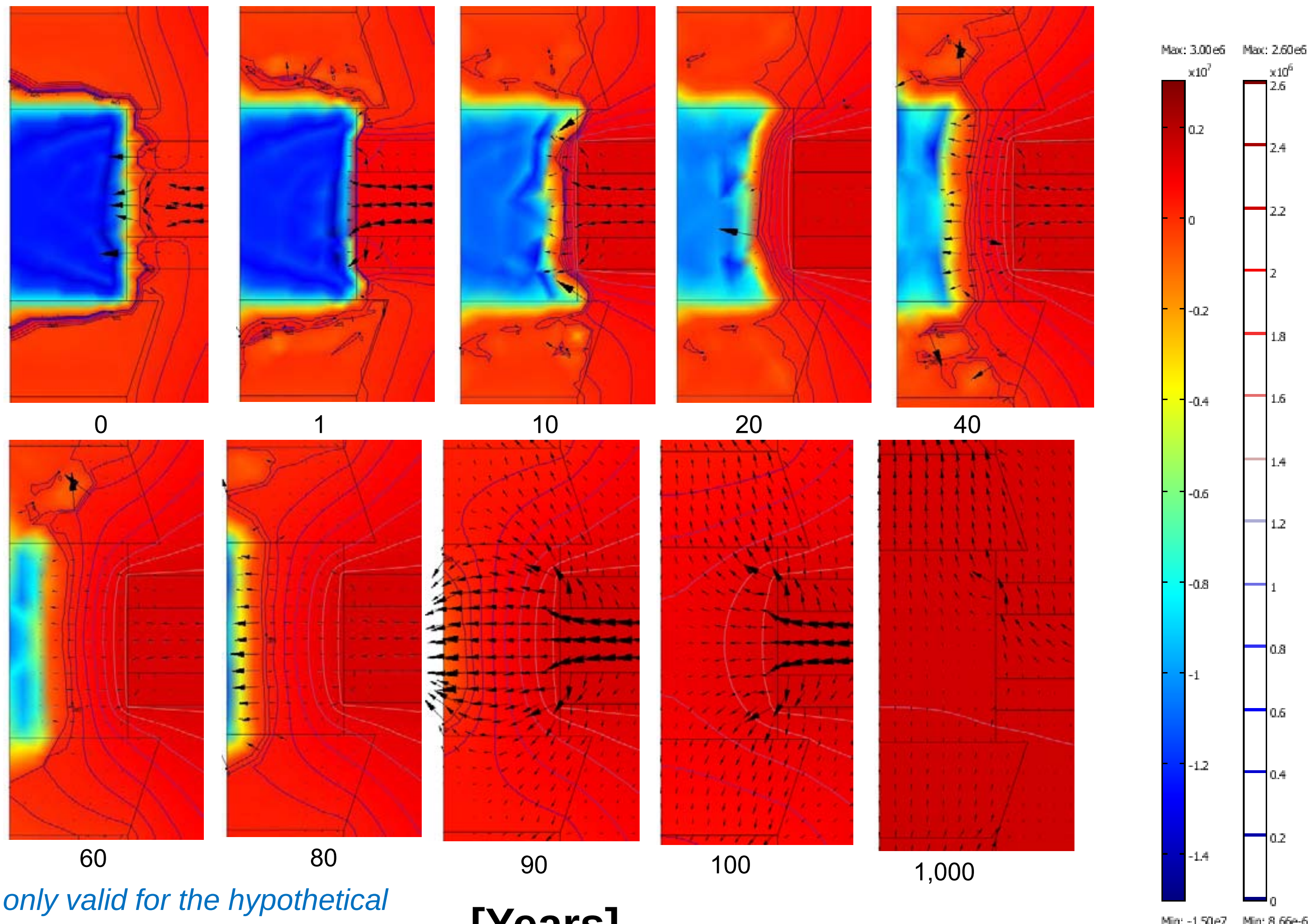


Porewater Pressure, Stage 2

Stage 2, groundwater flow into shaft seal



[Years]

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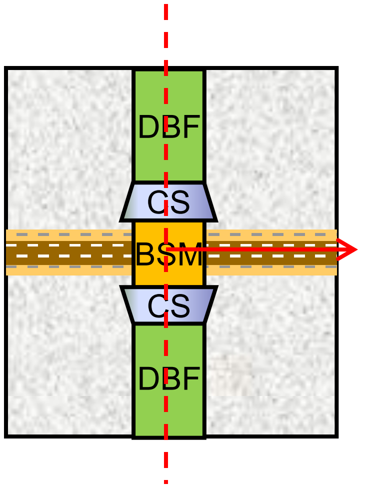
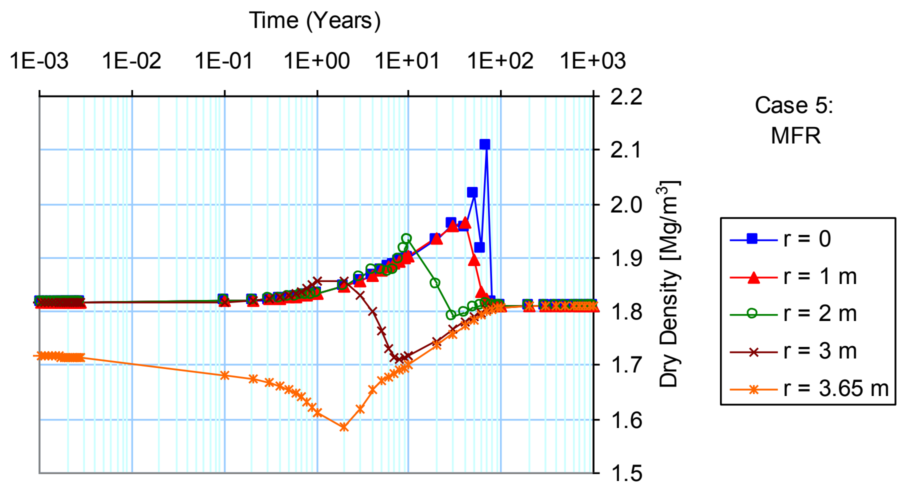
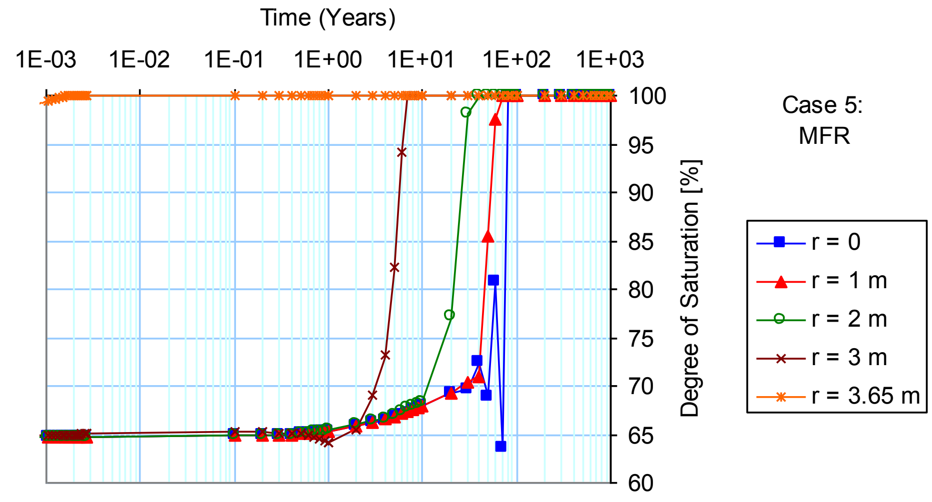
Saturation Degree and Dry Density of the BSM







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Conclusions

- This study has developed custom-additions in COMSOL
  - to couple Richard's equation and linear elastic model
  - to implement a custom SWCC and permeability model observed from the results of laboratory testing of the bentonite-sand mixture specimens.

- The results of the numerical modeling of a shaft seal using COMSOL shows a logical hydraulic and mechanical processes, which indicated that COMSOL can be used as a tool for further study of a shaft seal in a deep geological repository.

- Using current computer capability, the solution time required to complete the analysis to simulate 1000000 years HM behavior of a shaft seal described in this study was less than 1 hour, which is beneficial in building more complex model and formulations to simulate an actual shaft seal in actual geosphere conditions.

Recommendations

- Future studies recommended to improve simulation of a shaft seal includes:
  - Development of coupling formulation of multi-phase flow with mechanical constitutive model to improve HM simulation.
  - Coupling between HM processes with other processes such as thermal and mass transport.
  - Implementation of elasto-plastic model.

Thank you !

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