Geomechanics – Paving the Way for Low-Carbon Energy and Sustainable Cities

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LMS
Laboratory of Soil Mechanics

Table of content

EPFL

Introduction

Reduction of CO2 emissions

Energy transition

Eliminating existing CO2

Laboratory of Soil Mechanics - LMS

- LMS is a world-leading geotechnical research lab.
- We specialize in
  - Bio-improved soils
  - Energy geostructures
  - Nuclear waste storage
  - CO_2 storage
  - Unsaturated geomechanics

LMS courses: https://www.epfl.ch/labs/lms/educational-programs/

LMS Projects: https://www.epfl.ch/labs/lms/master-thesis-at-lms/

LMS contributions to the sustainable development goals

What are geomaterials?

- Materials of **geologic** origin
  - Soils
  - Rocks
- Rheological properties
  - Coulomb friction
  - Non-linear elastic
  - Anisotropic
  - Dilatant

Geomaterials play a role in

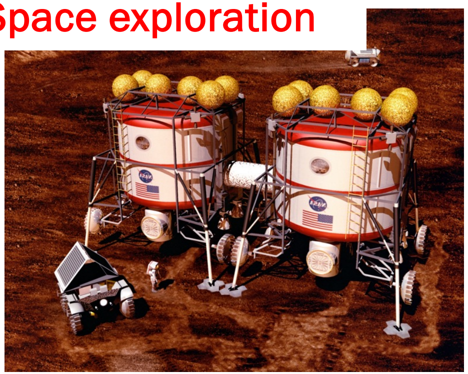
Natural hazards

Civil infrastructure

Energy & hydraulics

Underground construction

Space exploration



Role of geomechanics in a sustainable future

- Reduction of CO_2 emissions in geotechnics
  - Bio-improved soils
- Energy transition
  - Nuclear waste storage
  - Energy geostructures
- Eliminating existing CO_2
  - CO_2 sequestration

Reduction of CO2 emissions in geotechnics

Bio-Improved soils

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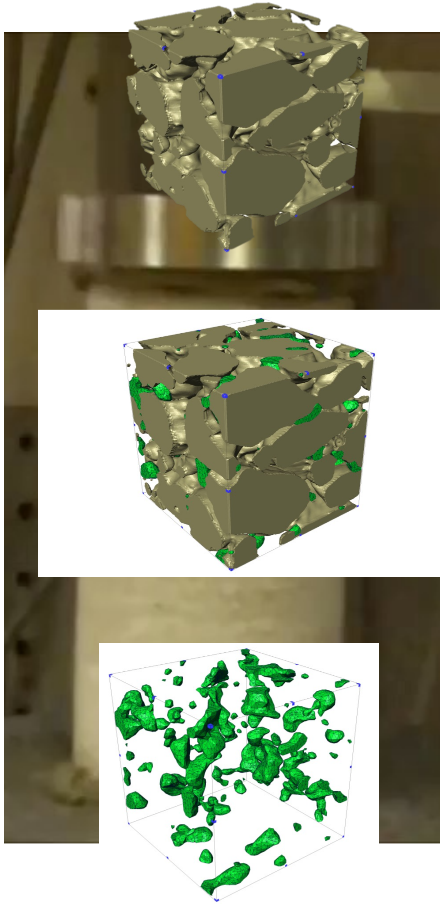
Soil Bio-improvement

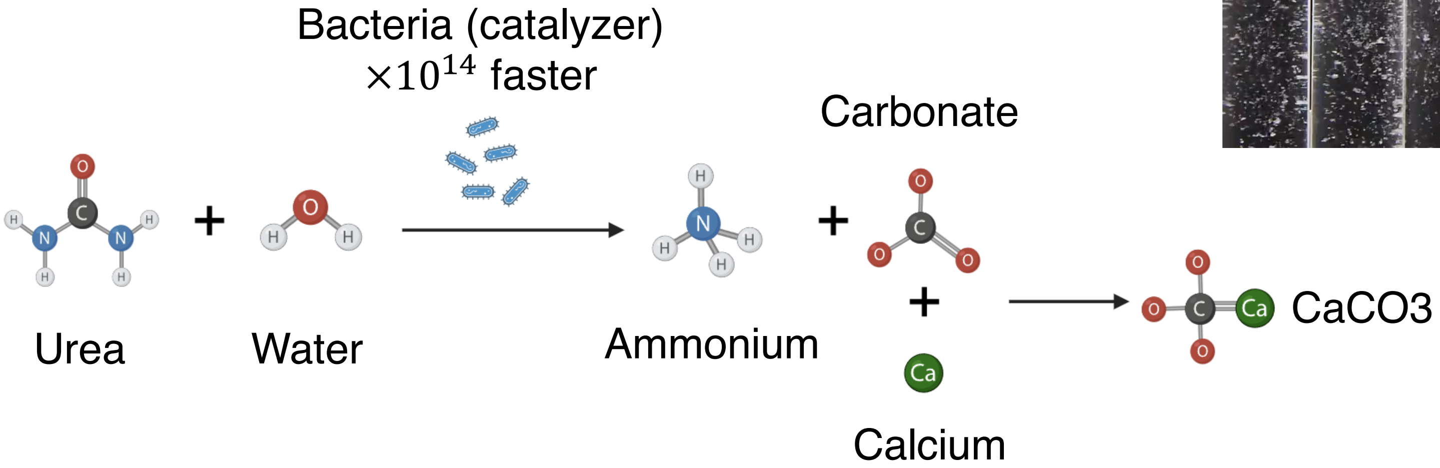
Increasing soil stiffness and strength using a liquid biological agent

- Applications
  - Foundation improvement
  - Tunneling
  - Erosion protection
  - Seismic retrofitting



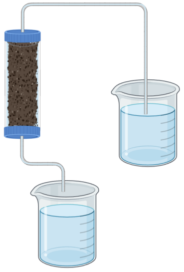
Chemical process

- **M**icrobially **I**nduced **C**alcite **P**recipitation (MICP)

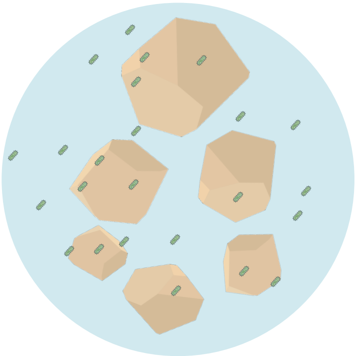


Multi-physical process

Injection



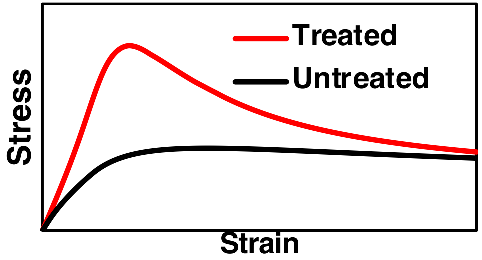
Transport



Reaction

Reactive transport models

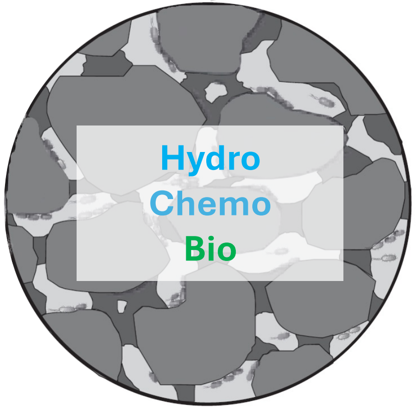
Mechanics



Geomechanical models

Reactive transport model

Input
Initial conditions & treatment characteristics



Output
Calcite content distribution in the soil domain

Chemo-physical processes

FLUID FLOW

- Porosity and permeability evolution
- **Degree of saturation**

REACTIVE TRANSPORT

- Advective rate
- **Traditional MICP**:
  - Bacteria attachment and decay
  - Ureolysis reaction
  - Calcite precipitation
- **Ex-situ hydrolysis MICP**:
  - Calcite precipitation

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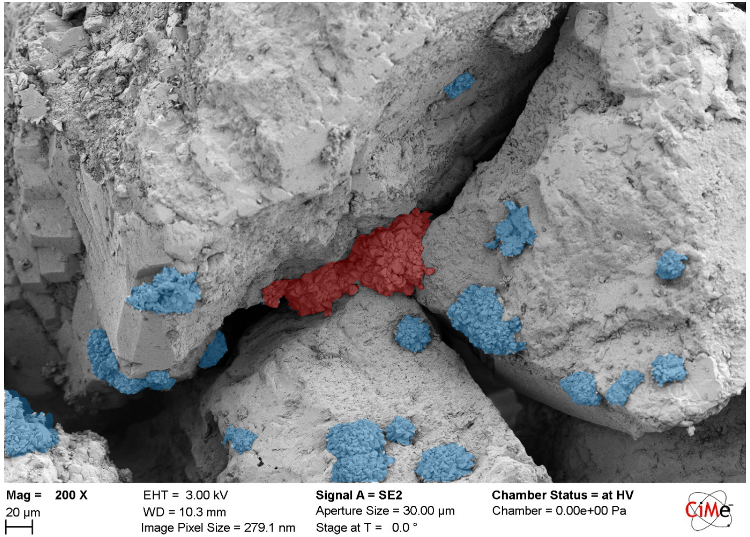
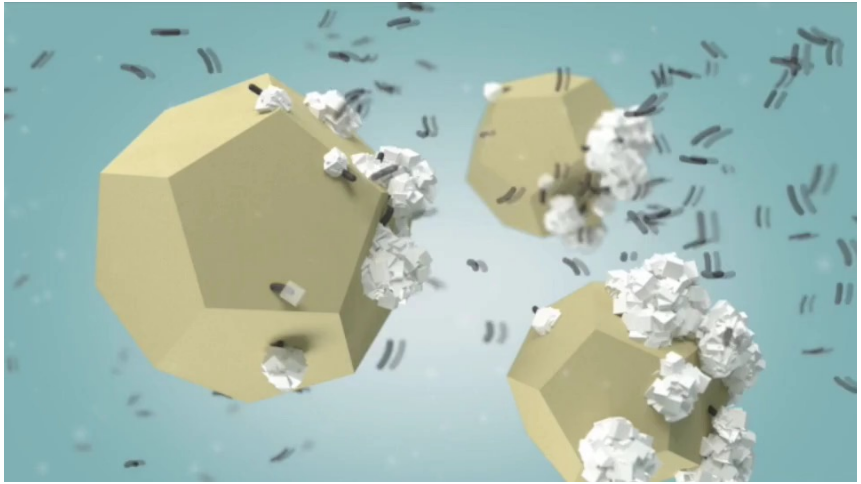
Calcite in the soil





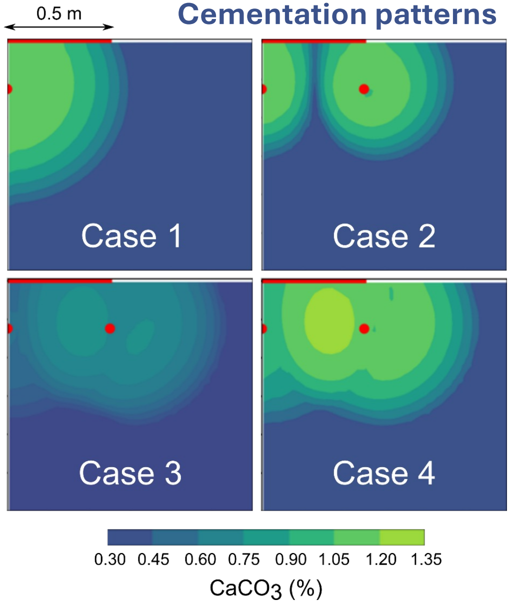
Geomechanical model

Mechanics

Extension from elasticity to **elasto-plasticity**

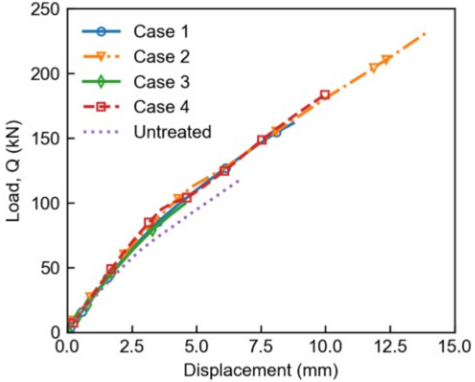
All input parameters from drained triaxial test

Cementation patterns

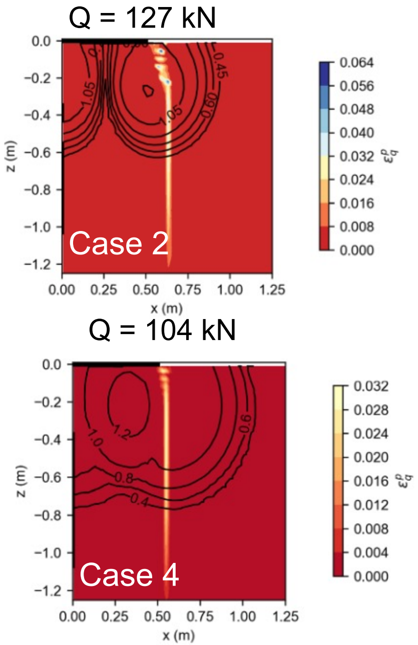


Bosch et al. (2024) Acta Geotechnica

Load-displacement curves



Plastic strain distribution



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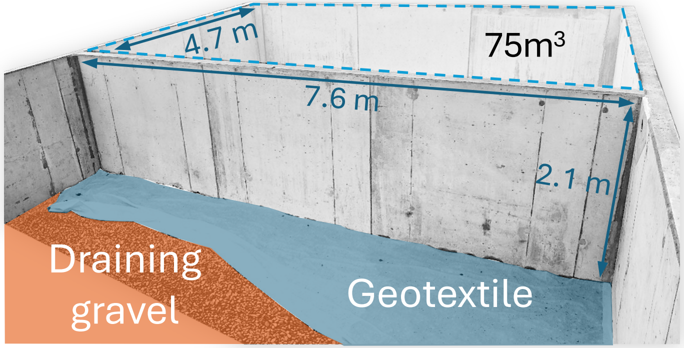
Introduction

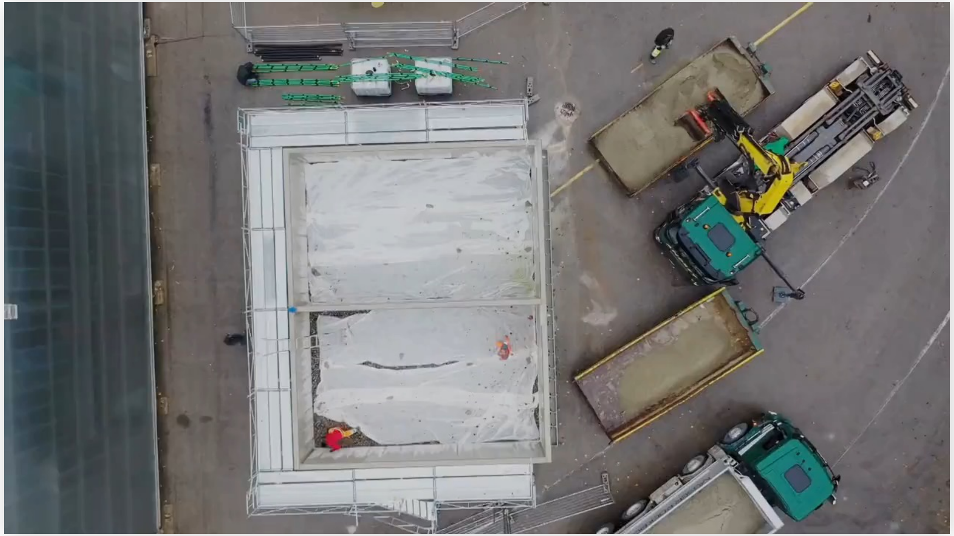
Reduction of CO2 emissions

Energy transition

Eliminating existing CO2

Large scale geo-mechanical lab





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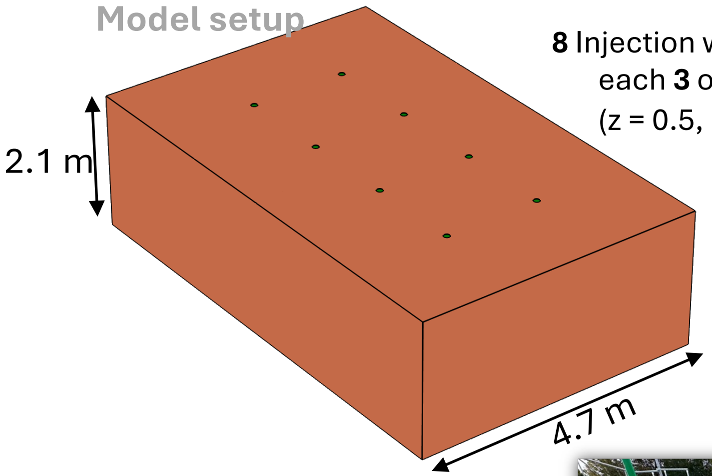
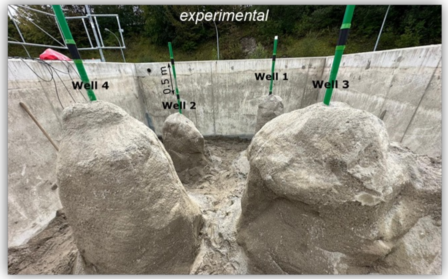
Large scale geo-mechanical lab

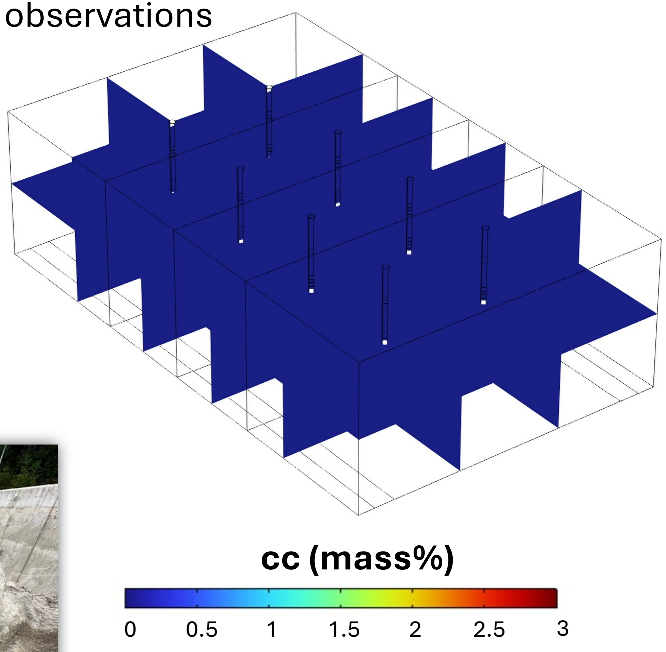


8 Injection wells
each **3** openings
(z = 0.5, 1.0 & 1.5m)



3D field scale evaluation

replicating main experimental observations



Energy transition

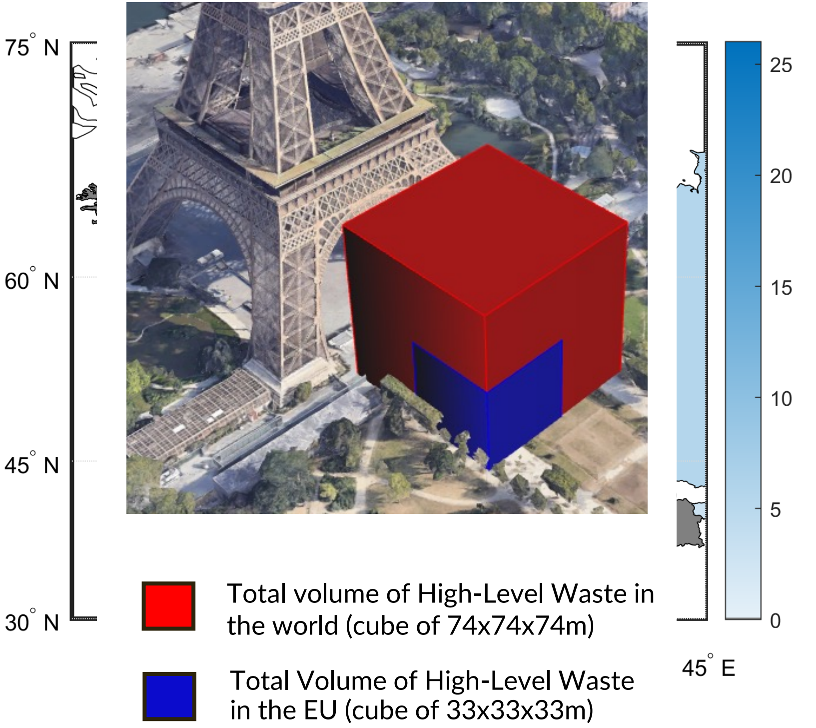
Nuclear waste storage

Nuclear energy – a clean and sustainable source

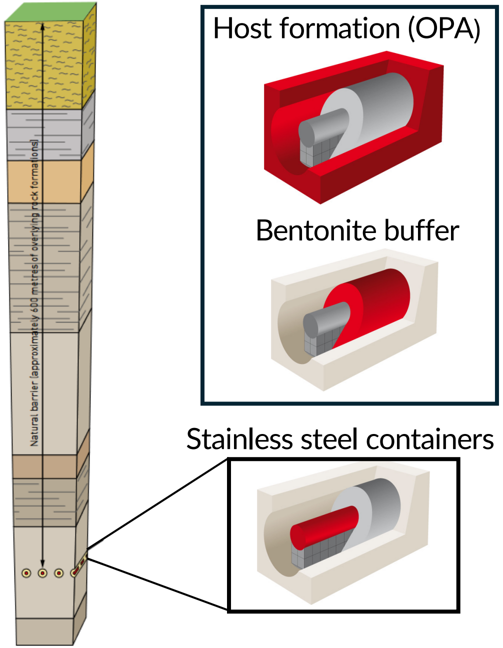
- Nuclear energy protects air quality
- Nuclear energy's land footprint is small
- Nuclear energy produces minimal waste

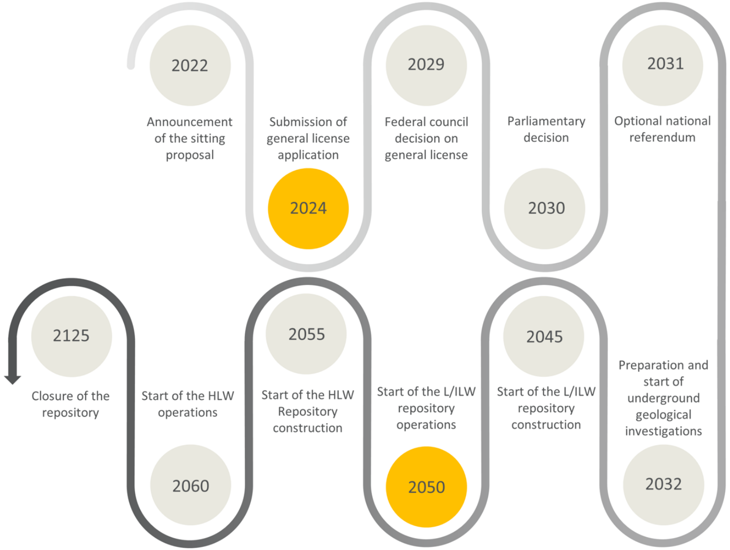
Nuclear waste production in Europe

- One-quarter of the electricity in Europe.
- 185 in operation, 15 in construction and 86 in the decommissioning process.
- Radioactive isotopes eventually decay to harmless materials.
- Nuclear wastes isotopes half life range from hours to dozens of thousands of years.



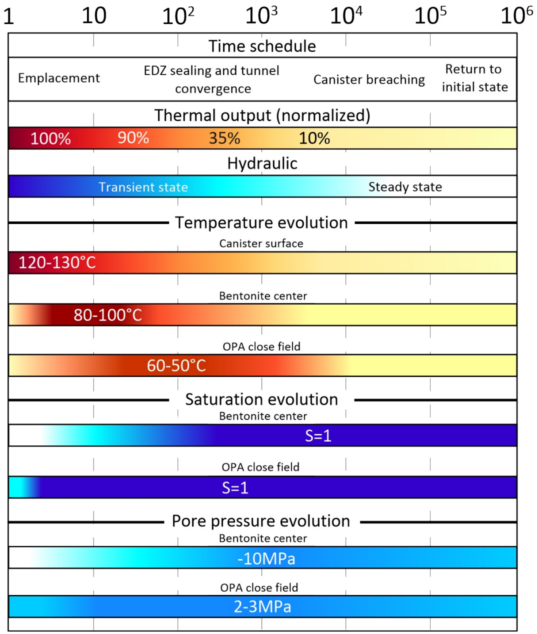
Swiss repository concept

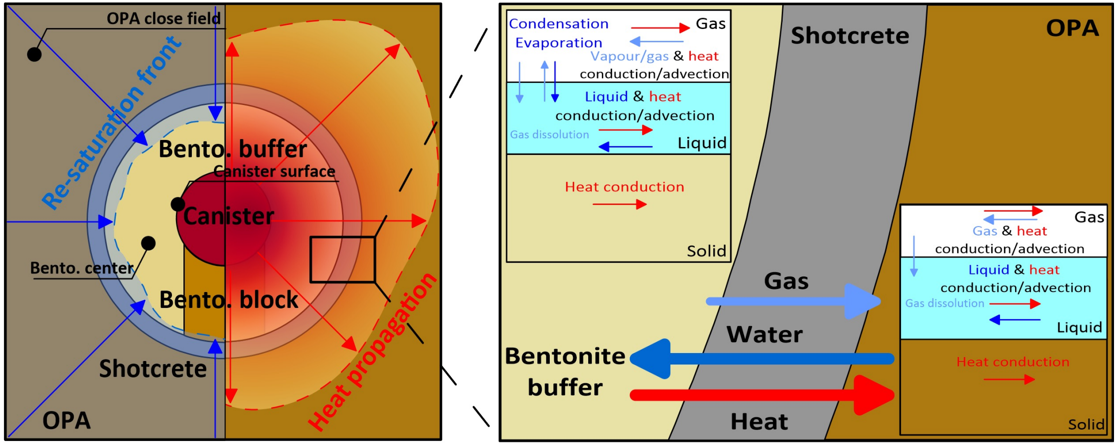




Source: https://nagra.ch

Multiphysical interactions around nuclear waste

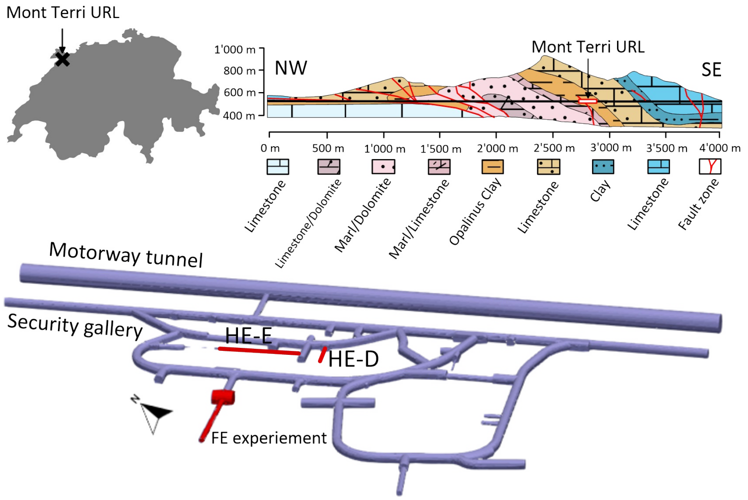




Source: Based on Leupin et al., 2016 and Gens et al., 2009

Mont Terri Underground Rock Laboratory (URL)

- Opalinus Clay, bentonite buffer and emplacement methodology are assessed in Mont Terri since 1996.
- 300 m deep underground.
  - Interaction from T → H and T → M
  - Heat transport mainly conductive
  - Clear impact of the anisotropy
  - No impact of the temperature on the EDZ
  - Clear impact of the excavation/ventilation



Source: Based on Nagra Report, 2019

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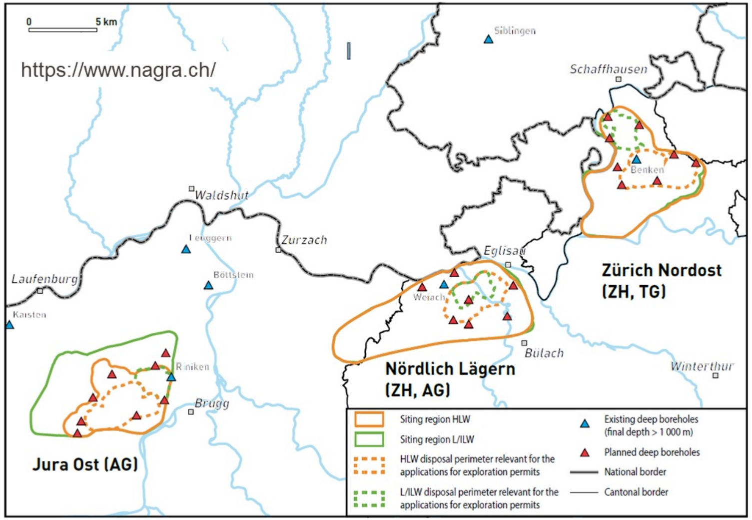
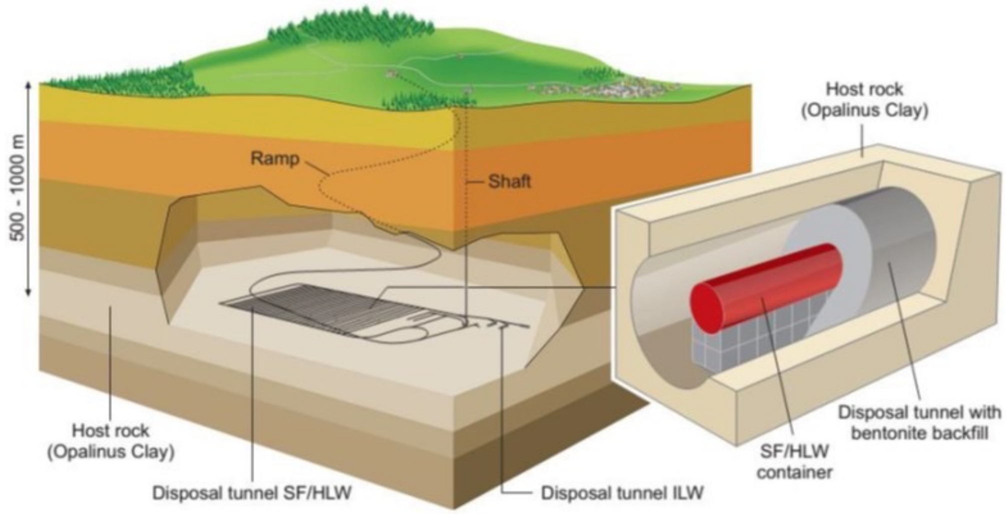
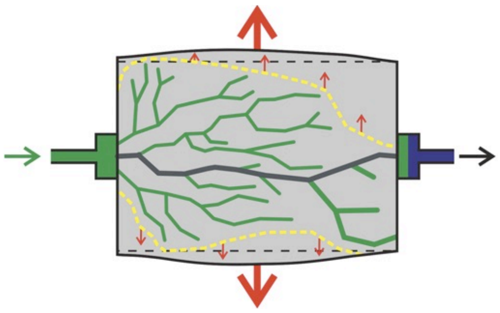
Site selection and characterization of host formation



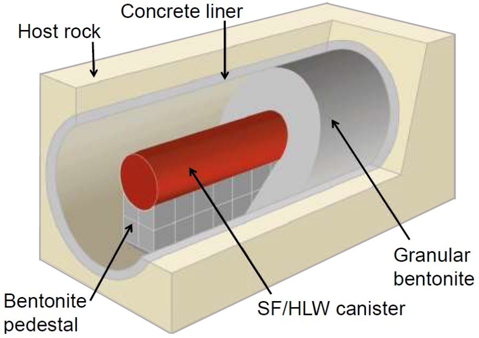
Characterization of THM processes

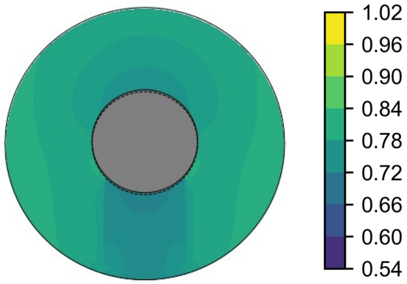


Gas sources (H_2) associated with the support structures and emplacement materials

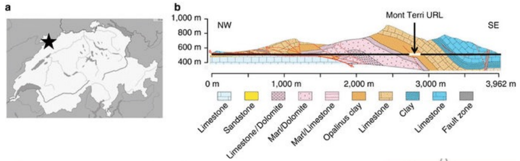


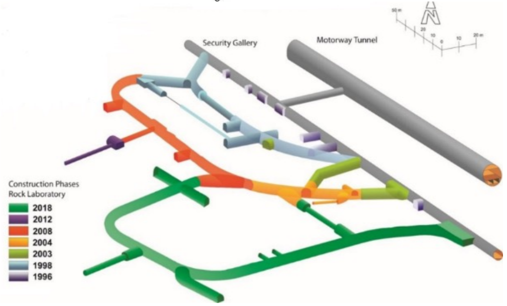
Large scale modelling for long-term behavior prediction

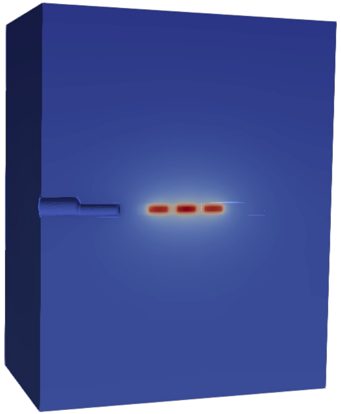




Predicted distribution of bentonite void ratio and canister position after saturation (100 years post-closure)







Energy transition

Energy Geostructures

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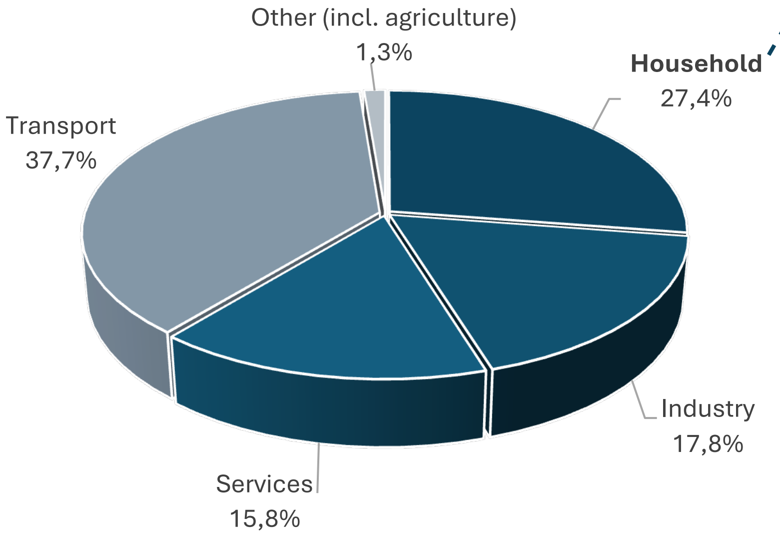
Introduction

Reduction of CO2 emissions

Energy transition

Eliminating existing CO2

Energy consumption in Switzerland



Heating and hot water	80.4 %
Kitchen appliances	4.4 %
Refrigeration	2.6 %
Lighting	1.8 %
Information and entertainment	2.5 %
Ventilation and cooling	2.0 %
Laundry	2.2 %
Various household applicances	4.2 %

OFEN, statistique globale suisse de l'énergie 2023, 09.07.2024
OFEN, Prognos 2020

Introduction

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Energy transition

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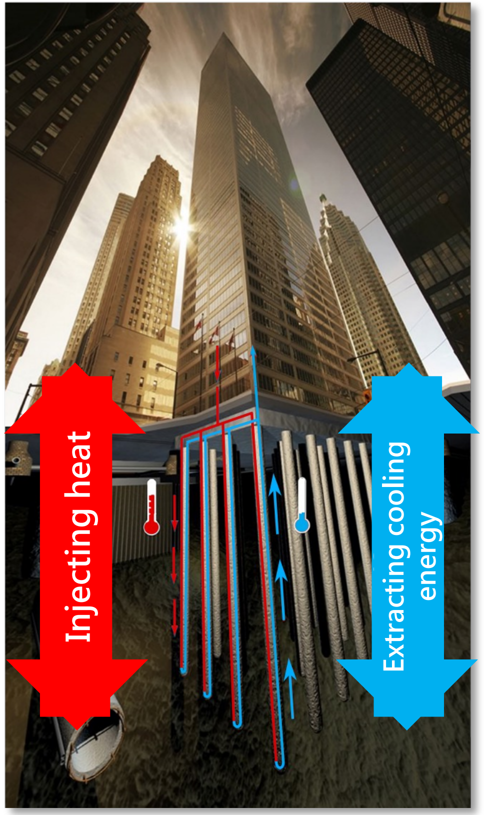
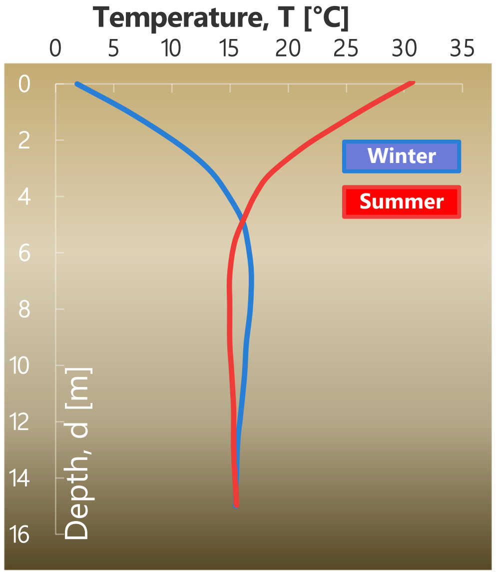
Soil energy capacity

Winter

Summer





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Introduction

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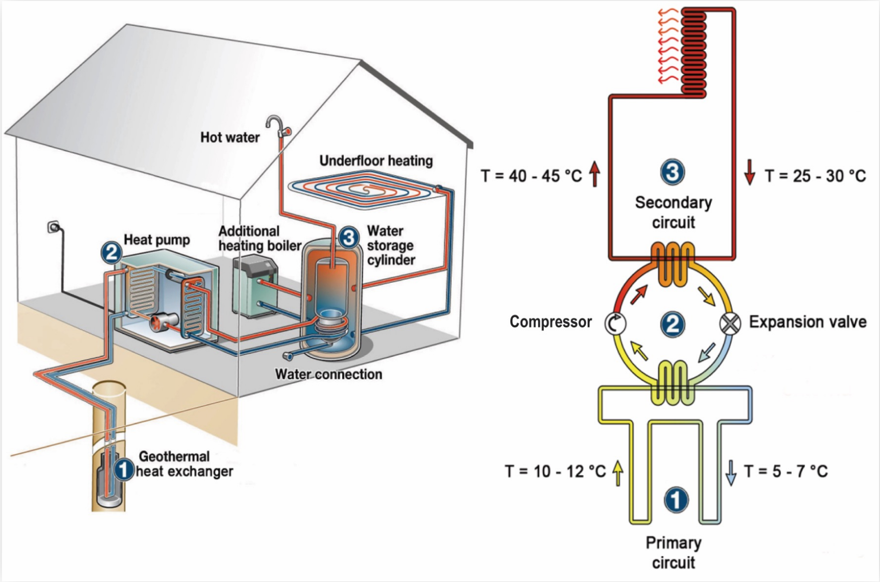
Ground source heat pump system

$$COP = \frac{Q}{W} \quad [-]$$

Q = Energy output after heat pump operation [kW]

W = Energy input for heat pump operation [kW]



1 kW provided

> 4 kW generated

¼ electricity

+

¾ heat from the ground

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Energy geostructures

Introduction

Reduction of CO2 emissions

Energy transition

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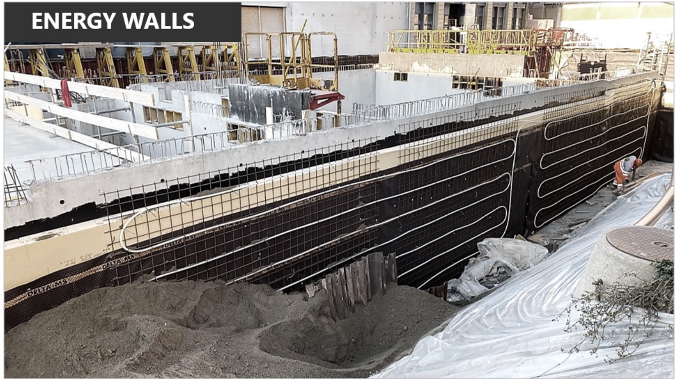

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Introduction

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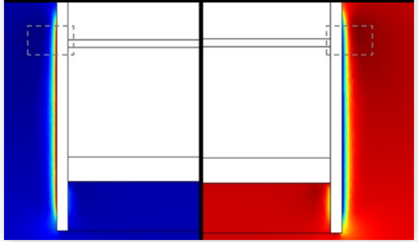
Challenges

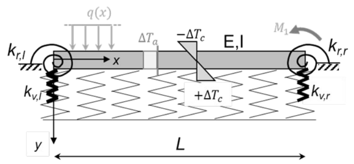
Which **multiphysical phenomena** are associated with the **geothermal and structural** support operations of **energy geostructures** ?

How should **energy geostructures** be **analysed** and **designed** from an **energy**, **geotechnical** and **structural** point of view ?

What will be the **behaviour** and **performance** of **energy geostructures over time** ?

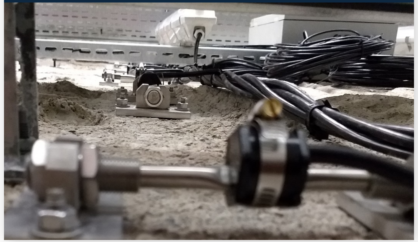
Thermal performance





Thermomechanical performance

In-situ testing and monitoring



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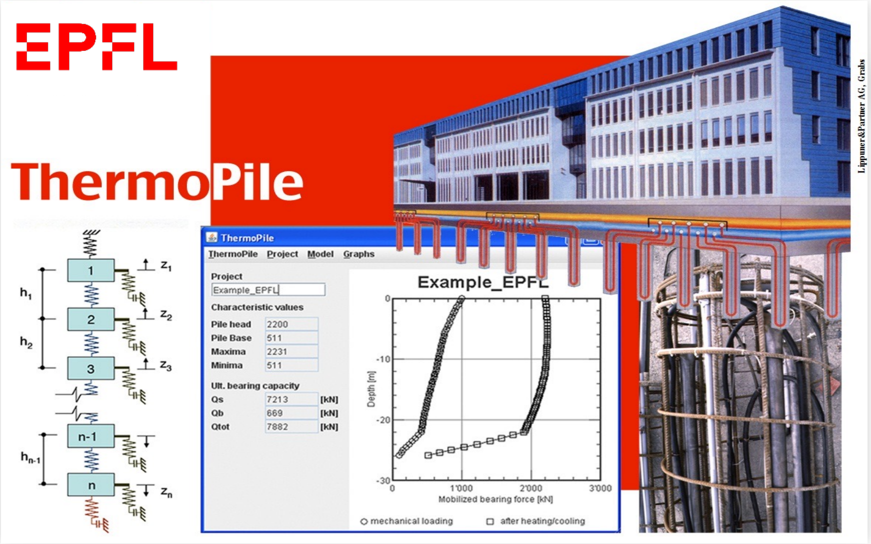
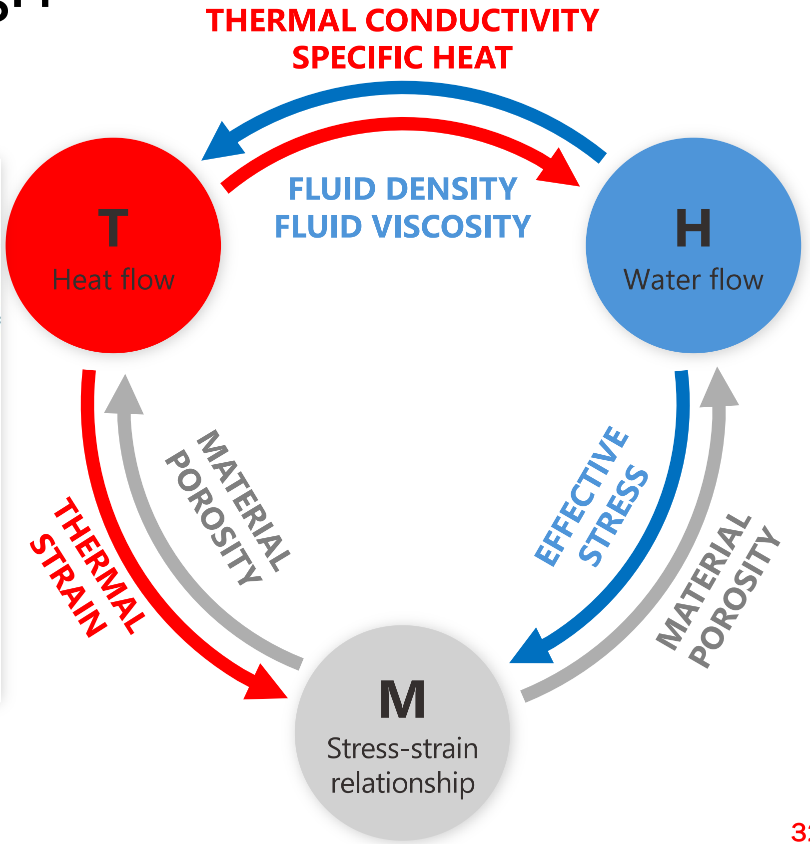
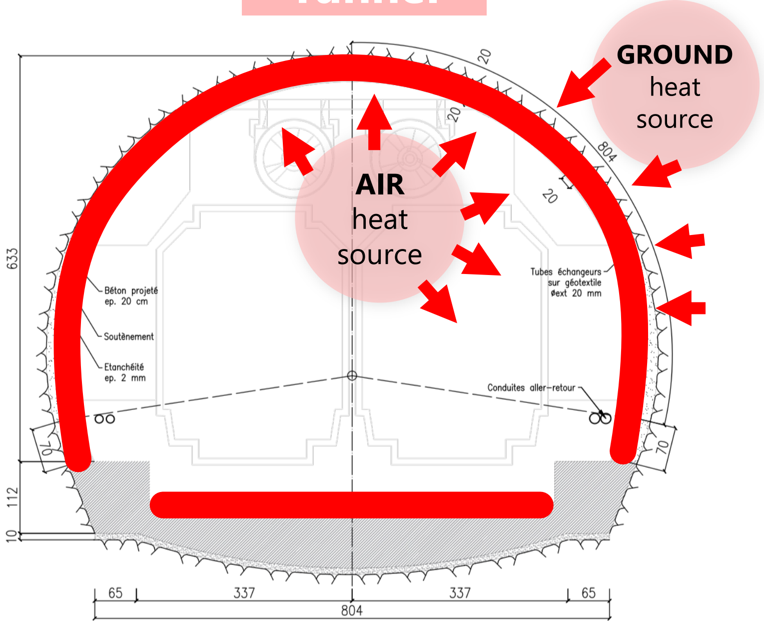
Performance and design



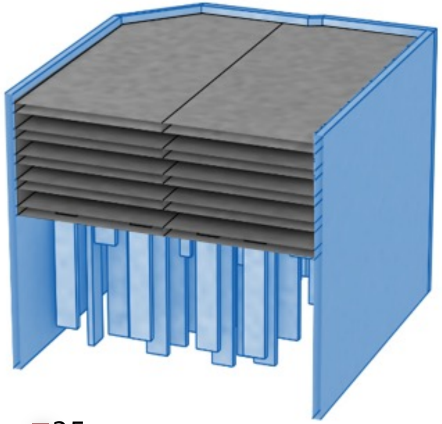


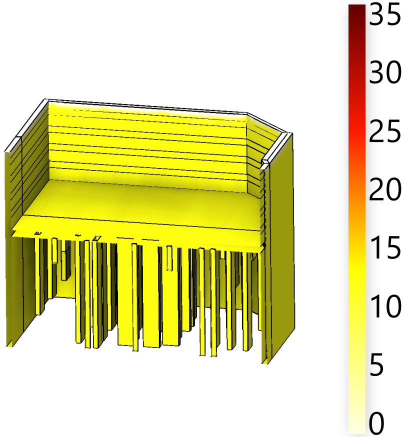
Design projects

Energy Tunnel

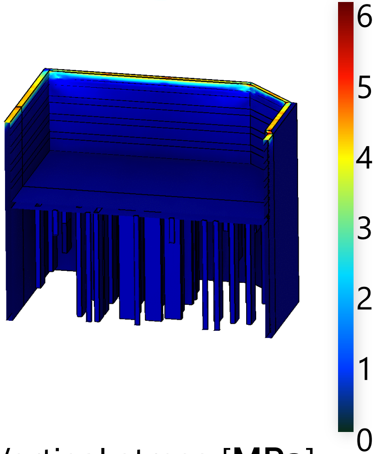


Energy barrettes and walls





Temperatur [°C]



Vertical stress [MPa]

Eliminating existing CO_2

CO_2 Sequestration

CO_2 storage potential in Switzerland

Mt CO_2 storage resources of major oil and gas fields

→ total of 310'000 Mt CO_2

(Global CCS Institute 2020)

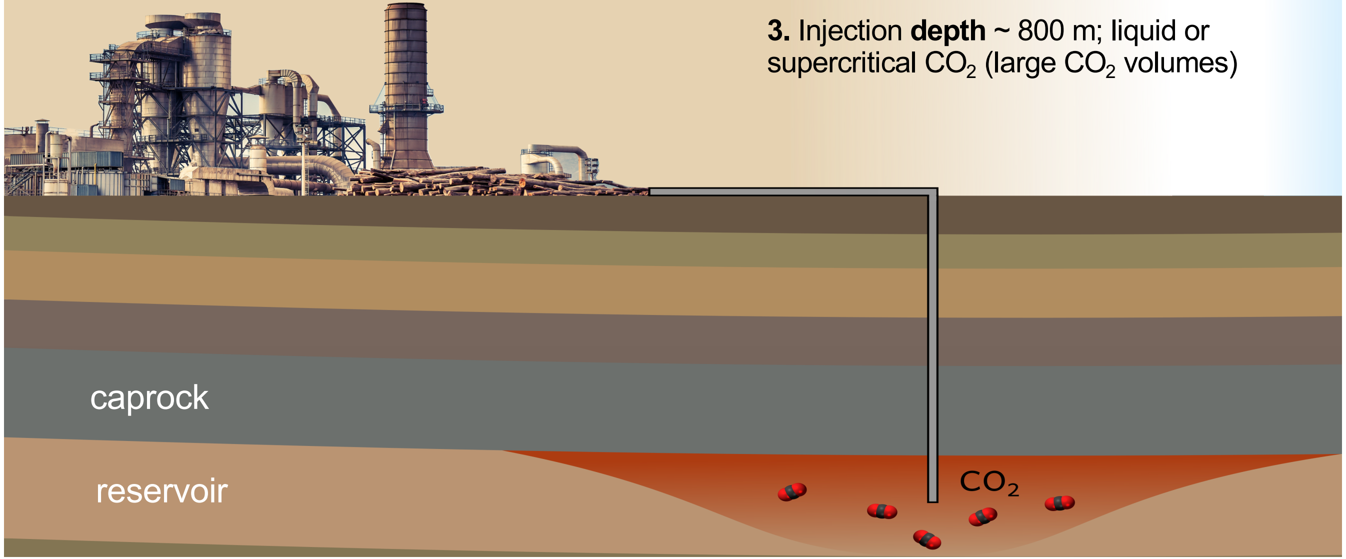
Main principle

There are no Basalts in Switzerland…
→ Onshore CO_2 storage in deep saline aquifers

1. **Porous reservoir** with sufficient storage volume

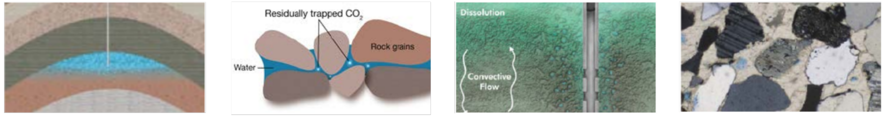
2. **Impermeable caprock** formation; hydromechanical barrier

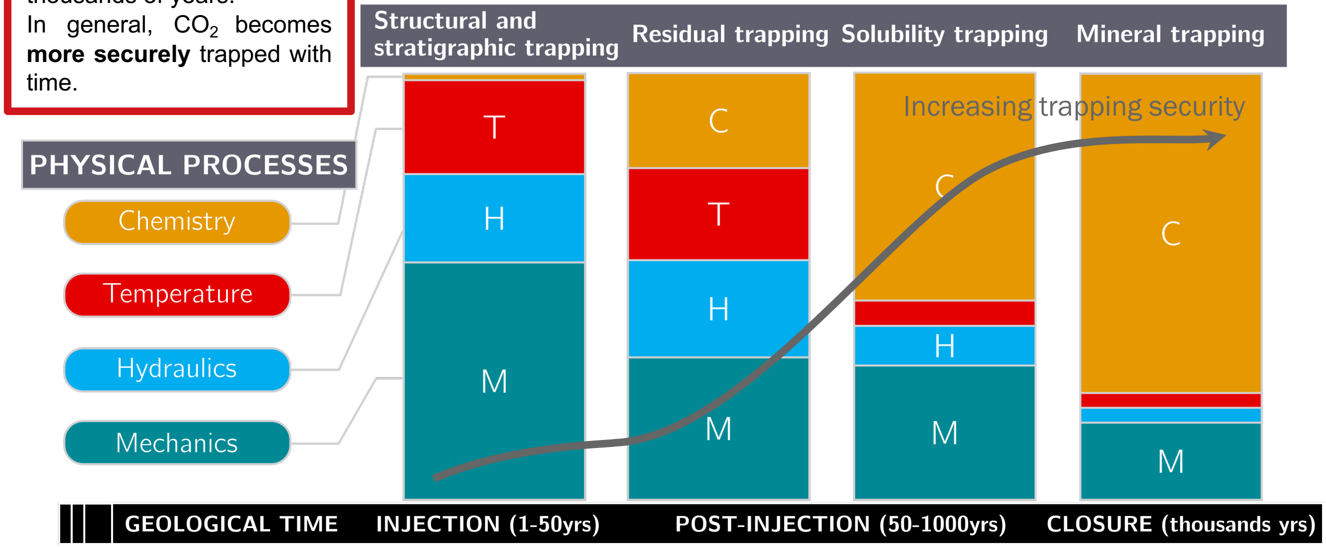
3. Injection **depth** ~ 800 m; liquid or supercritical CO_2 (large CO_2 volumes)



Trapping mechanisms

Trapping processes take place over many years at different rates from days to thousands of years.
In general, CO_2 becomes **more securely** trapped with time.

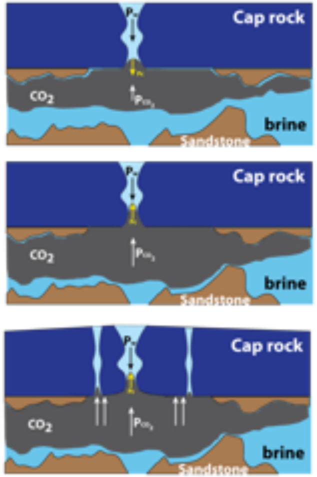




Engineering challenges

- Overpressure generation
- Fracture activation
- Surface uplift
- Induced seismicity
- Thermal effects
- Caprock integrity

Simulation of a 1 $MtCO_2$ yearly injection in a 100m thick aquifer



- *Sealing capacity* (CO_2 retention properties) should be high enough not to let CO_2 to saturate the material and flow through it
- Pressure build-up due to injection of cooler CO_2 might lead to caprock failure
- In-situ stress and temperature variations might lead to alteration of material properties: compressibility and strength
- Geo-chemical impact on mineralogy and permeability

(Minardi *et al.* 2021)

- Surface uplift is closely linked to CO_2 injection rates

(Bohloli *et al.*, 2018)

(b)

(Vilarassa *et al.* 2019)

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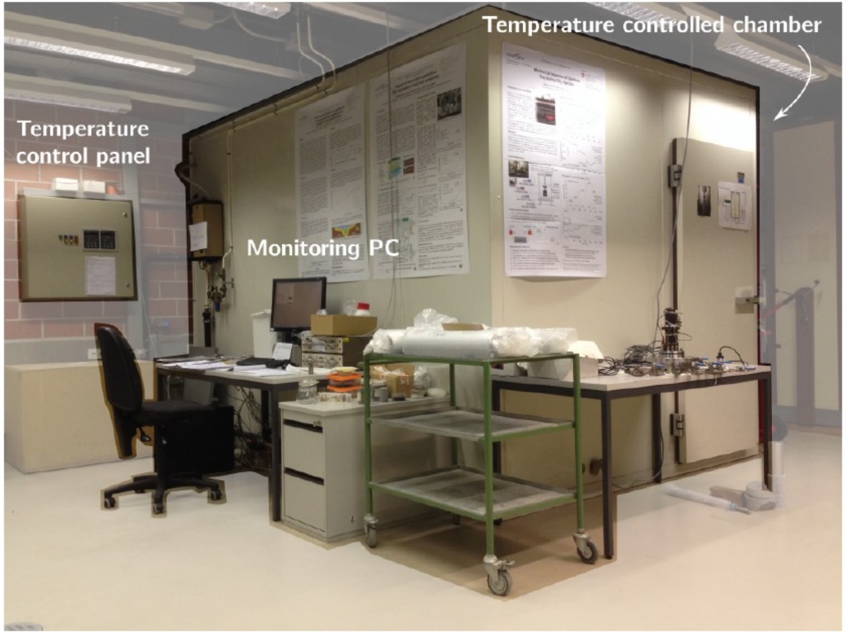
Advanced experimental testing



Dedicated facilities to geological CO_2 storage activities (LMS, EPFL)

Reproduction of real site conditions at the laboratory scale:

→ Temperature control room: 10-48°C ± 0.5°C
→ Gas, liquid and supercritical CO_2 injection

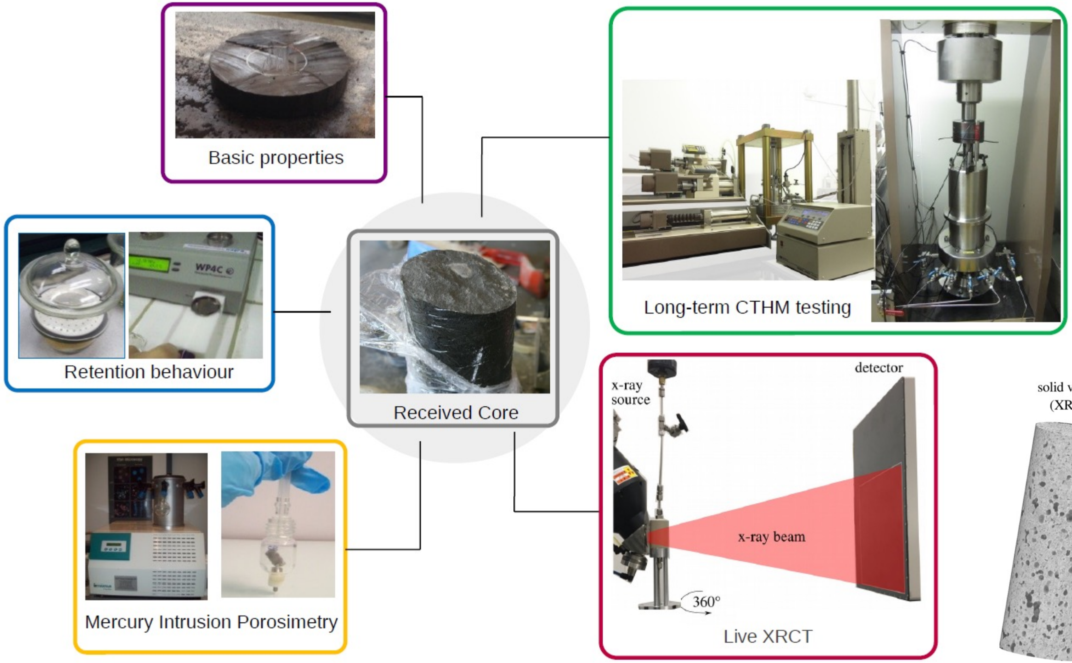
Geomechanical characterisation of relevant geological formations:

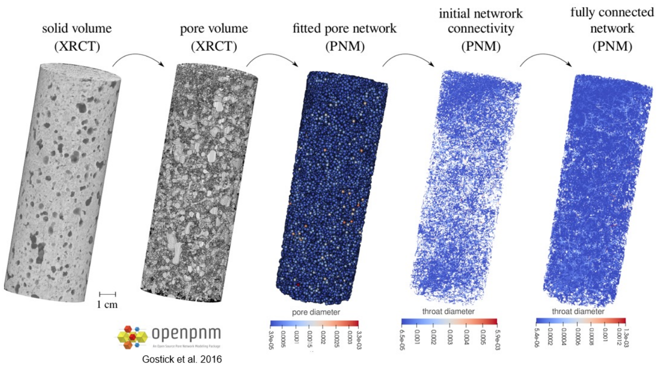
→ sandstones, limestones;
→ shales, mudstones;
→ basalts

Rigorous assessment of the coupled mechanisms:

→ **Mechanical** (e.g. stiffness, compressibility)
→ **Hydraulic** (e.g. permeability, capillarity)
→ **Thermal** (e.g. dilation, thermal gradient)
→ **Chemical** (e.g. dissolution, precipitation)

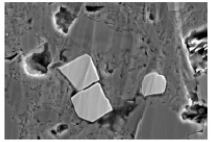
Experimental testing



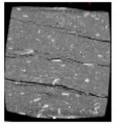


Multiscale characterization

pore scale ⟷ **lab scale** ⟷ **field scale**

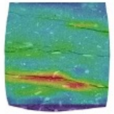


2 µm SEM image



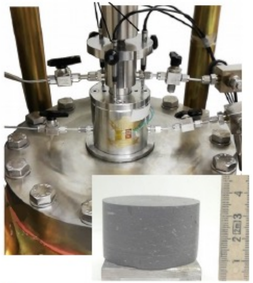
2 mm

3D x-ray image



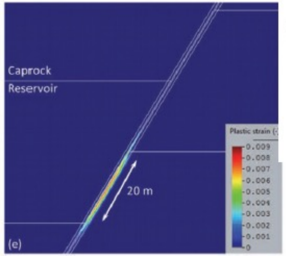
3D volumetric map

[Stavropoulou & Laloui 2022]



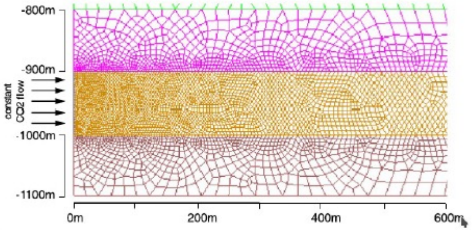
High pressure oedometre for CO_2 injection

[Favero & Laloui 2018]
[Minardi et al. 2021]



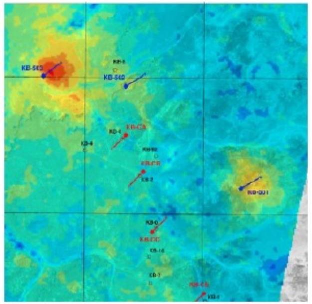
Numerical simulation of plastic strain after 1 year of CO_2 injection

[Vilarrasa et al. 2017]



Numerical model near the injection well

[Li & Laloui. 2017]



2 km

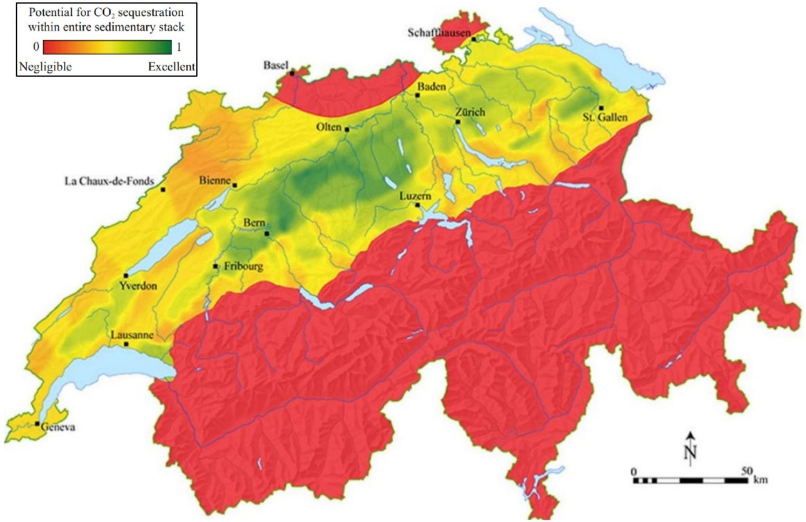
Satellite surface uplift measurements (In Salah)

SCCER SoE   SFOE   Mont Terri Project + + +   swisstopo   gaz nat   FNSNF   Accelerating CCS Technologies

CO_2 storage potential in Switzerland

CO_2 storage potential at 800-2500 m depth
(Swiss Molasse Basin)

theoretical storage capacity **2.7 Gt CO_2**



(Chevalier *et al.* 2010)

CO_2 storage potential in Switzerland

2018

Fundamental research
ETHZ, EPFL, UniBe, ..

2021

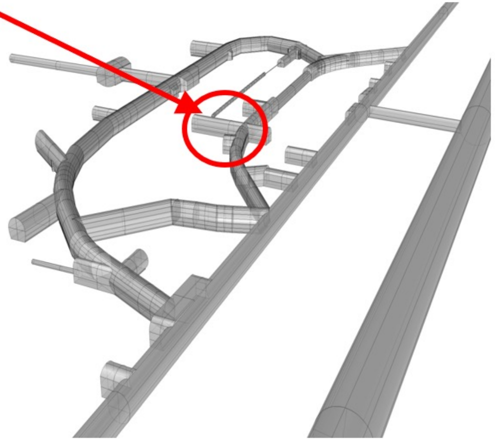
Elegancy ACT
CO_2 injection in Mont-Terri
Storage site selection

2035

Demonstration projects
DemoUp Carma
CO2-Appraisal

2040

Industrial scale storage?



Conclusion

Conclusion

- Urgency and importance of sustainable solutions
- Role of geomechanics in sustainable development
- Bio-inspired solutions for reduction of CO_2 emissions in geotechnical engineering
- Energy transition and sustainable infrastructure through nuclear energy and energy geostructures
- CO_2 storage potential and elimination of existing atmospheric CO_2