Groundwater flow module in *Code_Saturne* for nuclear waste storage applications

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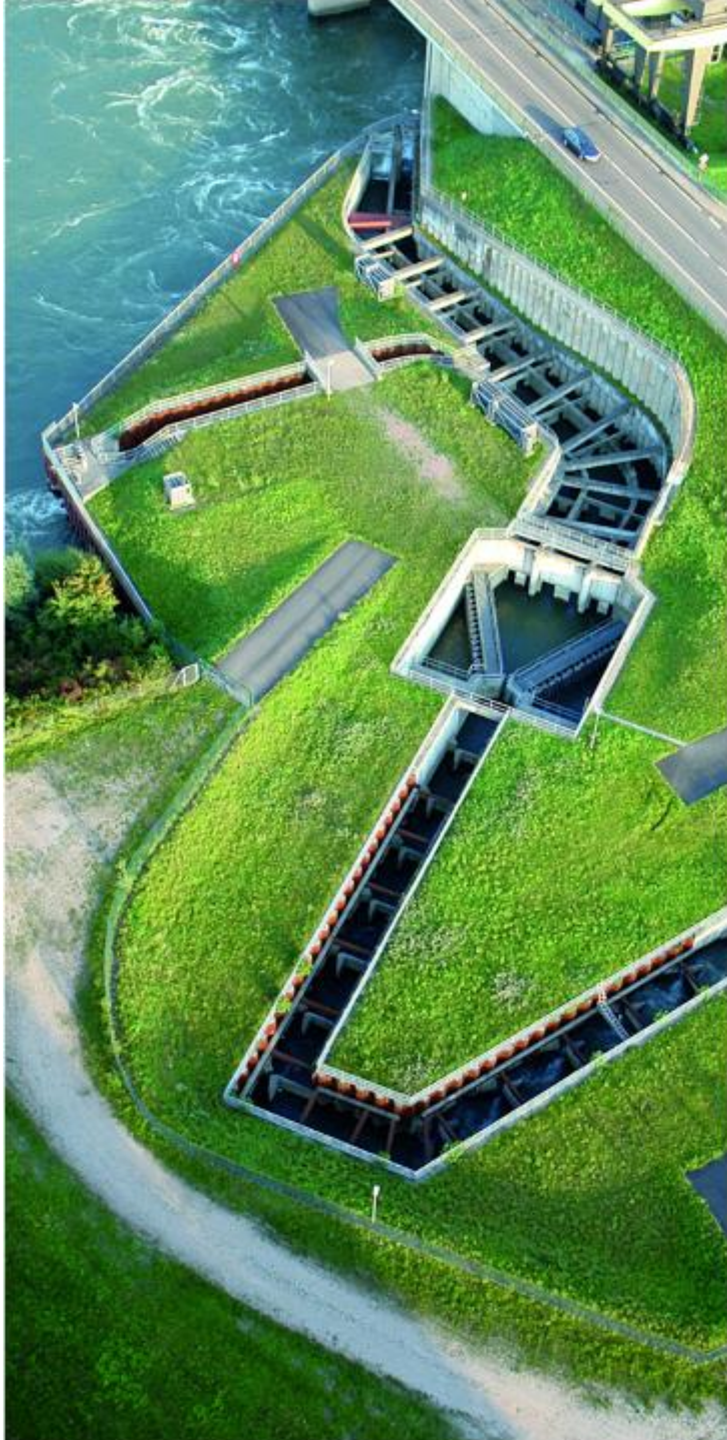
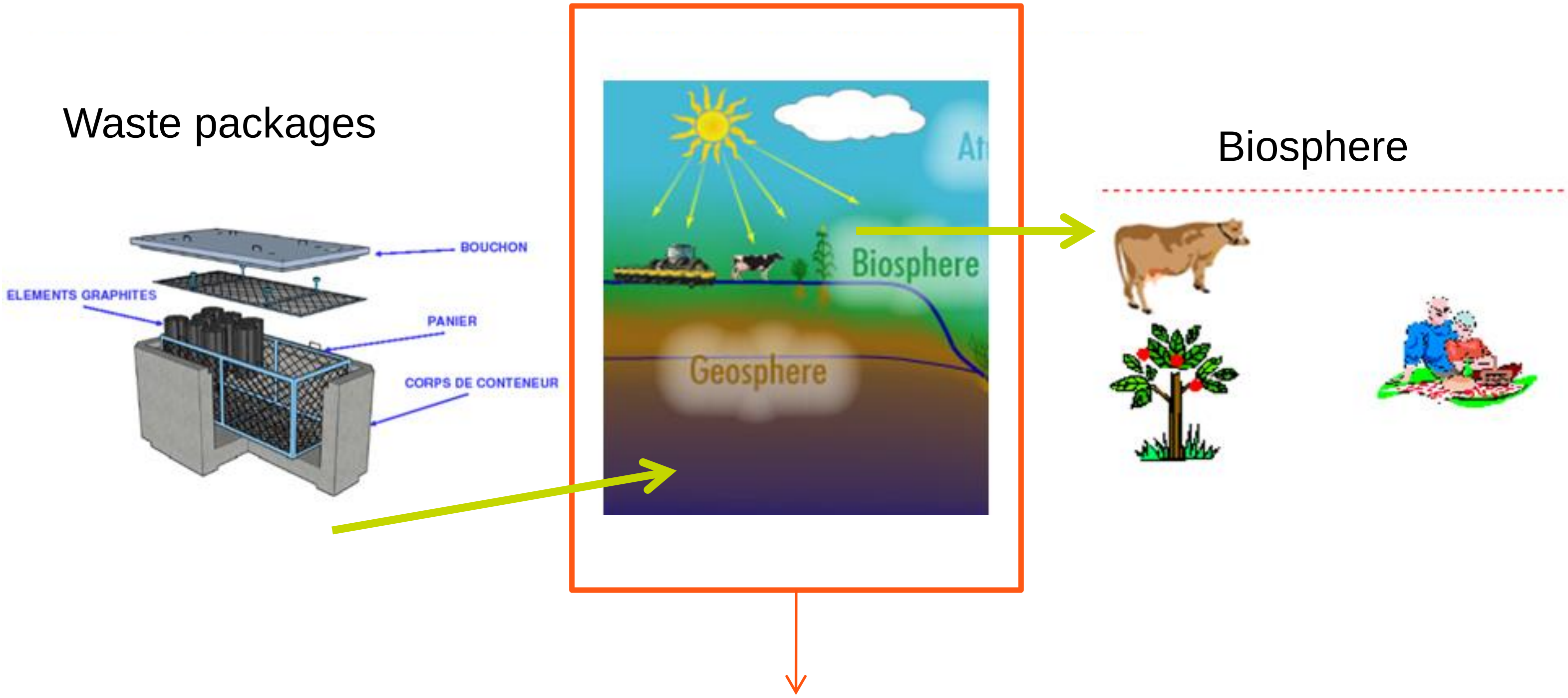


PURPOSE OF STORAGE: LONG TERM SAFETY

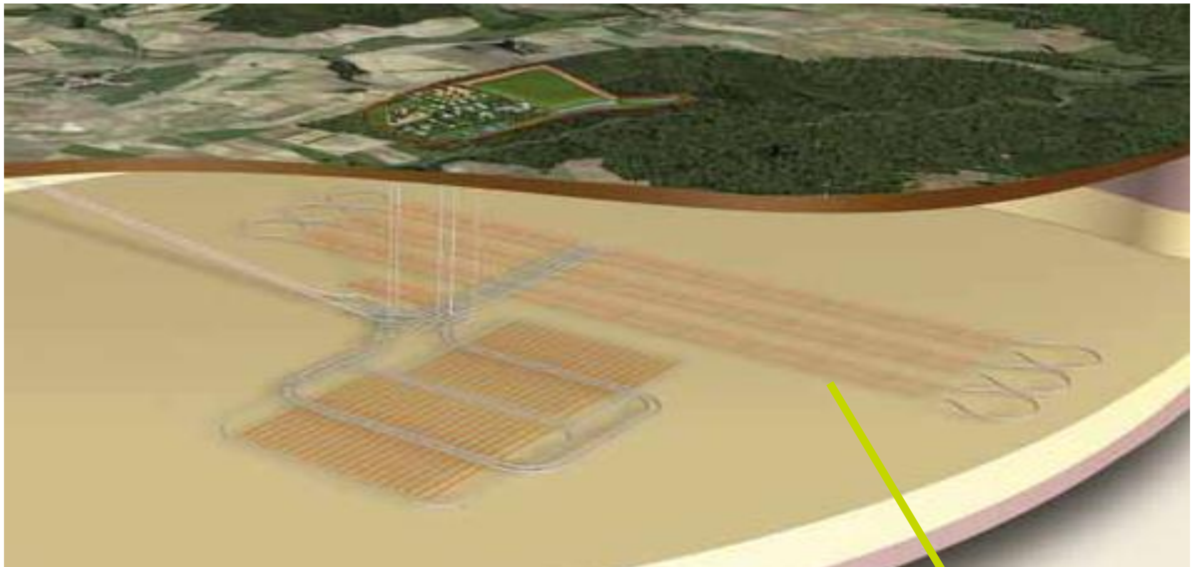
The flow of radionuclides reaching the biosphere should not exceed a certain value



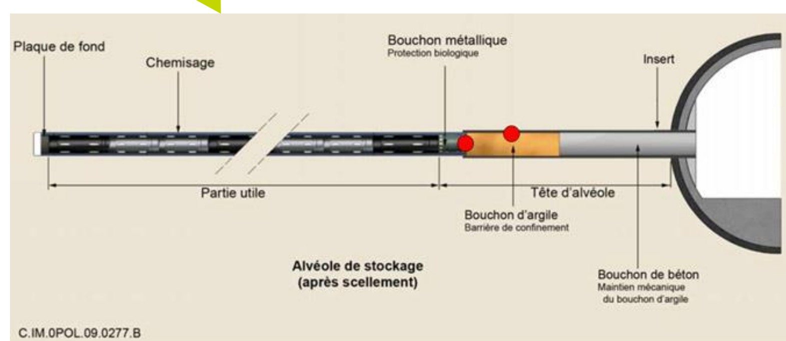
- Two possible pathways :
  - Migration through artificial tunnels, because of higher permeabilities
  - Migration through natural clay

A HPC PROBLEM MORE THAN AN HYDROGEOLOGY PROBLEM…

The physics is simple but the geometry is very complex

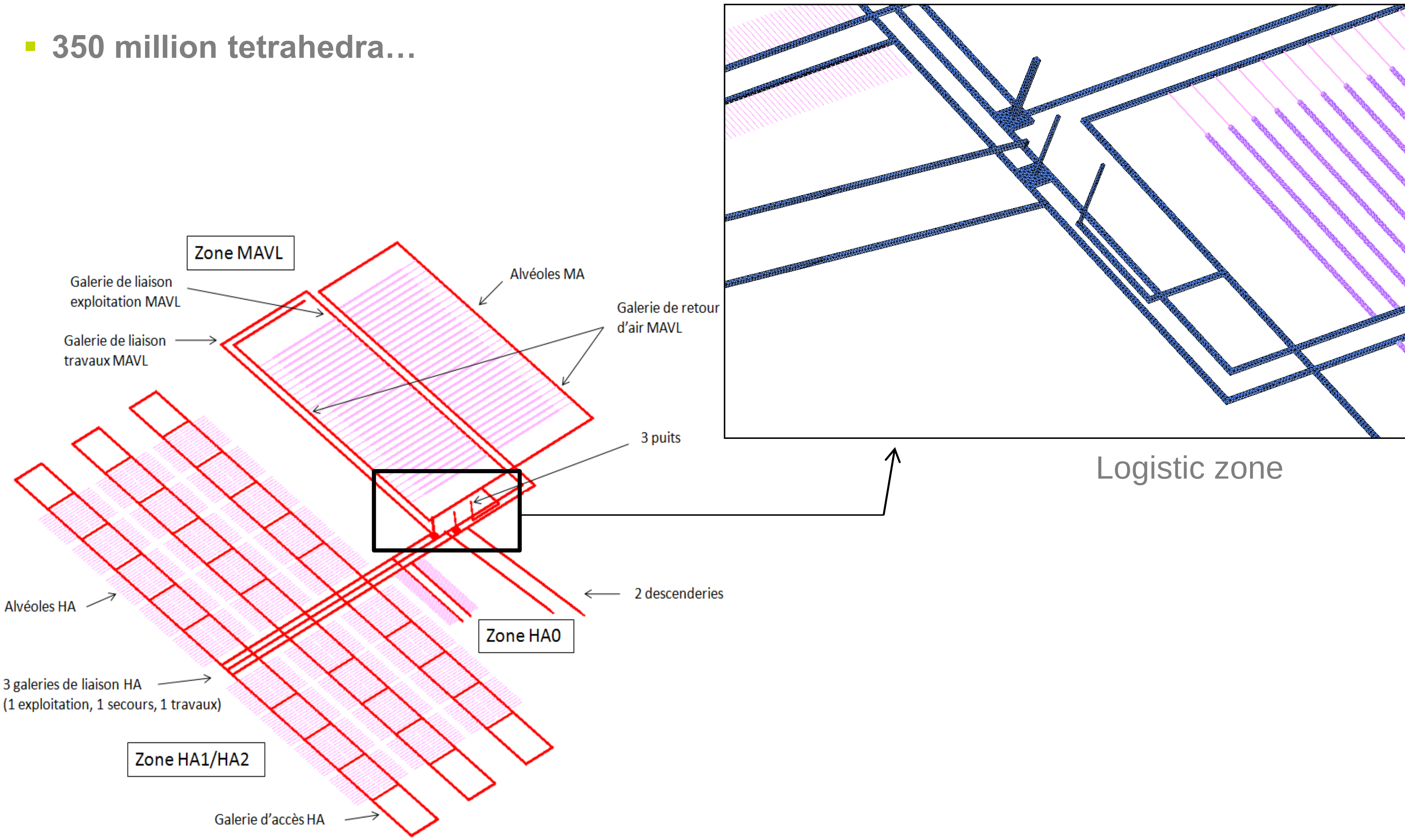


- **52 km of galleries**
- **2000 alveoles**
- **High disparities of spatial scales**



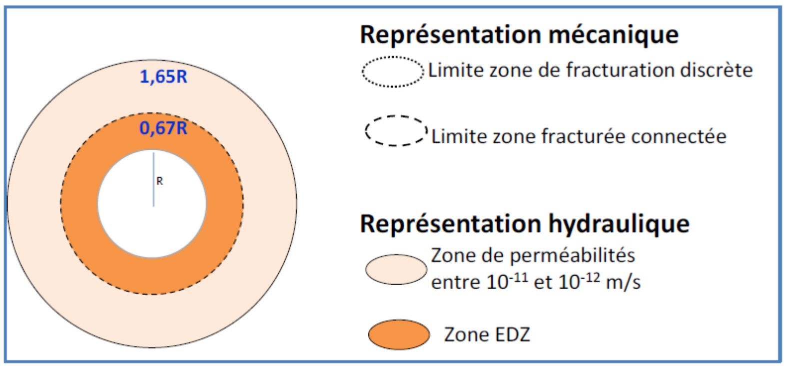
LARGE MESHES FOR COMPLETE GEOMETRY

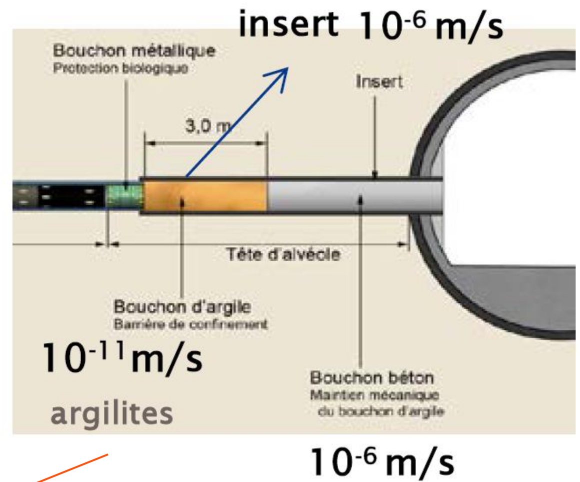
- **350 million tetrahedra…**

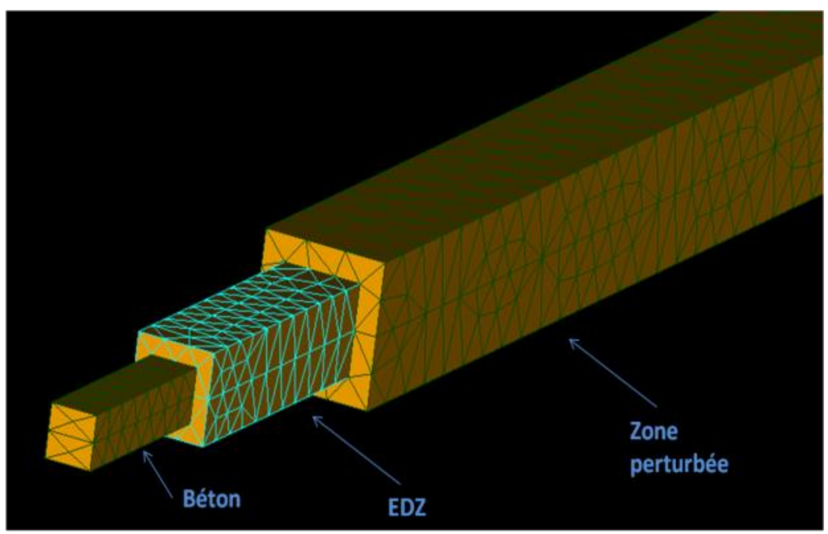


FROM LARGE SCALES TO LOCAL SCALES

- **One of the 2000 alveoles**







NEW GROUNDWATER FLOW MODULE

- **A saturated model is enough for deep nuclear storage purpose:**
  - Flow part = simple Laplace equation
  - Radionuclides transport = conventionnal transport scheme

- **BUT geometries are complex and require HPC optimisations…**

- **It has been decided in 2014 to pass:**
  - from an hydrogeology specialized code: ESTEL
  - to a HPC specialized code: *Code_Saturne*.

- **An hydrogeology module was developed in *Code_Saturne*. It is available in the version 4.0, but still has to be improved in terms of user interface.**

HYDROGEOLOGY MODELING

- **Mass conservation for stationary problems:** $\nabla . u = 0$ **(u: flow velocity)**
- **And Darcy Law:** $u = -K \nabla h$ **(K: permeability, h: pressure head)**
- **Lead to stationary Richards equation in saturated media:**

$$\nabla . (K \nabla h) = 0$$

Laplace equation, with a diffusion parameter K orthotropic, heterogeneous and highly discontinuous.

- **Then the flow is derivated from Darcy law, and used to transport a conventional scalar.**
- **These steps are close from pressure correction in *Code_Saturne*:**

$$\nabla . (\Delta t \nabla \delta p) = div(\rho u)$$

$$u = u - \Delta t \nabla \delta p$$

- **The hydrogeology module takes benefit of this similarity.**

UNSTATIONARY / UNSATURATED CASES

- **In its general form, the mass conservation writes:** $\frac{\partial \theta}{\partial t} + \nabla . u = 0$

with θ the moisture content, and permeability depends on θ.

- **Richards equation becomes:** $\frac{\partial \theta}{\partial t} + \nabla . \left(K(\theta) \nabla h \right) = 0$

- **It is closed by a soil law $\theta(h)$, usually highly nonlinear.**

Example: Von Genuchten law:

$$\theta(h) = \left(1 + |\alpha h|^n\right)^{-m} \qquad K(\theta) = \left(1 - \left(1 - \theta^{1/m}\right)^m\right)^2$$

- **It is solved in the Underground Flow module thanks to a Newton scheme, which ensures correct handling of nonlinearities and exact mass conservation.**

APPLICATION TO GEOLOGICAL DISPOSAL

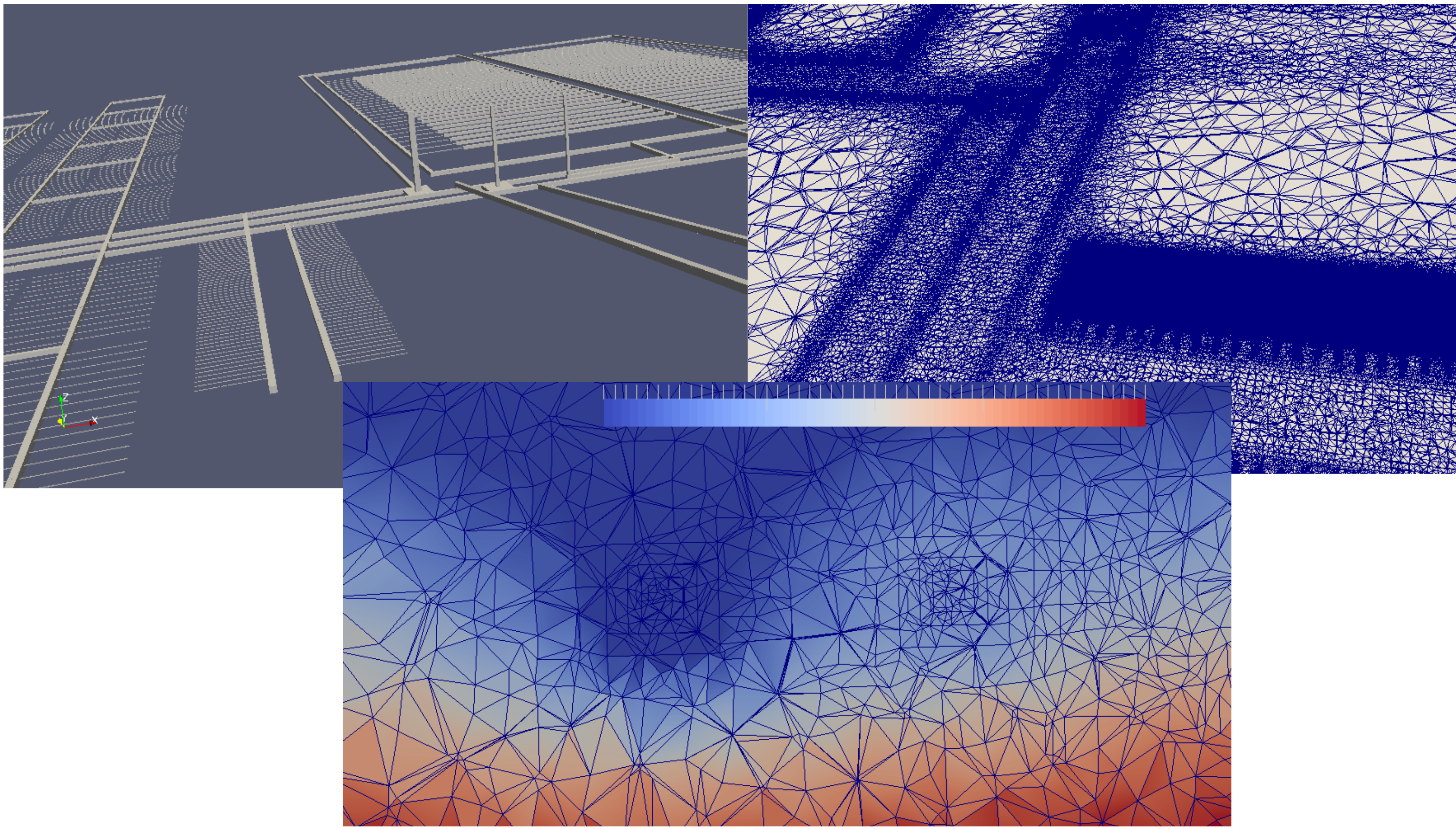
- **Methodology**
  - Mesh generation:
    - Python script for GEOM and SMESH SALOME module
    - Sequential on a big mem node of EDF cluster
  - Computation:
    - Parallel on standard nodes (1000 cores) of EDF cluster
  - Visualisation:
    - Done with ParaVis module (ParaView of SALOME)
    - Parallel on visualisation nodes of EDF cluster

- **Flow part:**
  - (+) Stationary solution (-) high physical properties ratio
  - New weighted gradient computation → convergence OK for isotropic soils

- **Radionuclides transport part:**
  - 1304 iterations for 1 million years
  - Convergence not guaranted for now…

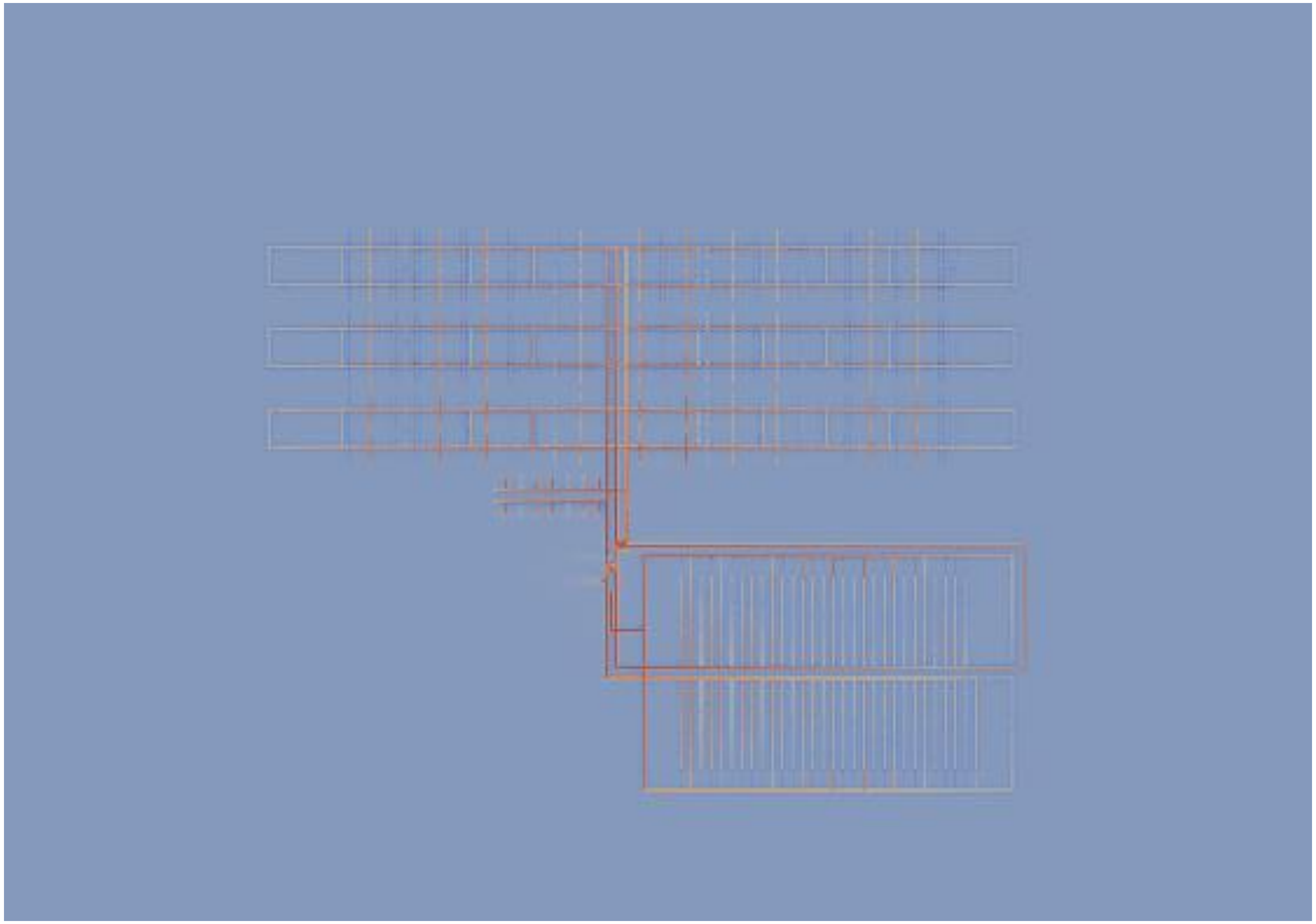
APPLICATION TO GEOLOGICAL DISPOSAL

- **Examples of hydro field**



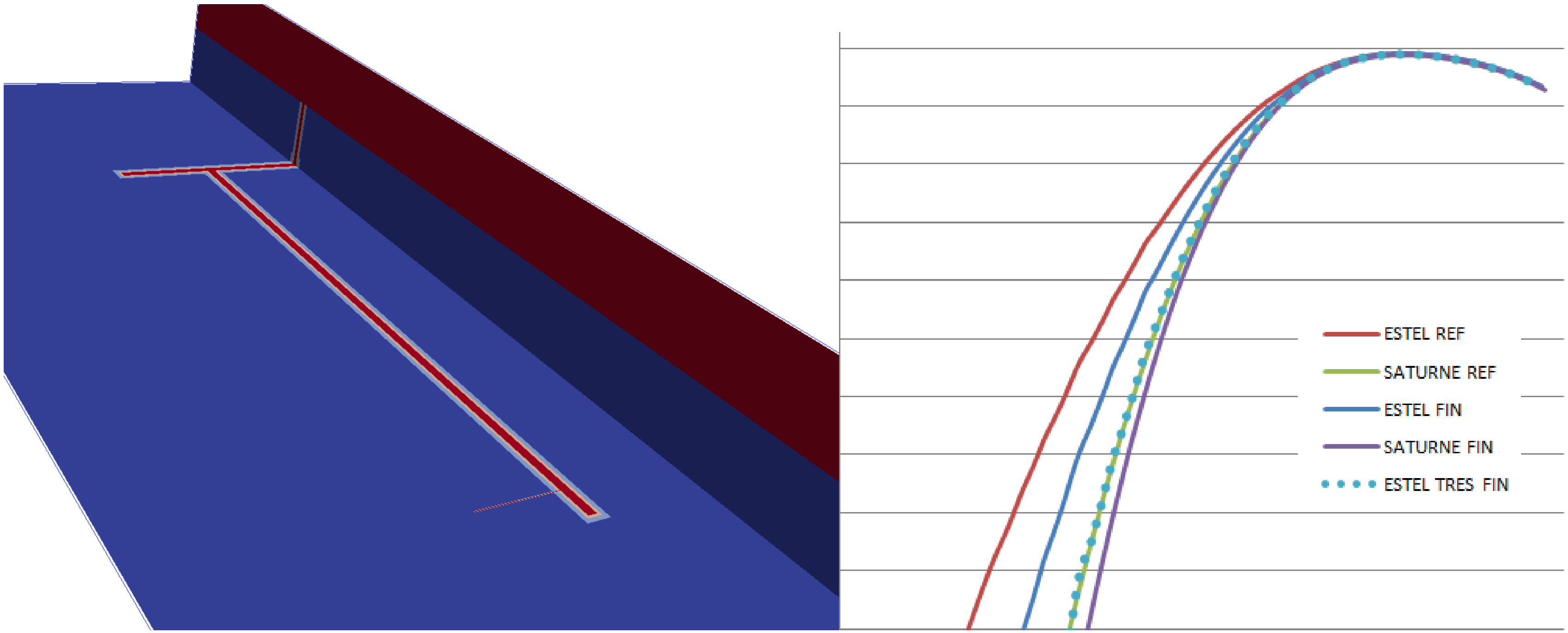
APPLICATION TO GEOLOGICAL DISPOSAL

- **Examples of hydro field**



APPLICATION TO GEOLOGICAL DISPOSAL

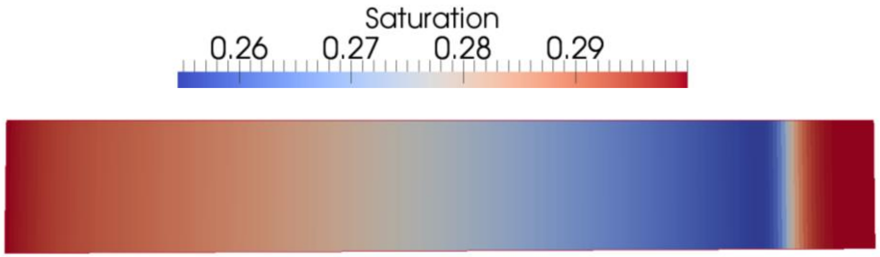
- **Simple case to understand instabilities in the transport part**



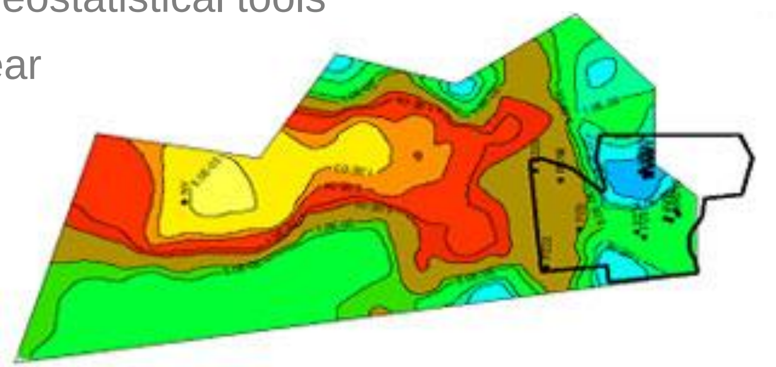
  - Upwind scheme coupled with the BiCGSTAB solver seems to be optimal

WHAT'S NEXT ?

- **Variable saturation flows based on Van Genuchten law**
  - Already coded and verified on a simple case



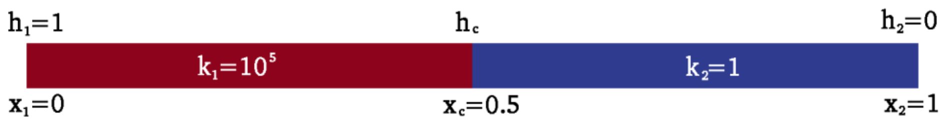
- **Management of geologic data**
  - Ground properties for are processed with geostatistical tools
  - A converter is planned for the end of the year

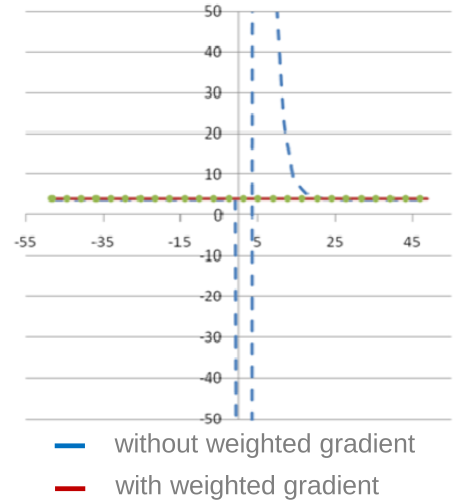


ISATIS data (from Geovariances Website)

ACTUAL STATE

- **Validation & Verification**
  - Validation case : PERMEABILITY_GRADIENT
    - Saturated and stationary pseudo 1D flow
    - Validation of the weighted gradient computation





  - Verification case: 38_HYDRUS1D
    - Unsaturated pseudo 1D flow
    - Verification of Richards solving procedure + delay and decay effects in transport

- **Documentation**
  - Theory: Done
  - Usage: Doxygen in progress

GROUNDWATER MODULE