# Rock mechanics of the Callovo-Oxfordian claystone at the Meuse/Haute-Marne Underground Research Laboratory and consequences for CIGEO repository design

G. Armand, A. Noiret, J. Zghondi, R. de La Vaissière, N. Conil, J. Morel, F. Bumbieler

Symposium « Rock Mechanics and Rock Engineering of Geological Repositories in Opalinus Clay and Silmilar Claystone »



## Legal Framework in France

### The 1991 Waste Act

- Creation of « Andra » as a public independent body
- 3 research areas for High Level Long-lived Waste: partitioning/transmutation; long term storage; geologic disposal

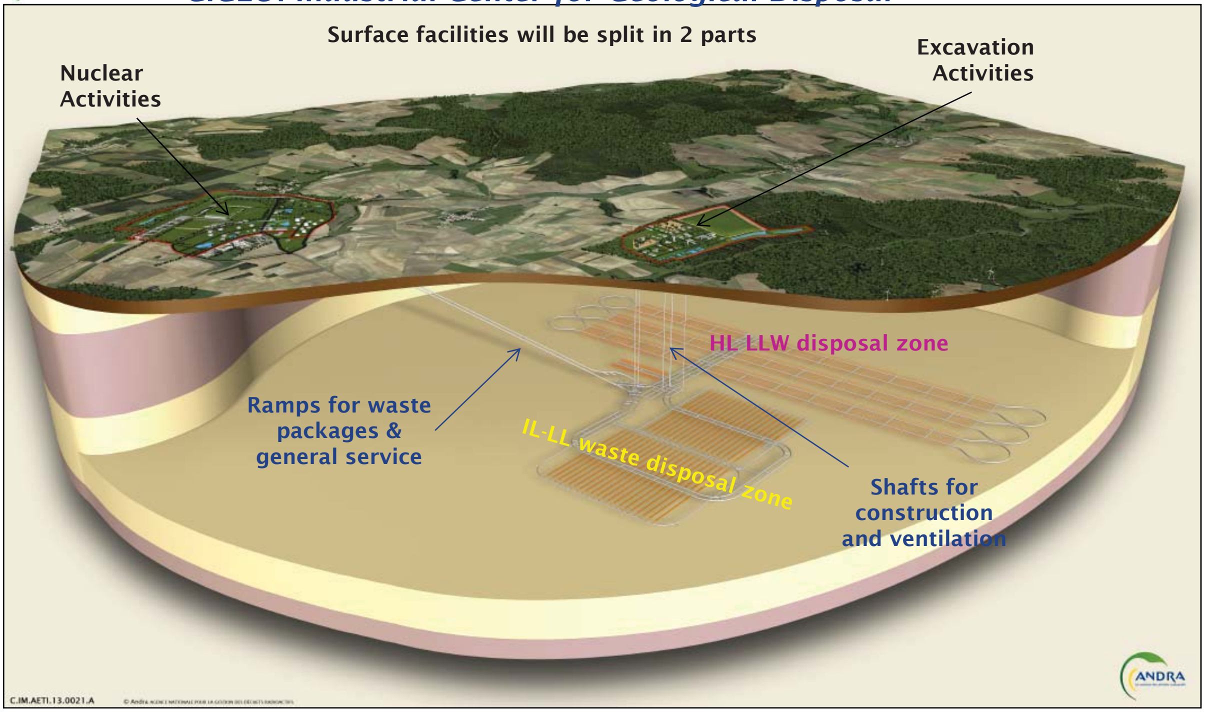
➢ **2005: Feasibility assessment of safe geological disposal in Callovo-Oxfordian claystone layer (Meuse/Haute-Marne URL)**

### The 2006 Programme Act: Reduce/avoid the burden on future generations

- Reduce volume and harmfulness of wastes
  - ⇒ SF reprocessing + waste treatment and conditioning
- Reference option <u>for final waste that can no longer be treated</u>: geological repository with respect to reversibility (100 y at least)
  - ☐ Application: 2015; Operation: 2025 ☞ **Cigéo Project**
- Continue research on interim storage (Andra) and partitioning/transmutation (CEA) and on a complementary basis.

## Architecture of CIGEO Project

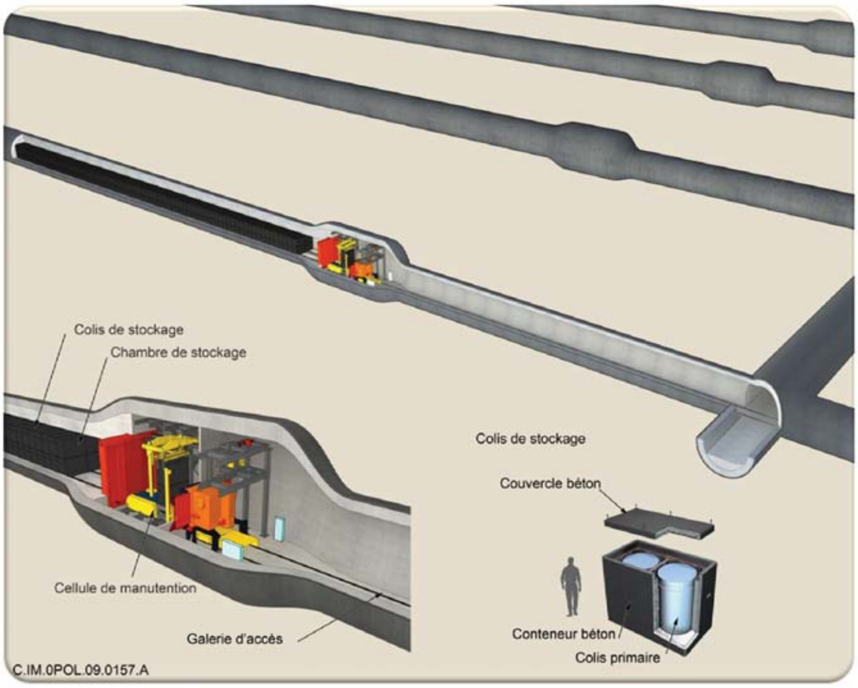
*CIGEO: Industrial Center for Geological Disposal*




Underground facility : cells will be added progressively as the operation progresses until they reach a total maximum area of about 15 km², after about 100 years



## Zoom on the IL-LLW disposal cell



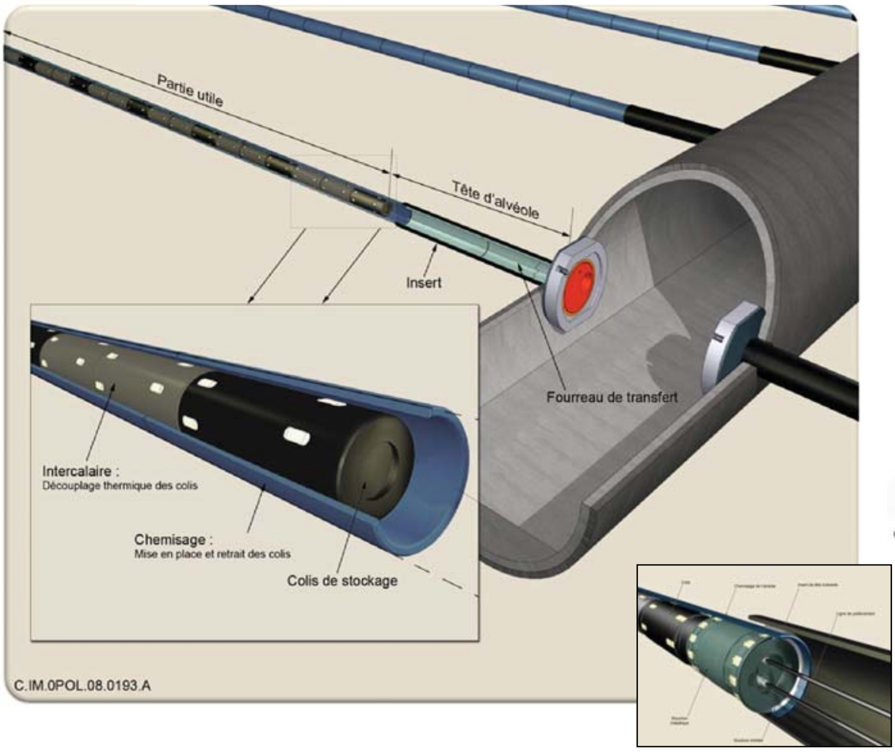

Length: ≈400 m

Excavated diameter: 9-11 m

2x2 or 3x3 packages

No. of containers: 800-1,900

## Zoom on the HLW disposal cell

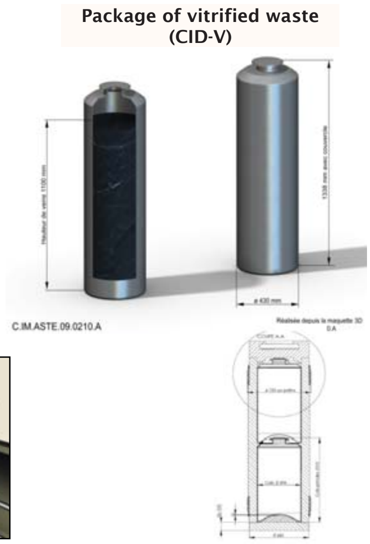



Length ≈ 80 m

Diameter: 70 cm

No.of containers: 7-20

(for 40 m)






## Needs in geomechanic

**Specific feature of such project**

- Underground nuclear facility
- Long operational life time
- Size (length of drift,…)

Need a good understanding of rock and structure interaction

- The Callovo Oxfordien THM behavior
- The structure behavior (concrete,…)
- It is necessary to take into account the consequences of the construction method (velocity of digging, time between digging and installation, type of material as structure

**Design of different elements of the repository**

**Input for the performance assessment calculation**

## Geomechanical research at the URL

**The performance/safety assessment and technology demonstration are the main objectives of research programs. In geomechanic:**

- To study hydro mechanical behavior of claystone during drift and shaft excavation (short and long term behavior)
  - Impact of digging and support method
  - Orientation of drift
- To characterize the Excavation Damaged Zone (EDZ)
- To characterize the Thermo Hydro Mechanical behavior
- To perform sealing experiments
- To study the impact of gas transfert in the rock/EDZ/seals

**EDZ characterization for safety assessment calculation**

**HM behavior to design support of the repository drifts**

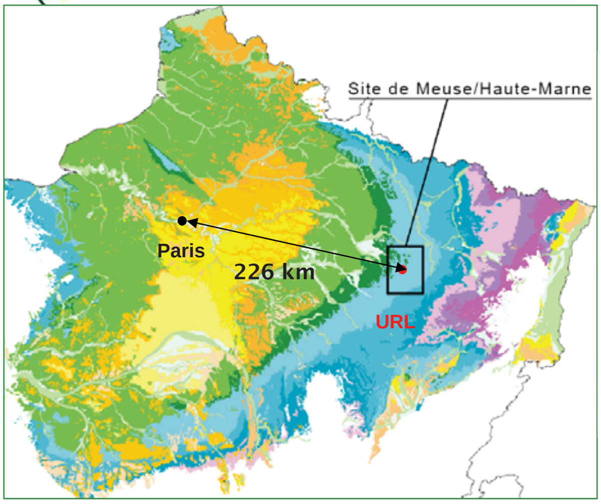
In situ experiment serve for demonstration issue

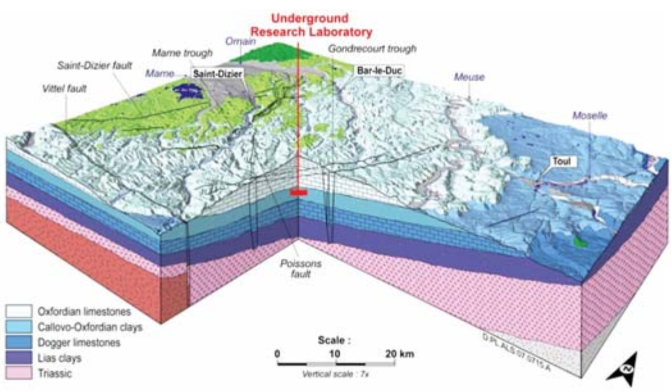
In situ measurements are compared with numerical modeling and useful to validate and develop HM model



# The Callovo Oxfordian claystone

# The Callovo-Oxfordian argillite at the MHM site (Bure)




- Age: 155 million year
- Depth at the site: ~500 m
- Thickness at the site: ~130 m

- Mineralogy: ~ 45% clay + carbonates and silicates
- low water content
- No free water, no water flow
- Diffusive transfer only
- Retention capacity

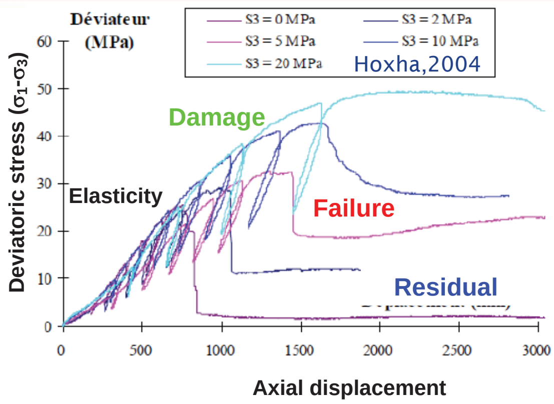
 

# Rock properties of the COX

## Callovo Oxfordian claystone properties at the 490 m level:

- Mineralogy:
  - 50-55% clay minerals
  - 20-25% carbonate
  - around 25% quartz silts
- Very low permeability ($5.10^{-20}$ m²)
- Short-term behavior, triaxial test: non linear and post-peak depending on $\sigma_3$
- Long term behavior, uniaxial creep test:
  - Creep strain rate increases non-linearly with the applied deviatoric stress
  - Creep rate (Andra 2005):

    *$4.10^{-12}$ < creep rate <$1.60.10^{-12}$ (test duration 1 to 3 years)*
  - Long-term behavior according to the modified Lemaître's model




| Rock parameter | Ind. | Value |
|---|---|---|
| Bulk specific gravity | ρ | 2.39 g/cm³ |
| Porosity | n | 16±2% |
| Young modulus | $E_\perp$ | 4000±1470 MPa |
| | $E_{//}/E_\perp$ | 1.2 to 1.5 |
| Poisson Ratio | ν | 0.29±0.05 |
| **Uniaxial compressive strength** | **UCS** | **21±6.8 MPa** |
| Hoek & Brown criteria | | |
| S | | 0.43 |
| m | | 2.5 |
| $\sigma_c$ (MPa) | | 33.5 |
| **Intrinsic permeability** | **k** | **$5\times10^{-20}$ m²** |
| Water content | w | 7.2±1.4 % |

# HM behavior of drift
# (at the main level of the URL)



## Experimental strategy for the study of drift behaviour

**1- Use the underground laboratory for observing real behavior of drift under natural conditions**

- Each drift excavation in the URL is a geomechanical experiment in itself

**2- Sequencing of drift construction to highlight the role of support/excavation methods**

- Start with "soft" support drift to study the behavior of COX
- Skip to rigid support emplaced after a delay of several months
- Then emplace rigid support sooner after the excavation of the gallery

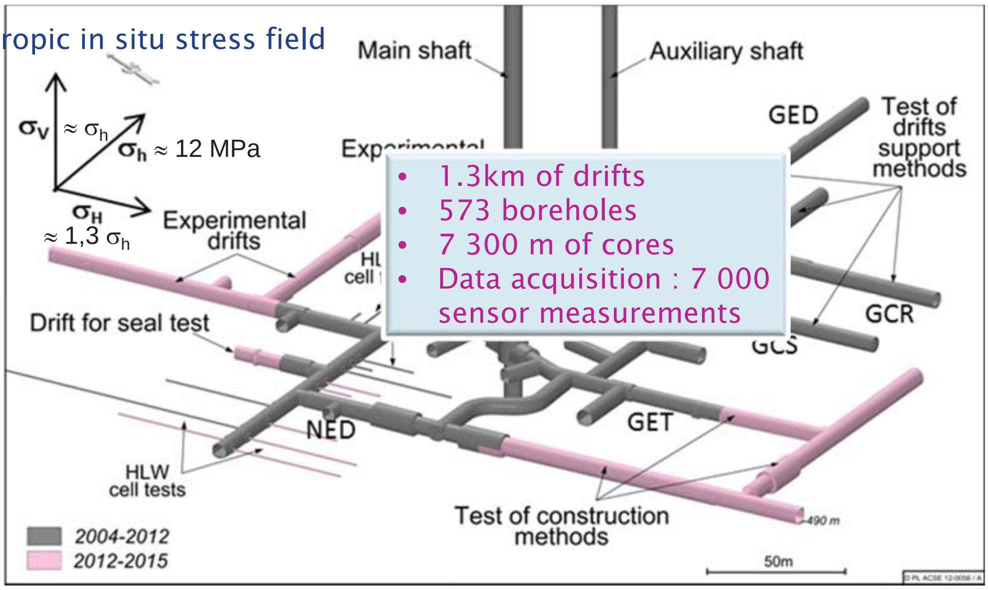
**3- Using parallel drift to compare the different behavior**

**4- Use mine by experiment (borehole emplaced before the excavation) to study the HM behaviour (at short and long terms)**

# Meuse/Haute-Marne underground research laboratory

**A huge program of experiments is planned to characterize the response of the rock to different drift construction methods**

Anisotropic in situ stress field




- 1.3km of drifts
- 573 boreholes
- 7 300 m of cores
- Data acquisition : 7 000 sensor measurements



# Excavation methods

- Test different excavations and supports in parallel drifts to better understand the behavior of the drift by comparison (from low support to stiff support like concrete segments)



**Road header under shield**


DRD/MFS/14-0038 © Andra AGENCE NATIONALE POUR LA GESTION DES DÉCHETS RADIOACTIFS

# Different drift supports (1/2)





radial rockbolts (3 m long),
18 cm of fiber reinforced shotcrete,
12 yieldable concrete wedges (hiDcon®)

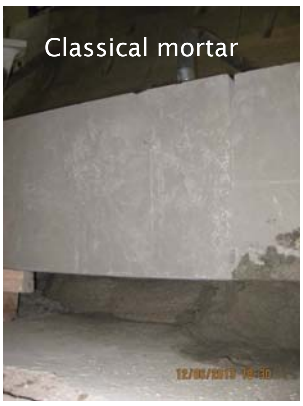
≈ GCS drift + 27 cm of concrete casted in place 6.5 month after excavation

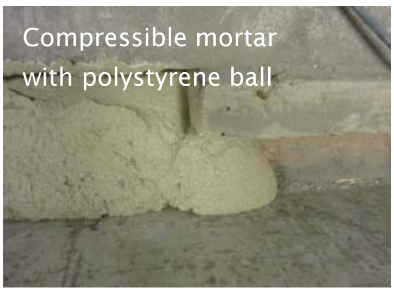
radial rockbolts (3 m long),
45 cm of fiber reinforced shotcrete emplaced in four layer



# Different drift supports (2/2)

- Segment emplacement method
  - ☐ Segment of 45 cm thick
  - ☐ Gap filling with radial injection of mortar

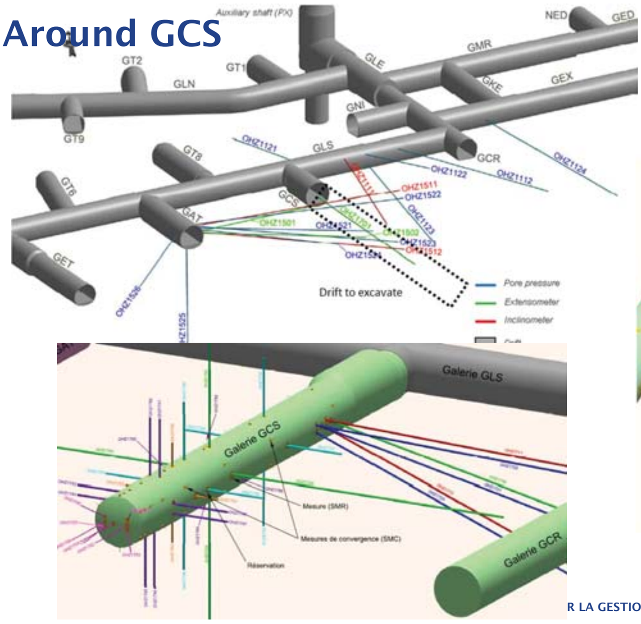


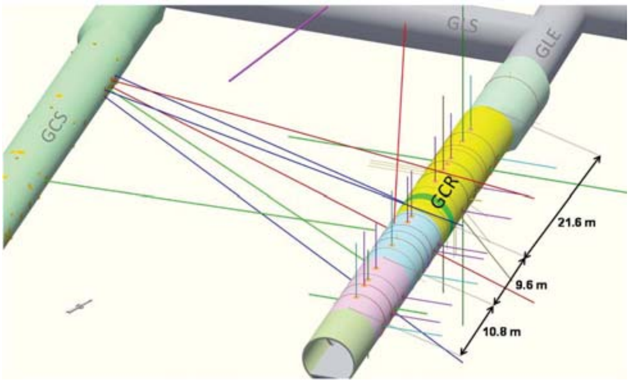
## Mine by experiment

- Experimental set up: “Mine by experiment”
  - ☐ Boreholes (Displacement, pore pressure) emplaced before excavation
  - ☐ Convergence measurements, geological survey, boreholes (displacement)
  - ☐ Borehole to characterize EDZ (permeability measurements, velocity survey,

**Around GCS**




**Around GCR**



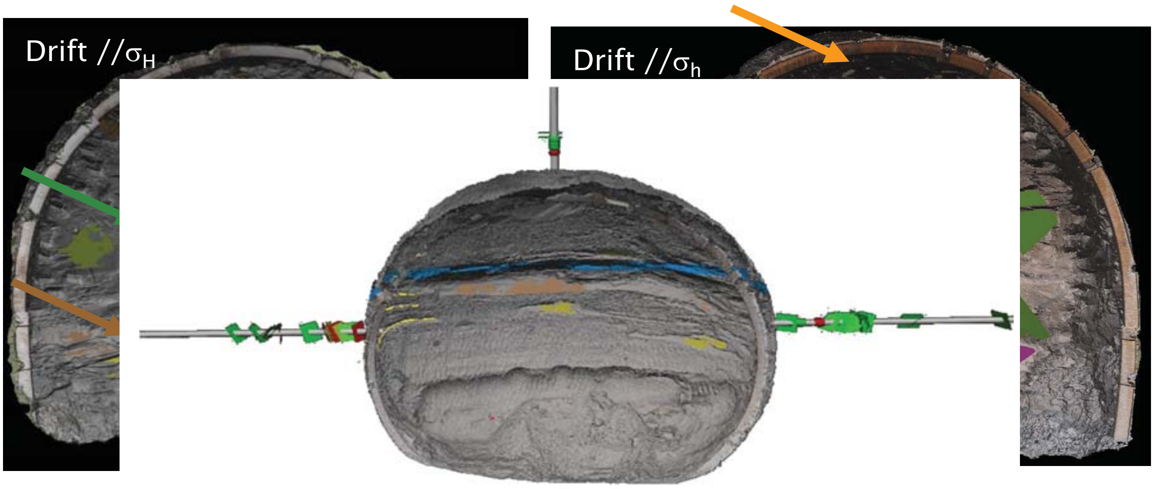



## Some example of results on drifts:

## Excavation induced fracture

## HM behaviour of drift

# Geological survey




Fracture sup
Fracture infé
Fractures du bombement - extension

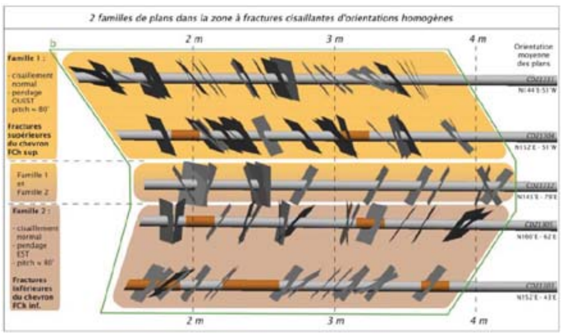
- 3D scan is performed to map the front face and analyze fracture orientation (GEOTER)
- Fractures types are the same in the two directions but number location and extent differ

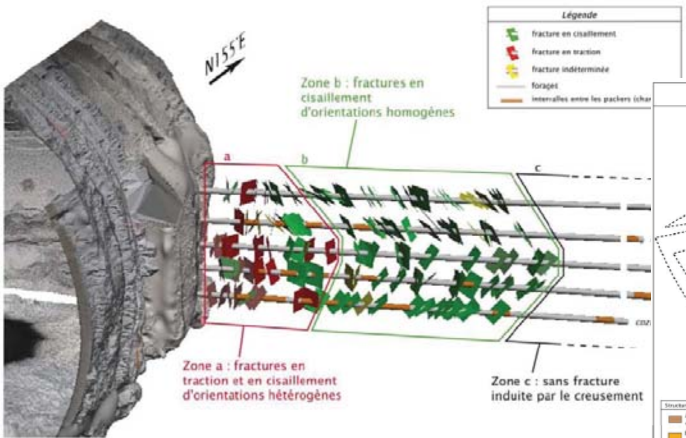


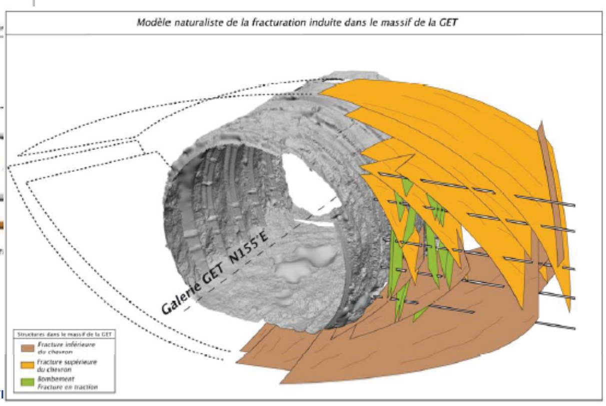
# Induced fracture in drift parallel to $\sigma_H$

**Structural analysis in an area with numbers of borehole exhibits :**

- Complex pattern
- Extent of shear fracture is larger than tensile fracture
- Deep in the rock the shear fracture are visible on different borehole

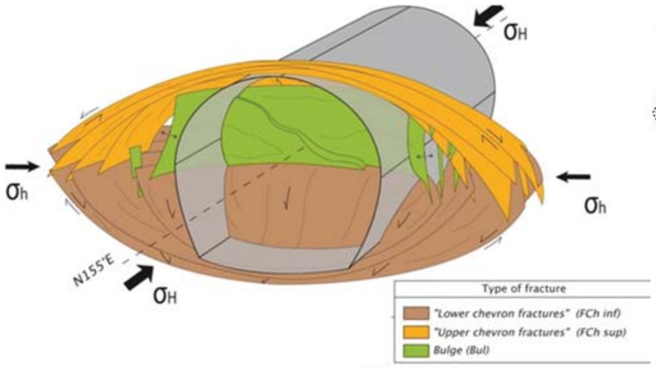


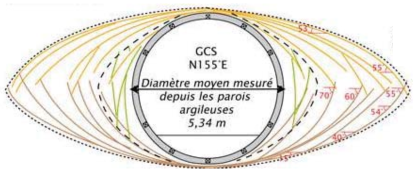



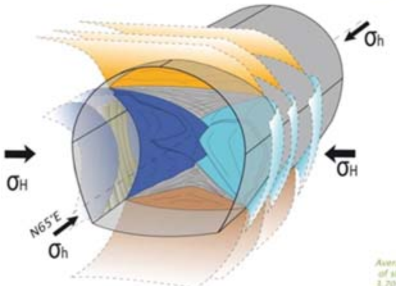



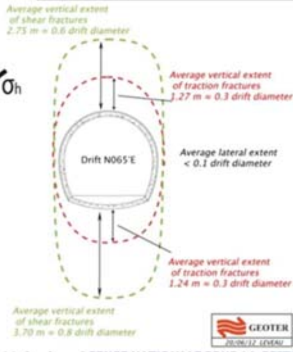
# Induced fractures network

- Type of fracture are similar but the extend depend of dirft orientation versus in situ stress state



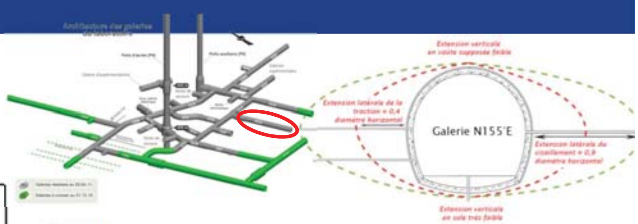




| Drift Orientation | | Extensional fractures extent | | | Shear fractures extent | | |
|---|---|---|---|---|---|---|---|
| | | Min. | Average | Max. | Min. | Average | Max. |
| N65 // $\sigma_h$ | Ceiling | 0.2×D | 0.3×D | 0.4×D | 0.5×D | 0.6×D | 0.8×D |
| | Wall | 0.1×D | 0.1×D | 0.2×D | - | - | - |
| | Floor | 0.2×D | 0.4×D | 0.5×D | 0.8×D | 0.8×D | 1.1×D |
| N155 // $\sigma_H$ | Ceiling | - | 0.1×D | 0.15×D | - | - | - |
| | Wall | 0.01×D | 0.2×D | 0.4×D | 0.7×D | 0.8×D | 1.0×D |
| | Floor | - | 0.1×D | 0.15×D | - | - | - |

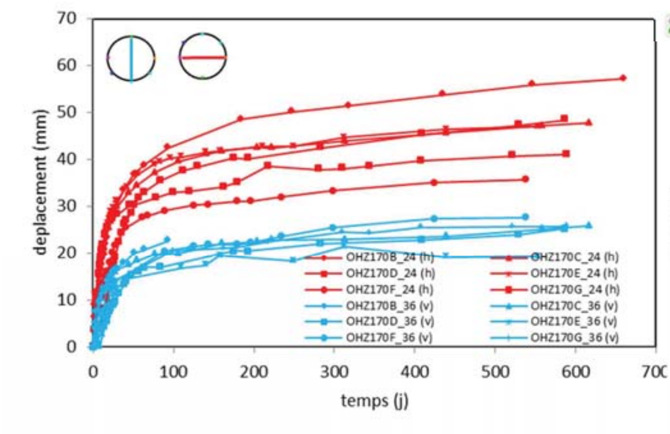

G. Armand, F. Leveau, C. Nussbaum, R. de La Vaissiere, A. Noiret, D. Jaeggi, P. Landrein, C. Righini, 2014, Geometry and Properties of the Excavation-Induced Fractures at the Meuse/Haute-Marne URL Drifts, Rock mechanic and Rock engineering, Volume 47, Issue 1, pp 21-41

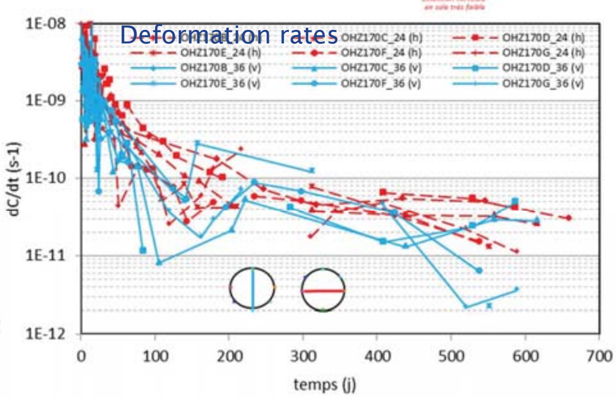



# Convergence for drift // σH




## Drift GCS (// to to $\sigma_H$)

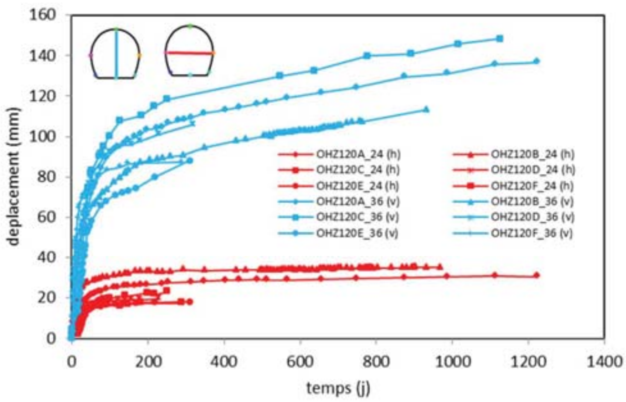


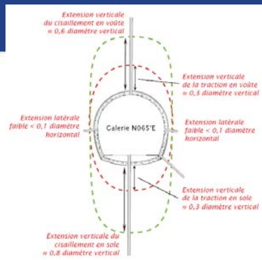



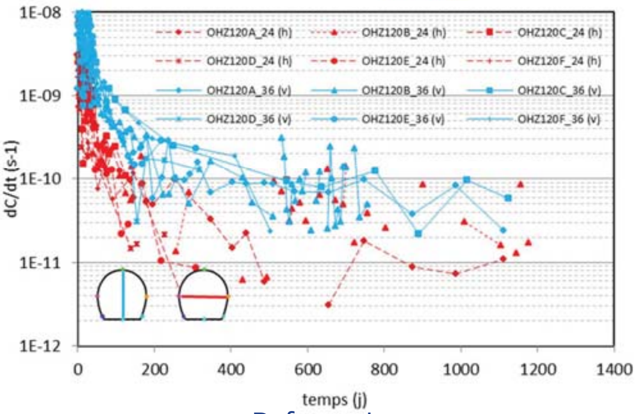

- Horizontal convergence is higher the vertical one (ratio of 2,1)
- Velocity decrease as a function of time
- No significant difference between excavated with pneumatic hammer and road header

## Convergence for drift // σh

### Drift GED // to to $\sigma_h$



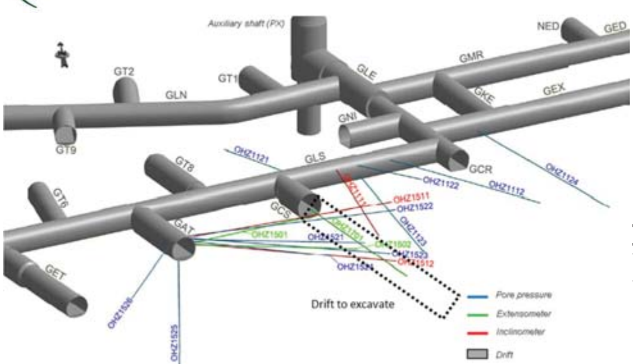

Deformation rates

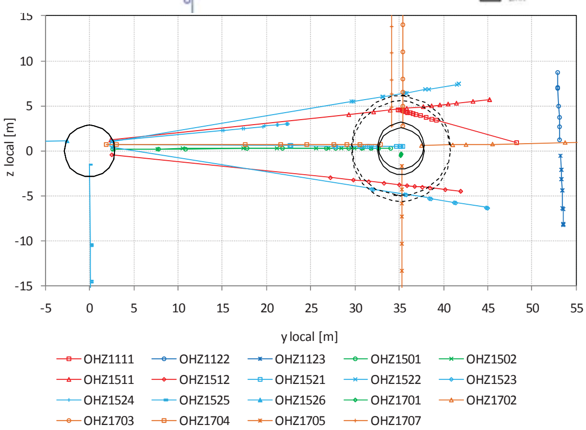
- Horizontal convergence is higher the vertical one (ratio of Cv/Ch = 4 to 5 )
- Velocity decrease as a function of time
- After 1 year , rates $<10^{-10}$ $s^{-1}$

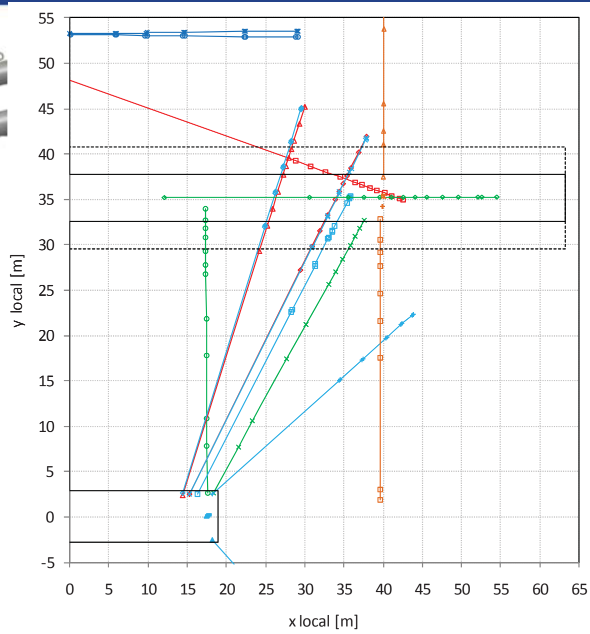
- ❑ Convergence depends of the drift orientation
- ❑ Highest convergence is observed where the extend of induced fractures is larger

## Location of the boreholes network



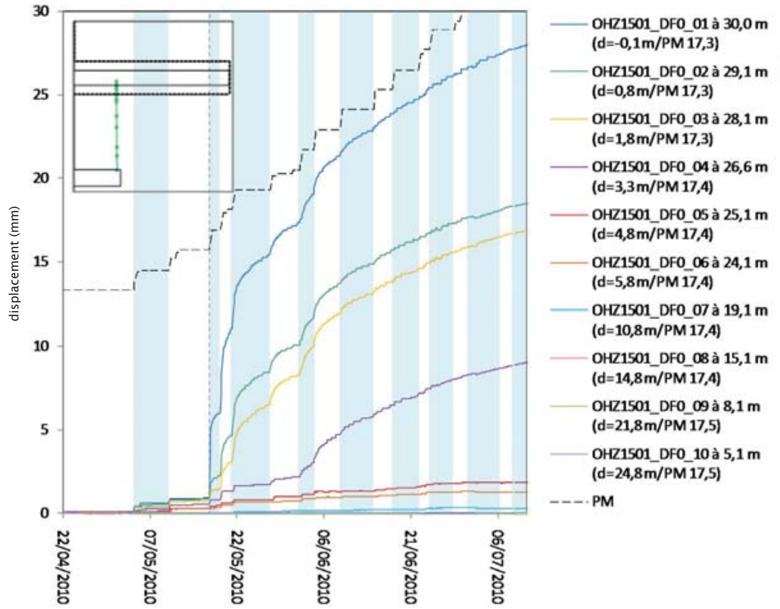

19 boreholes (mine by test et SMR)

- 8 extensometers
- 3 inclinometers
- 8 multipacker systems

# Horizontal radial displacement

- Extensometer drilled horizontal from the GAT to the GCS and the last anchor (01) is nearly at the sidewall of the GCS

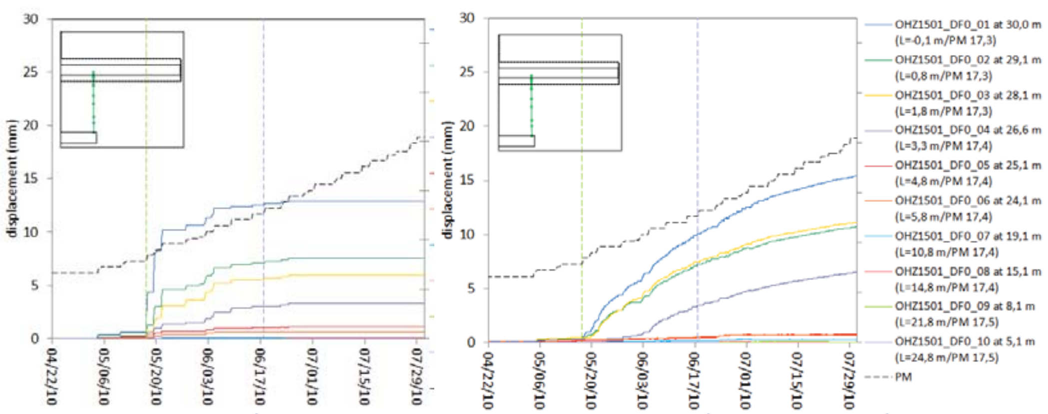



- Steps of excavation are visible:
  - ☐ 2 spans ahead the front, around 2.4 m
  - ☐ 7 spans beyond the front face, around 8.4 m. At this distance, the long-term behavior is predominant on the instantaneous strain



# Horizontal radial displacement

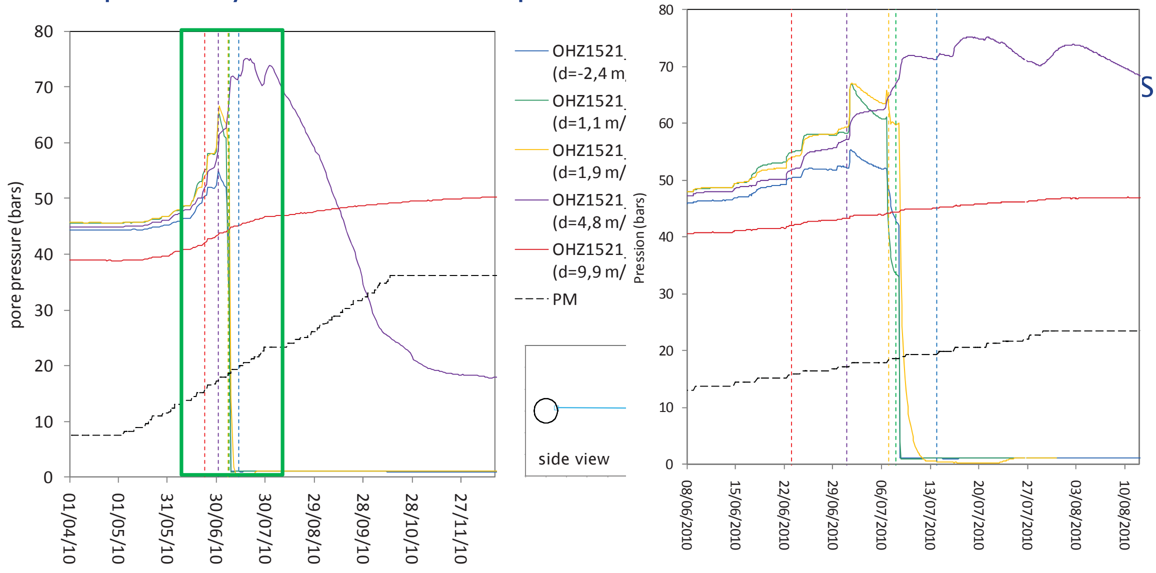
- Radial deformation measured in drift GCS has been reanalyzed in order to separate instantaneous and differed response to digging.




- Elastoplastic deformation represents 40%–45% of the total deformation at 90 days, and around 30% at 900 days.
- Farther 5.8 m deep in the rock, differed deformation is very small. The contribution of the far field is about 5% of the total elastoplastic deformation, 4% of the differed deformation at 90 days and less than 1% at 900 days.
- the very small contribution of the far field to the total deformation at the wall exhibits that the differed deformation comes from the near field

# Pore pressure response (horizontal)

- Multipacker system located oblique horizontal from the GAT to the GCS

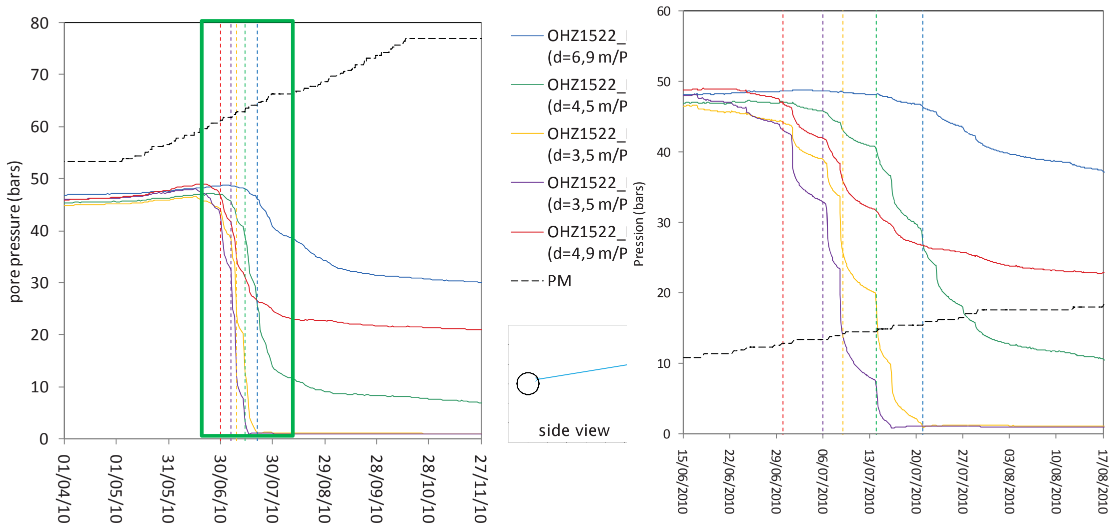



- The distance of influence of the excavation is estimated at 20 m
- Overpressure of several MPa (3 MPa in chambers 4 at 4.8 m from the GCS wall)
- Drop of pressure at the front crossing

# Pore pressure response (vertical)

- Multipacker system located oblique and rising from the GAT to the GCS




- Lower overpressures in the vertical direction (1order of magnitude difference with the horizontal plane)
- Drop of pressure is observed near the front face and stabilization as a function of the pore pressure gradient
- Despite the initial stress state is nearly isotropic around the GCS drift, the pore pressure response is anisotropic

DRD/MFS/14-0038 © Andra AGENCE NATIONALE POUR LA GESTION DES DÉCHETS RADIOACTIFS

# HL-LL waste disposal cells

## Micro tunnel of 70 cm in diameter



## Step by step approach with demonstration and scientific objectives

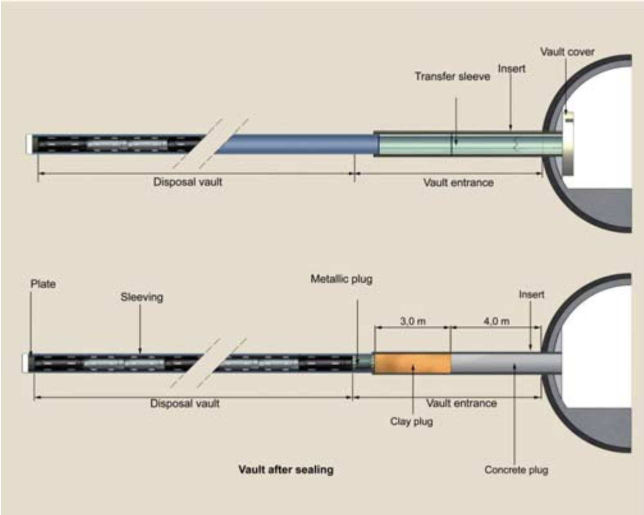
- test the making up of the cell (head & usable part)
- Study the behaviour of the cell under isothermal condition
- test the making up of different equipments into the cell (base plate, shield steel plug and closing plate),
- verify the suitable working of the head insert to absorb the thermal dilation of the sleeve,
- provide data on the casing behaviour under thermal loading,
- verify the design of the cell head to limit thermal gradients on the drift wall,
- study the THM behaviour of the interface between rock and casing and of the surrounding rock.

## CAC and TEC experiment :smaller scale experiment on steel casing in boreholes

# Andra concept for HL-LL waste disposal cells

Horizontal micro tunnels, about 700 mm in diameter and 100m long, cased with steel sleeves

- Usable part used for containers disposal,
- Head part (“insert”) 10 m long used for cell sealing
- End steel plug (base plate), shield steel plug and closing plate




Demonstration program in the URL to test the feasibility of construction and the behaviour of such disposal cells

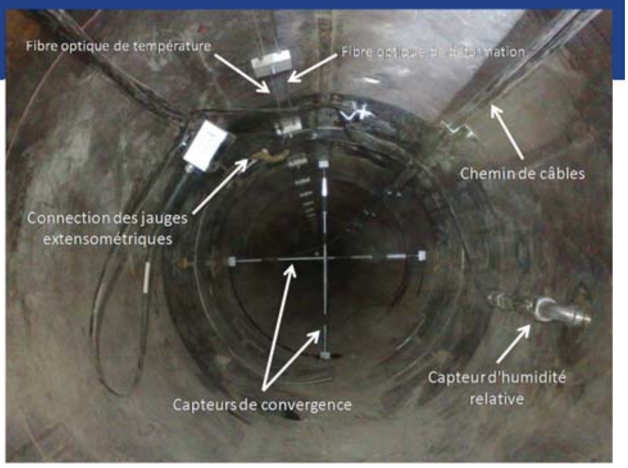
- Laser guided auger drilling machine
- Casing pushed in place during drilling by 2 m long elements welded or socketed to each others
- Retraction of the machine after excavation

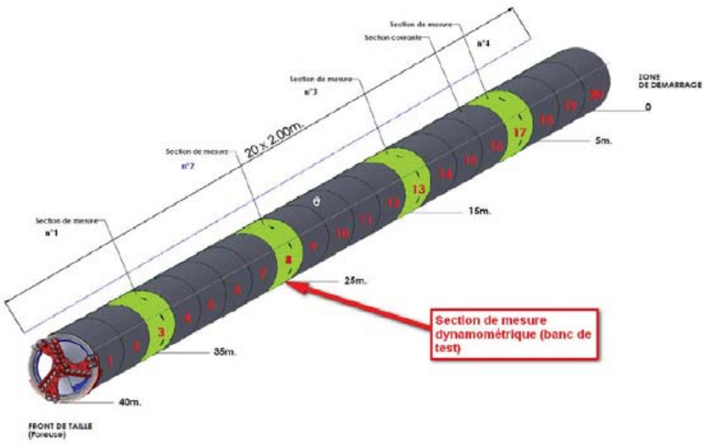


# ALC experiment

- Phase 1 (2009): cell of 20 m length
- Phase 1 bis (2010): cell of 40 m length
- Phase 2 (2011): cell of 40 m length with sensors on the sleeve

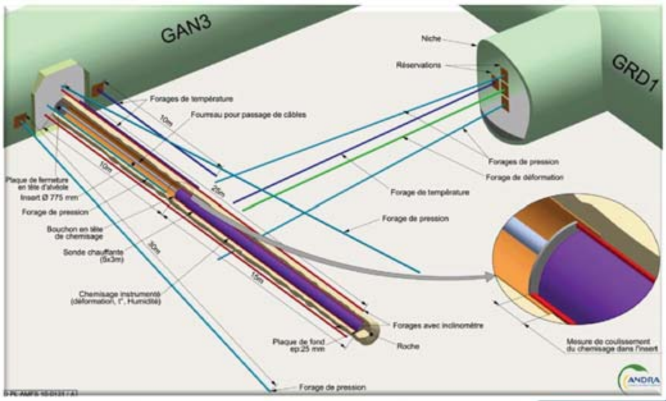
  Insert of 7 m to test emplacement of the head
- Phase3.1 (2012): cell of 100 m length




## HLW disposal cells

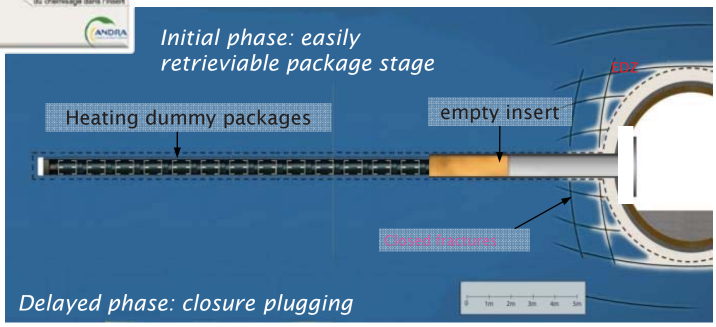
)) Phase 3.2 (2012/2013):




- Full-sized reproduction of a HLW cell (WP3 of EC project LUCOEX) => THM behavior

Main objectives :

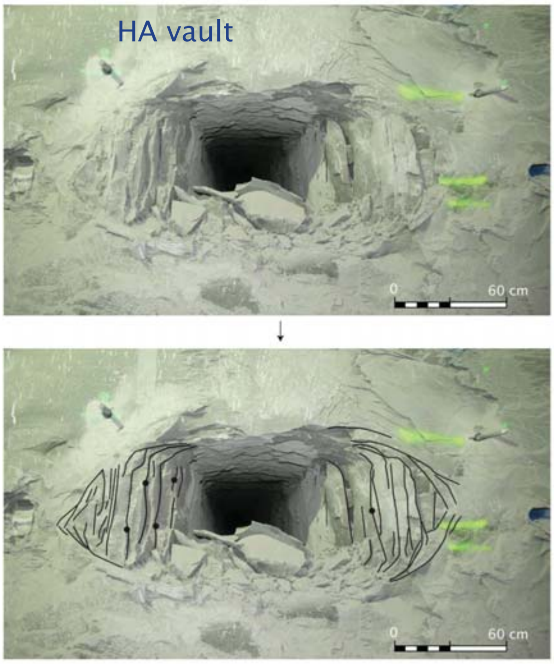
- Test the making up
- Verify the design of the cell head to absorb the thermal dilation of the casing and to limit thermal gradients on the drift wall.

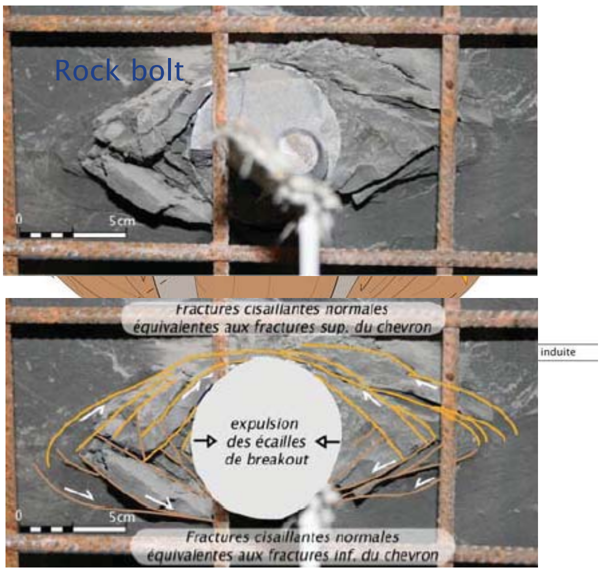





## Excavation induced fractures around micro tunnel

### Similar shape of fracture pattern at different size (//$\sigma_H$)

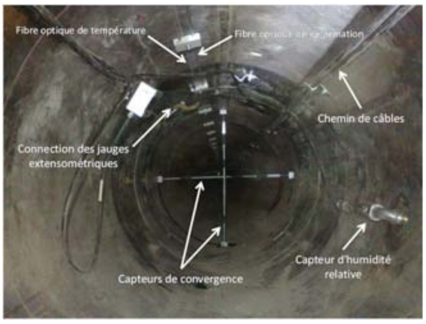


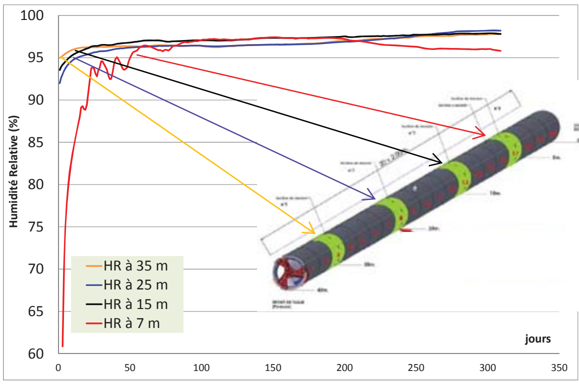
# HA cell // to $\sigma_H$ (CAC1601)

## Objective (Phase 2)

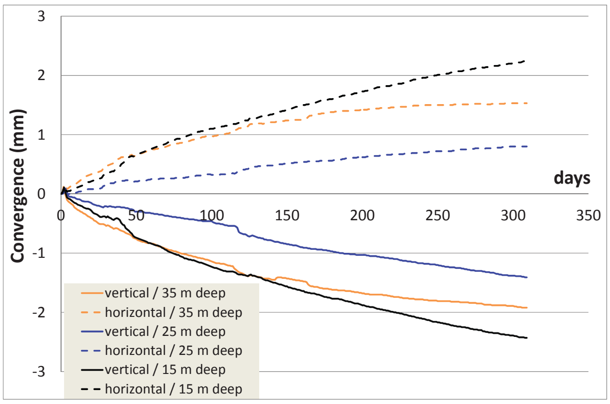
- Behavior of the void : water arrival versus time dependant behaviour and closure of the void
- Loading of the steel casing
- Test of optical fibers method
- HM behaviour of the micro tunnel




*Relative humidity in the void*

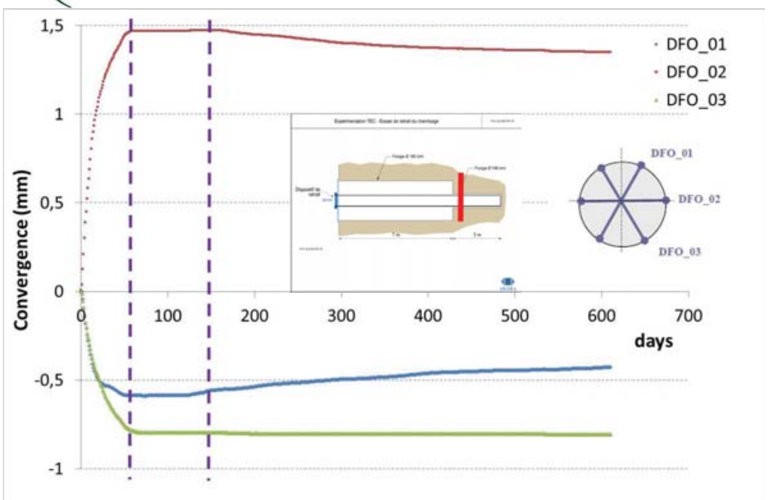



*Convergence of casing*

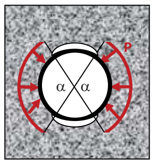




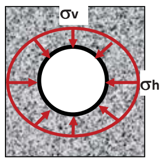

# Expriment in borehole with steel casing (1/2)




**t < 60 days**
Loading localized in the horizontal direction

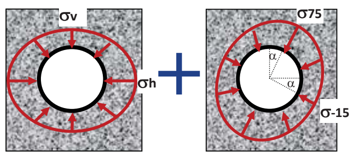


**60 days < t < 160 days**
anisotropic loading
σh > σv

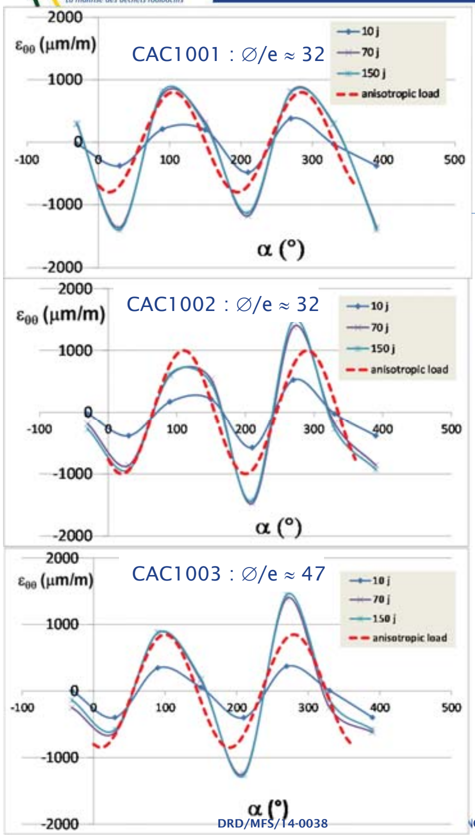



- steel N80 (σy = 550 MPa)
- Borehole : Ø = 146 mm
- casing : $Ø_{out}$ = 143 mm, thickness = 4,5 mm

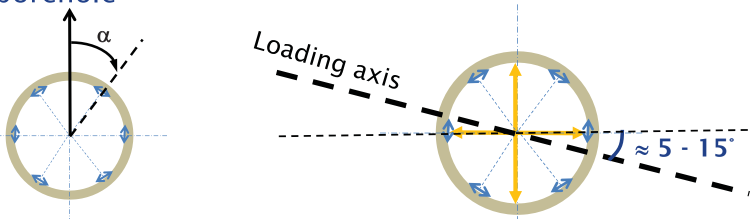
**t > 160 days**
Decrease of anisotropic loading

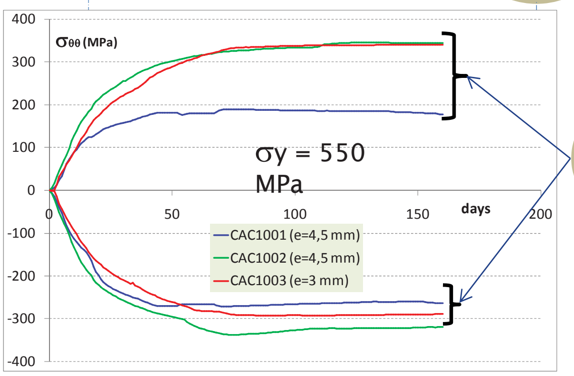


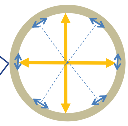
## Expriment in borehole with steel casing (2/2)




Orthoradial deformation at 8 m deep in borehole



Remain in elastic domain, no problem of stability of the casing
But it will contribute to corrosion under stress which is a difficulty for the design of the casing



## HL-LL waste disposal cells

### The experiment performed at the URL serve to optimize the concept

- In 2009 the reference length in the concept was 40 m and all cell are parallel to $\sigma_H$
  - It was demonstrate that a longer depth could be reached= **now reference length = 80 m**
  - It was confirmed that excavation of cell along $\sigma_H$ is better than $\sigma_h$
- Elastic deformation in traction have been observed (due to the difference of convergence rate in horizontal and vertical direction) and will contribute to corrosion under stress
  - Backfill the void in between the casing and rock (concrete with bentonite)
  - A test has been performed in November 2013

## Summary (1/2)

### Experiments in the MHM URL serve to

- Demonstrate feasibility of a deep geological repository and upscale data obtained on sample (diffusion/retention, permeability,...)
- Demonstrate the working of the different concept
- **Optimize** the different concepts
- Data based to develop/validate model

### But you also need

- Fundamental research to assess the physical process in order to develop model to extrapolate data to the lifetime of a repository
- Safety calculation to always check if optimization do not decrease the safety
- At the beginning of the repository construction, final design will be tested in the repository to check in the repository conditions if predicted behavior is observed.



## Summary (2/2)

### Behavior of the drift

- Two major phenomena can be distinguished :
  - Elastoplastic and damage mechanisms seems to be predominant at short terms
  - Drift 's deformations develop as a function of time
- During excavation work, fractures network are induced (mainly shear fracture 75%, extensional fracture 25%)
- The extend of the fracture network depend on the drift orientation versus the in situ stress field and could not be explain by the anisotropy of the stress field
  - No impact of the method of excavation (BRH versus MAP)
  - Shear fractures (deep in the rock) exhibit low transmissivity
  - With water uptake, fractures transmissivity decreases drastically
- Anisotropic convergence of the drift are observed :
  - anisotropy of convergence develops in two opposite directions in drifts parallel and perpendicular to $\sigma H$
  - major convergence is measured where the fracture zone is located
- Differed deformations
  - After one year, deformation rates are in the same velocity range than the one measured on creep test or lower.
  - Most of the differed deformation appears in the fractured zone

# Thank you for your attention

# Danke Ihnen für Ihre Aufmerksamkeit

# *Merci pour votre attention*

G. Armand, F. Leveau, C. Nussbaum, R. de La Vaissiere, A. Noiret, D. Jaeggi, P. Landrein, C. Righini, 2014, Geometry and Properties of the Excavation-Induced Fractures at the Meuse/Haute-Marne URL Drifts, Rock mechanic and Rock engineering, Volume 47, Issue 1, pp 21-41

G. Armand, A. Noiret, J. Zghondi, D.M. Seyedi,2013, Short- and long-term behaviors of drifts in the Callovo-Oxfordian claystone at the Meuse/Haute-Marne Underground Research Laboratory, Journal of Rock Mechanics and Geotechnical Engineering 5,pp 221–230