30 years of monitoring experience in HADES

18th Exchange Meeting
"Instrumentation and monitoring in radioactive waste repository research"

SCK•CEN Club-House – Mol
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ESV EURIDICE GIE

Outline

Reasons / needs for monitoring (objectives)

Monitoring implementation cases

- construction related (shafts & galleries)
- field characterisation / investigation of phenomena
- THM(C) model validations
  - upscaling from lab results

- description and results
- experiences / lessons learnt
  - “critical success factors”

Challenges and perspectives for repository monitoring

Reasons / needs for monitoring

Construction related objectives

- feasibility / safety of deep excavations in Boom Clay (1980-1987)
- assessment of advanced construction technique (1995-2007)
  - applicable (validation of the design)?
  - influence on host formation properties

In situ characterisation of the host clay formation

Model validation / confidence building

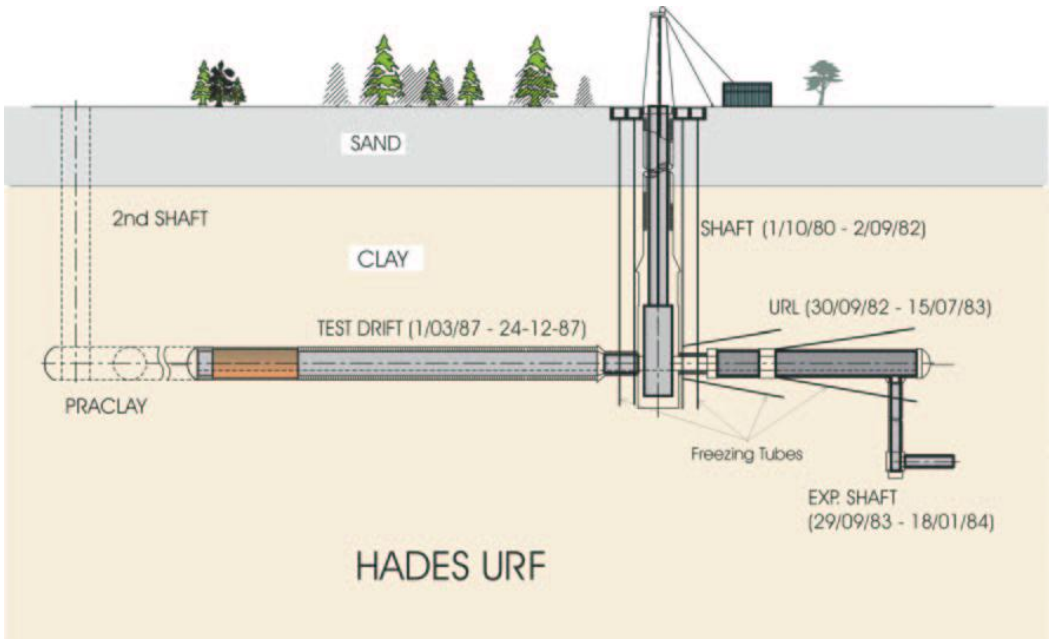
- geotechnical (THM) – natural barrier and EBS materials
- migration / solute transport
- geochemical, microbiological phenomena and understanding

→ *input data for PA*

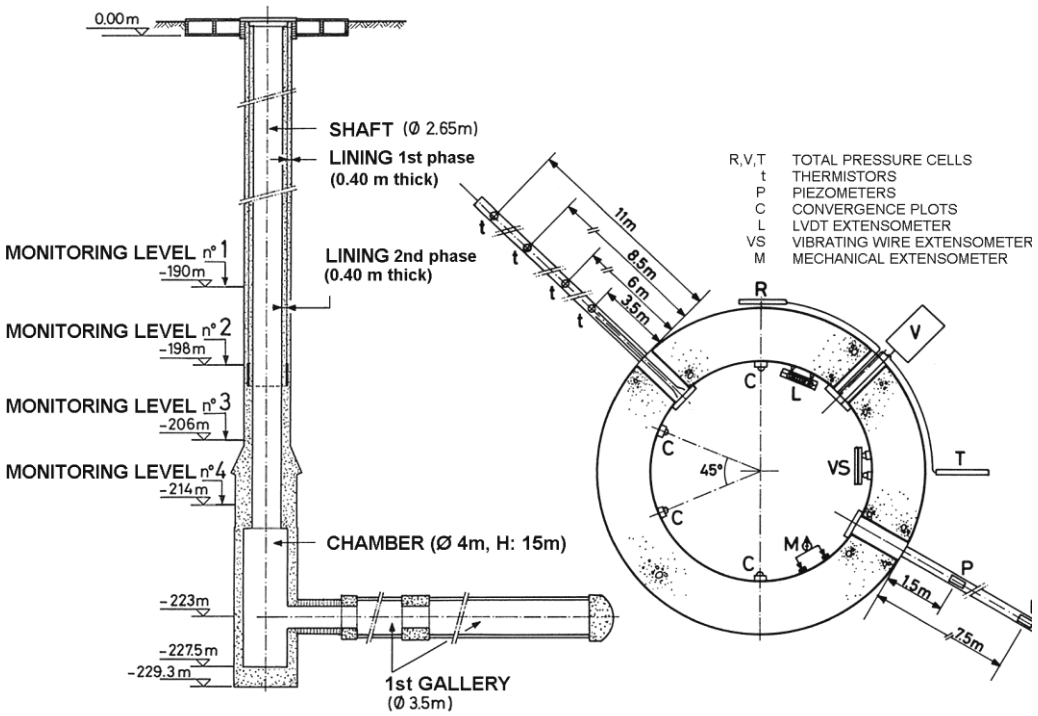
Monitoring in the pioneering phase

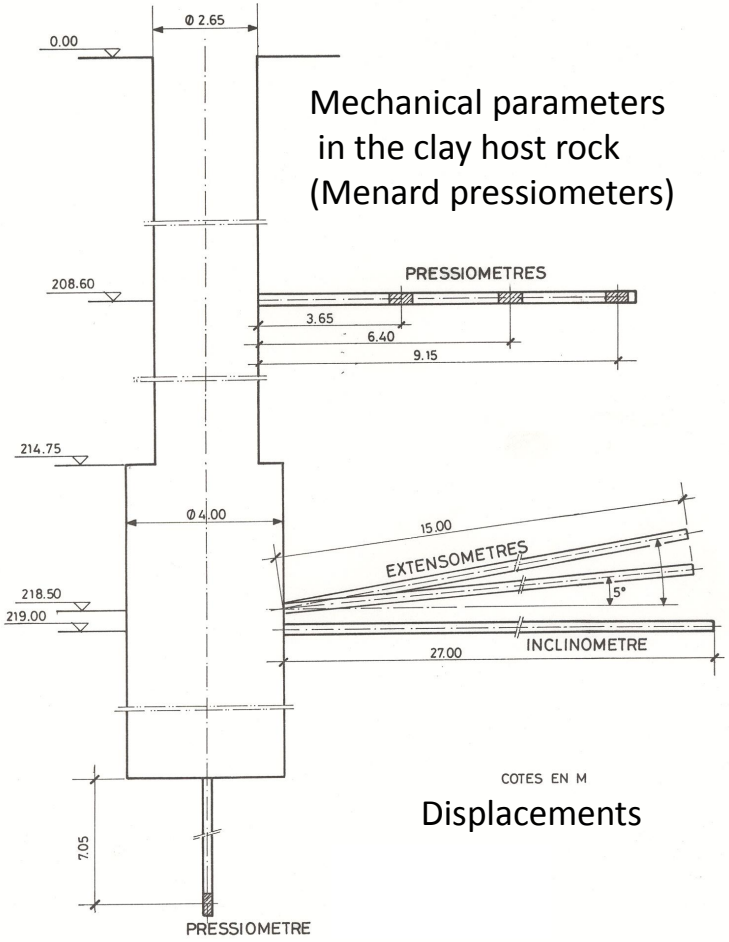
Case studies

- First shaft
- Mine-By test (Test Drift)
- Sliding ribs



Monitoring of the first shaft





Mechanical parameters in the clay host rock (Menard pressiometers)

Displacements

Rather extensive monitoring set-up

Main results of the shaft monitoring

High total pressures, due to freezing

- equilibrium around 2 MPa
- combined with manual excavation – quick and large convergence near bottom part

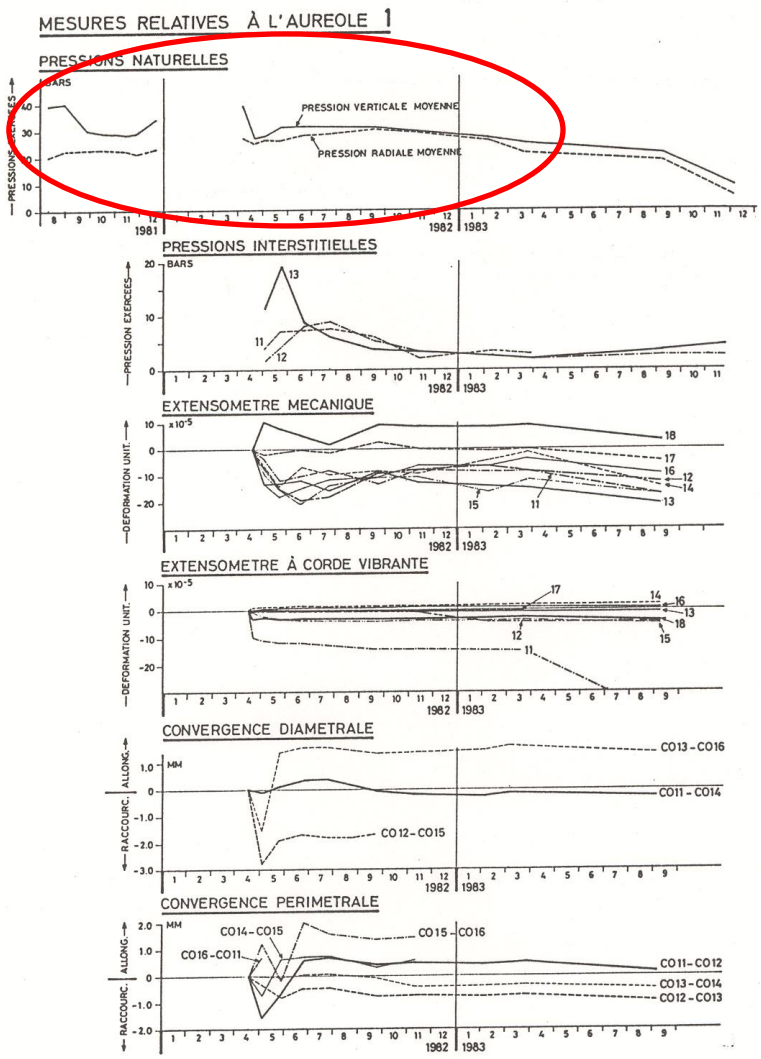
High porewater pressures

- higher in frozen environment
- higher in clayey (vs. silty)
- equilibrium between 5 and 10 bar

Temp > 0° only after 2 years

Deformation on shaft lining

- different upper and bottom part:
- upper part (dual layer) : compression and ovalisation
- bottom part (monolithic): expansion



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… and a first assessment of sensor performance

Total pressure cells:

- vulnerable due to hydraulic tubing
- displacement of clay host rock around shaft lining

Porewater pressure sensors and thermistors reliable

Pressiometer, inclinometer and extensometer

- deformation of access tubes

Convergence measurements inside lining: mixed results

- mainly due to working conditions (moving work platform,…)

Monitoring inside the first gallery (URL)

First attempt to measure total stress through “stress monitoring stations” (SMS) complicated by

- large boreholes
- backfill grouting

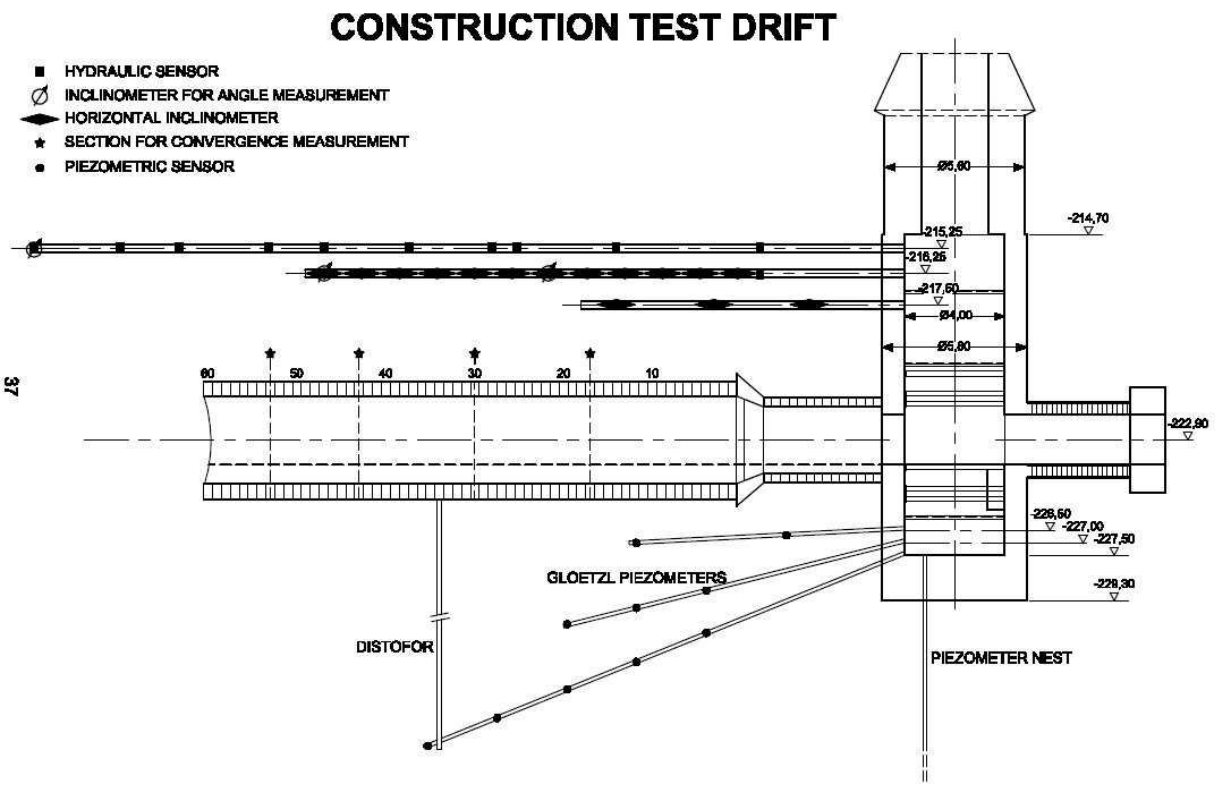
Large variety of instrumentation

- strain gauges to monitor the lining
- multifilter piezometers (CP1)
- corrosion set-up’s
- first EBS tests (BACCHUS)
- migration tests (clay core percolation tests)

Lessons

- importance of non-intended observations
  - unfrozen clay behaviour
  - thermal effects, e.g. water inflow in heated corrosion test tubes

Mine-by test of the Test Drift



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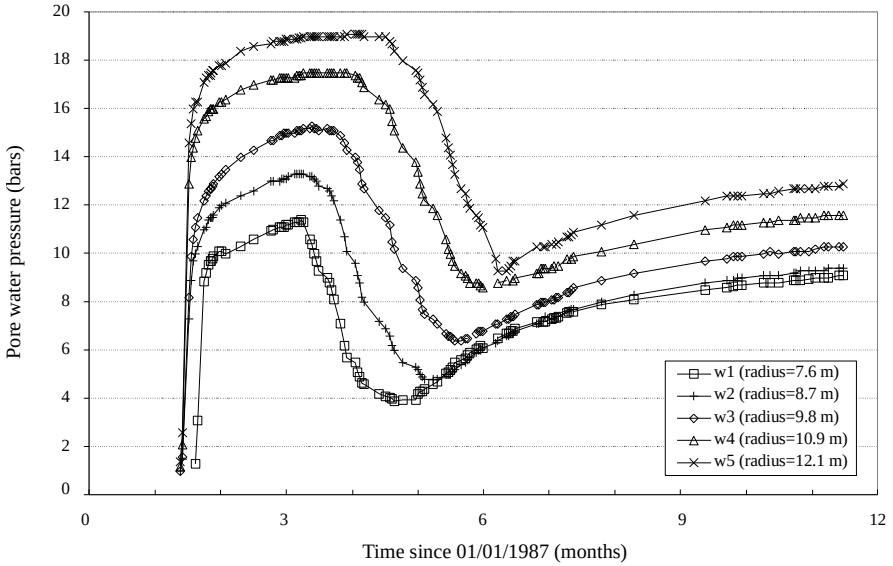
Mine-by test of the Test Drift

Piezometer data and displacement data proved very useful for back analysis

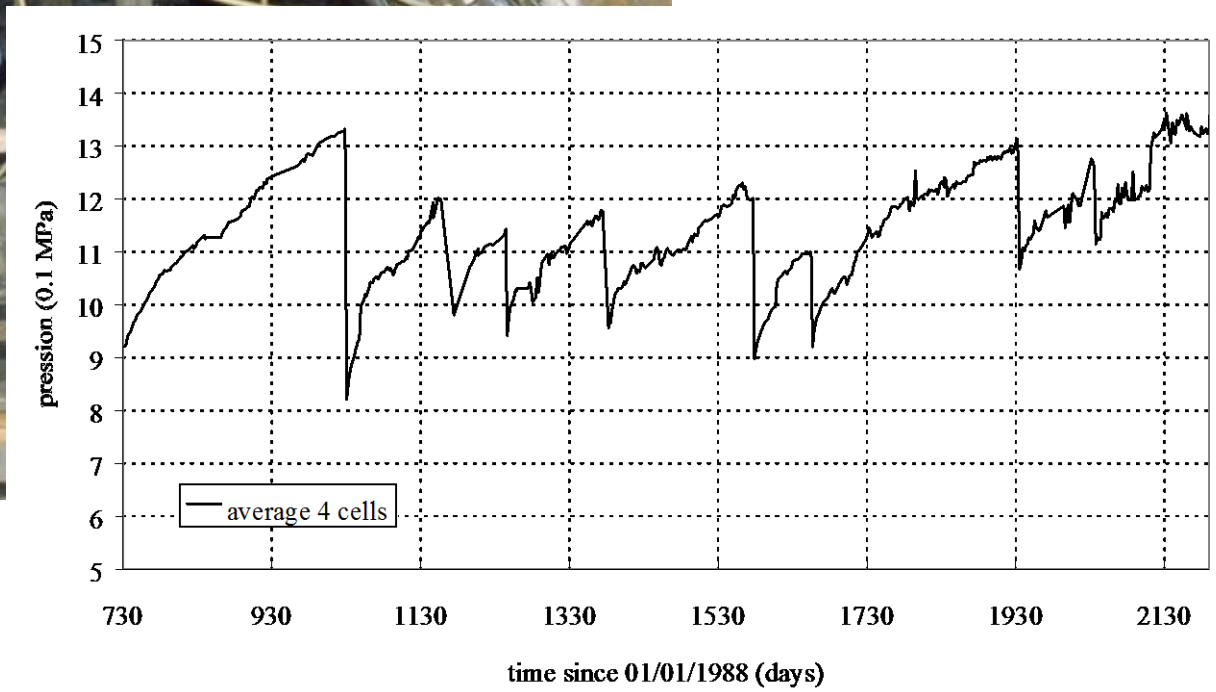
- comparison with 2nd phase excavations

Sensors in gallery lining total pressure, load cells up to 10 y lifetime

- mixed results



Monitoring of the sliding ribs



Monitoring of industrial excavation techniques

Verification of design

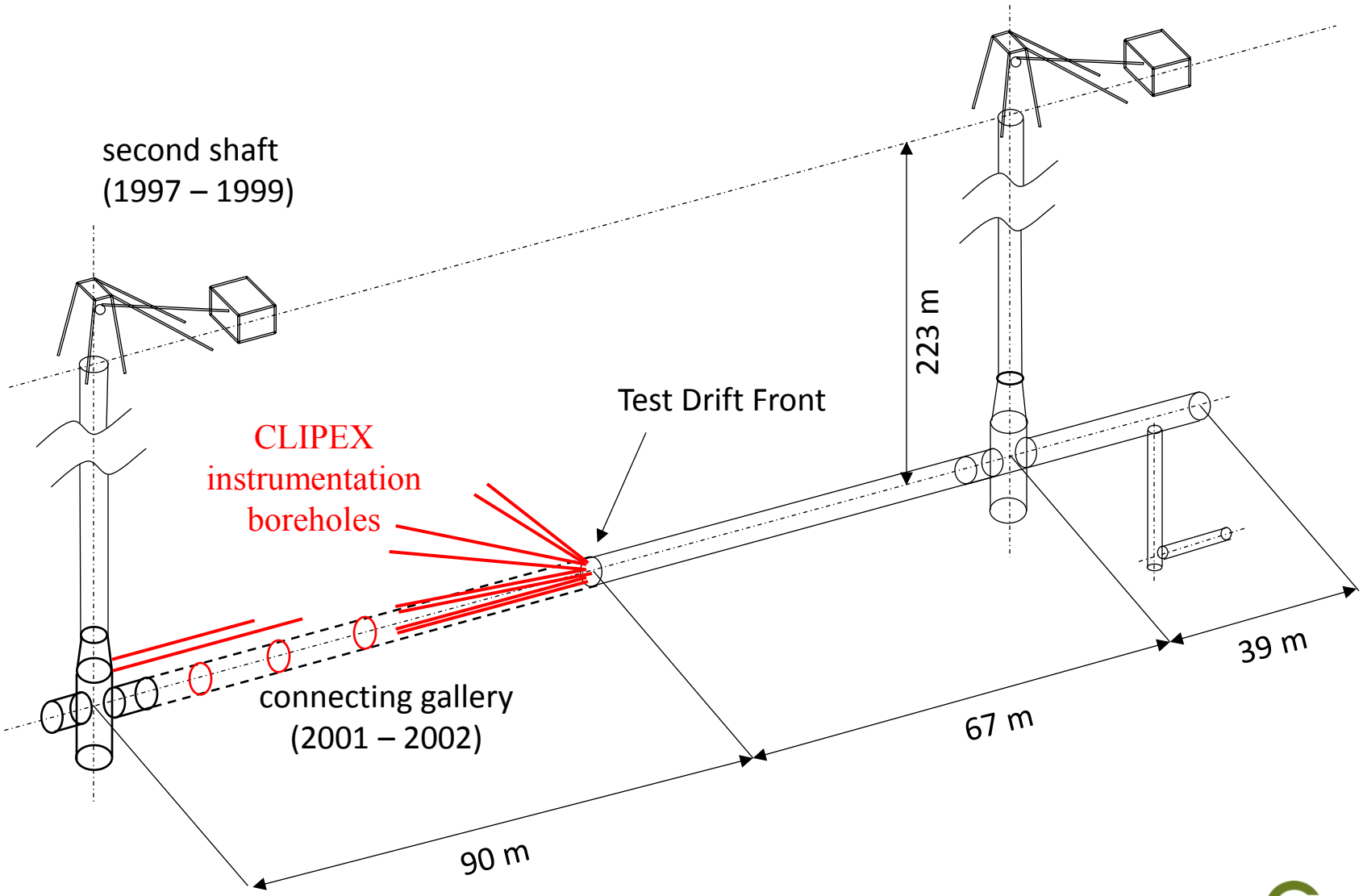
- short term excavation technique / tunneling machine
- comprehensive host rock monitoring programme (CLIPEX)
- longer term monitoring cases
  - porewater pressure evolutions
  - build-up of stress in gallery lining

Connecting Gallery Excavation

New construction method entailed some risks

- use of a shield → risk of blocking
- short starting distance
- use of wedge block system
  - world first at this depth
  - adaptations were necessary
- instantaneous convergence of Boom Clay
- geometry of the shield based on modelling

Three instrumented areas (CLIPEX)



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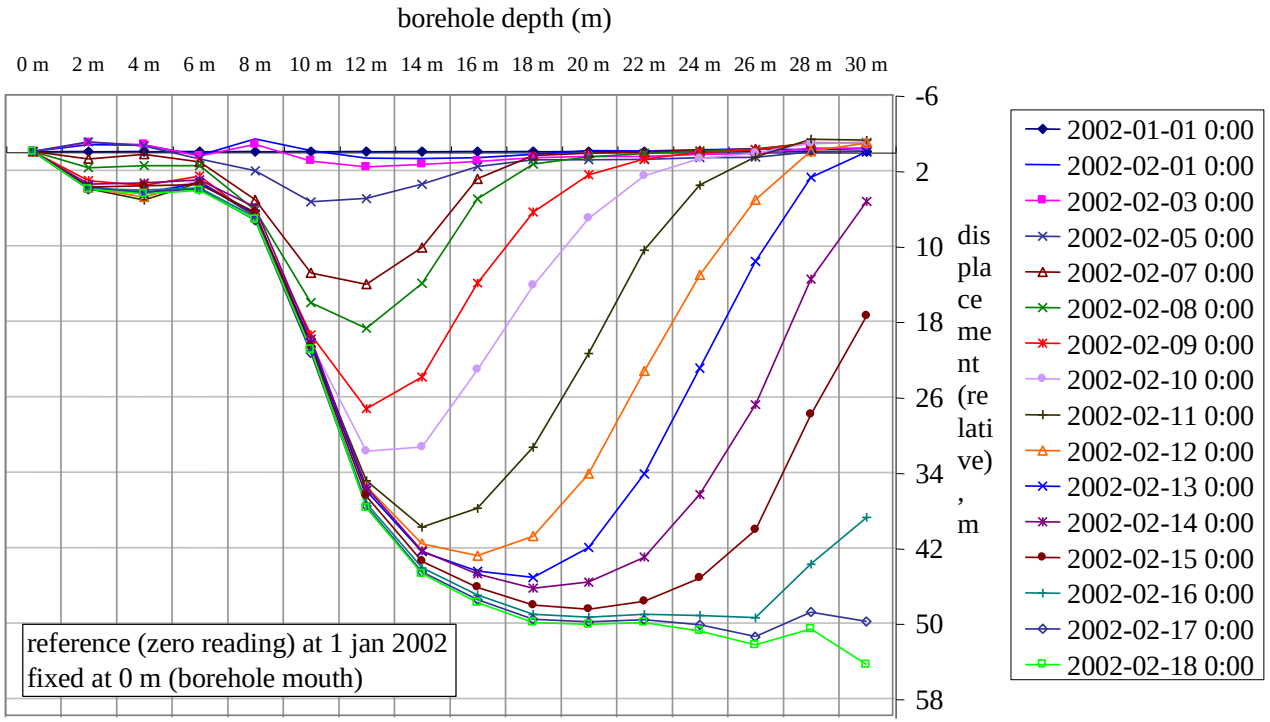
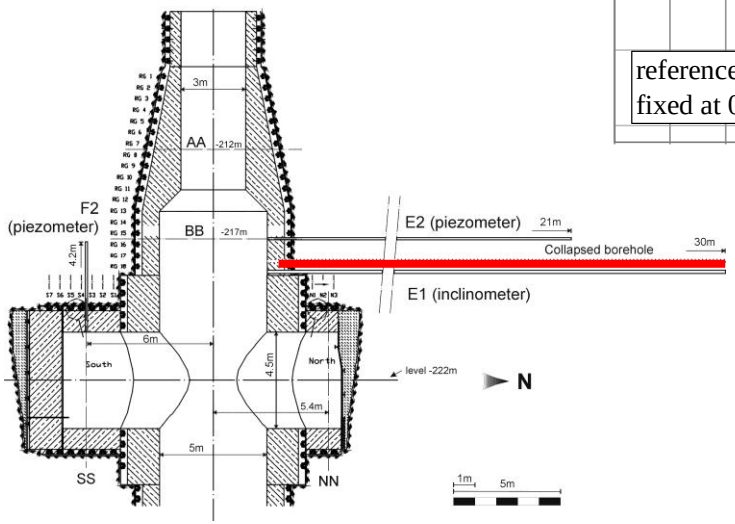
Inclinometer : host rock radial convergence





less than half the convergence compared to Test Drift

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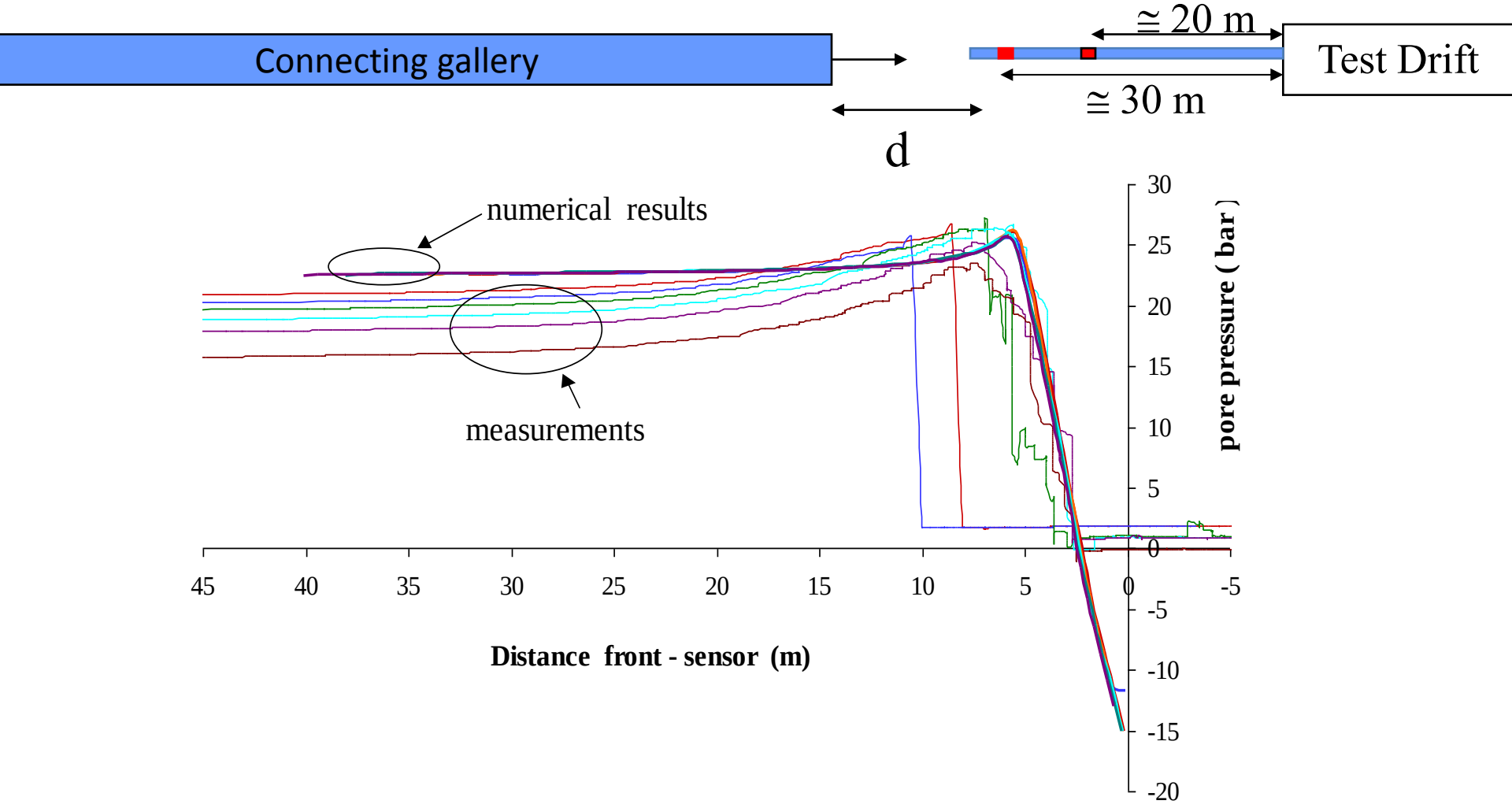
Observed and expected porewater pressures



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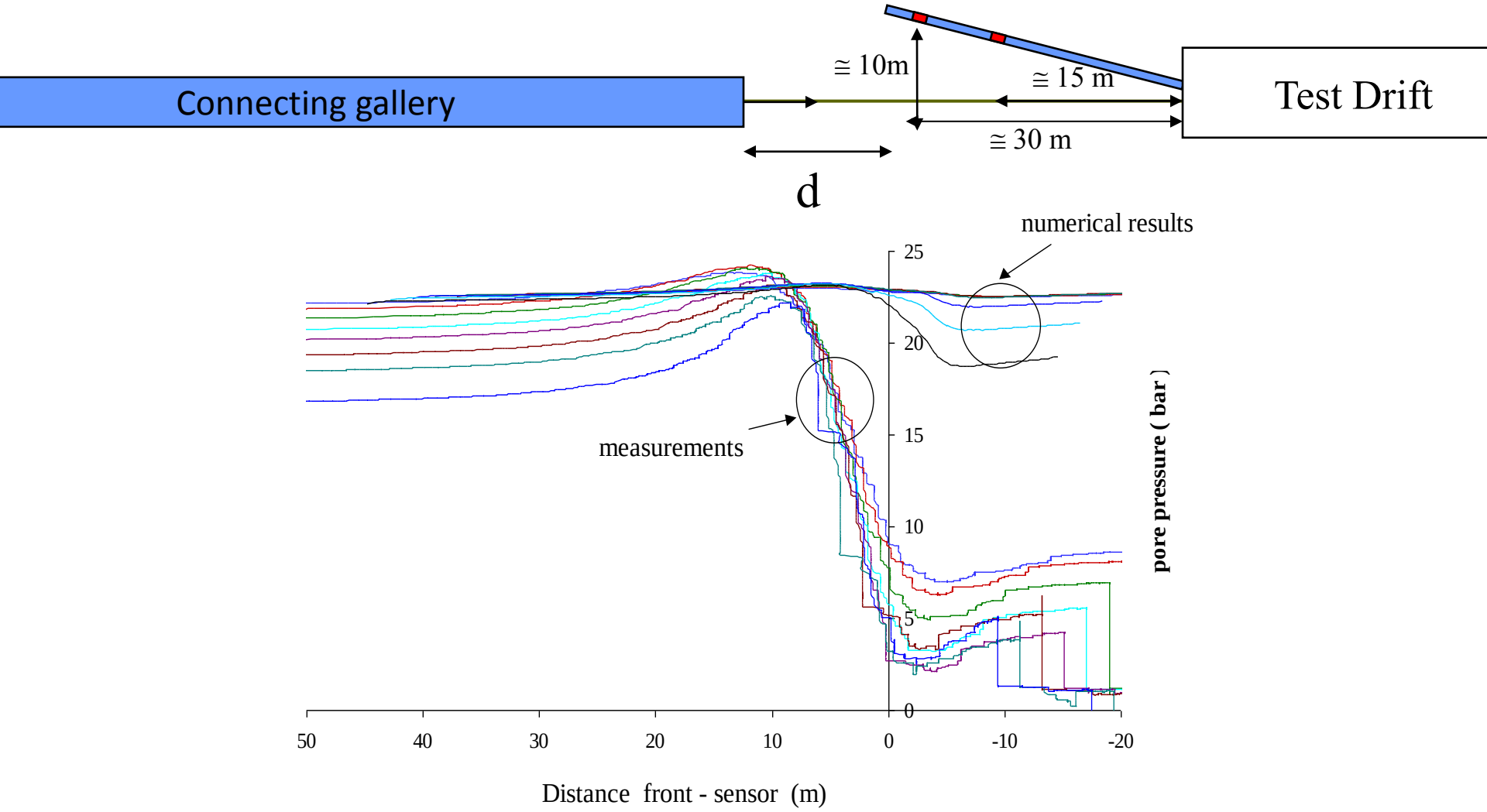
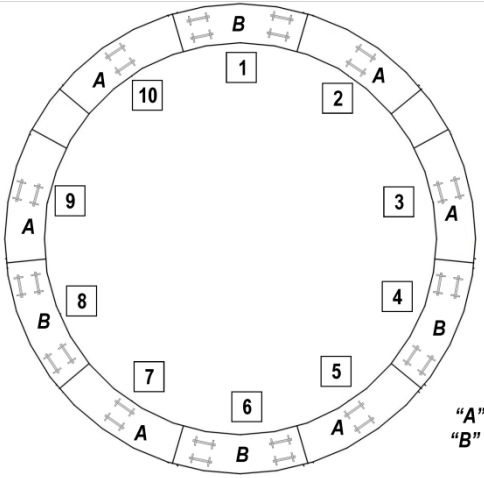
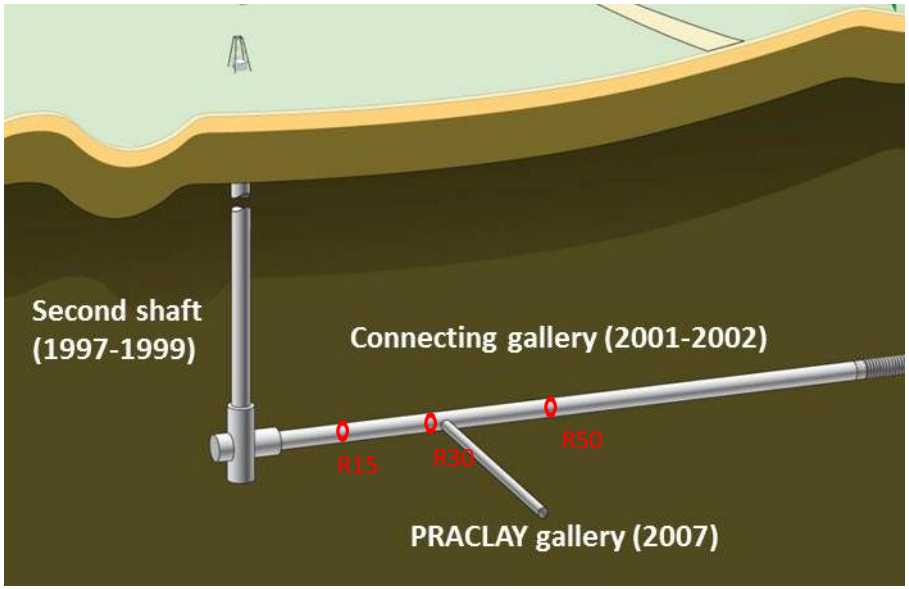
Observed and expected porewater pressures



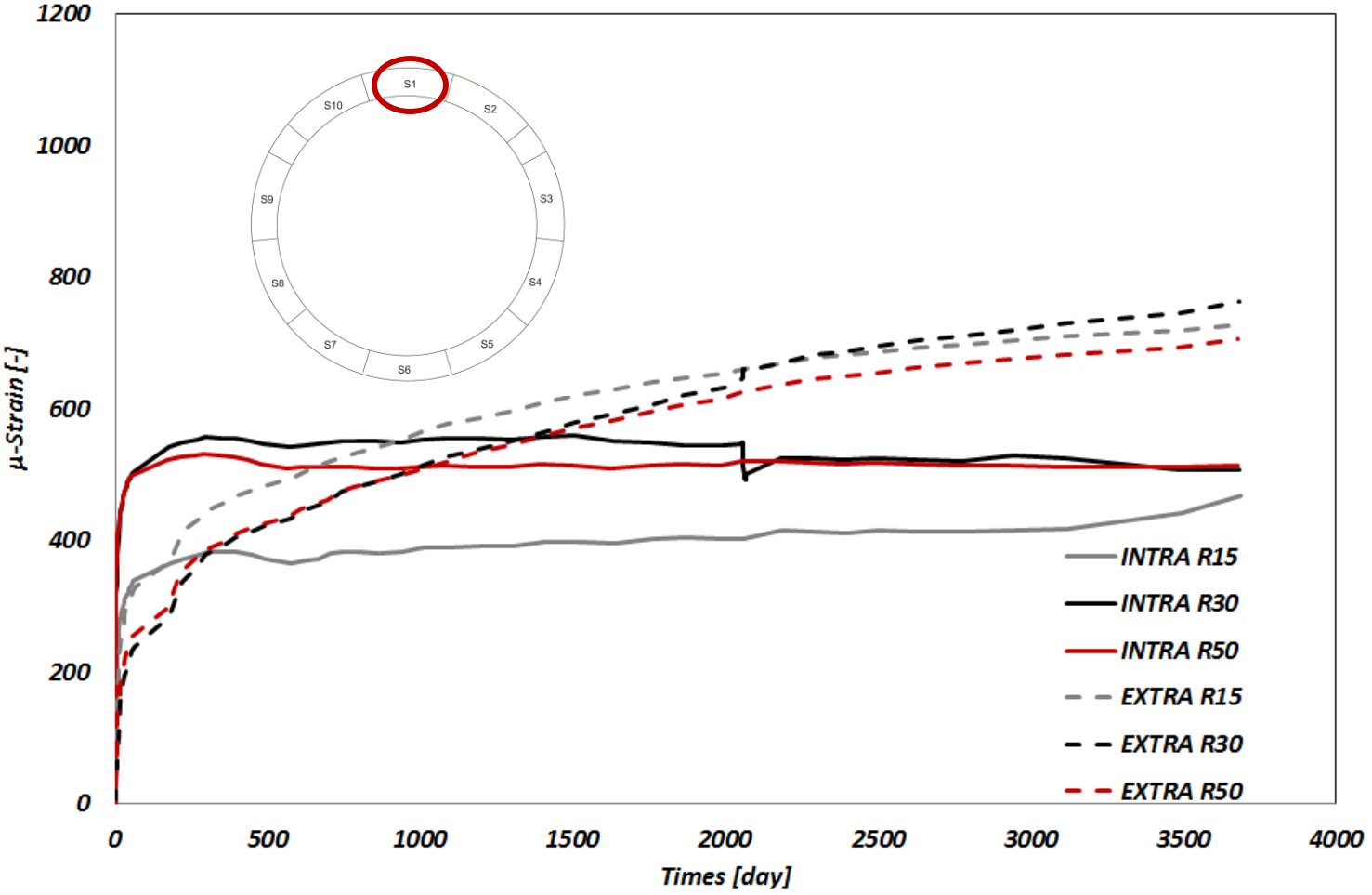
Monitoring of gallery lining



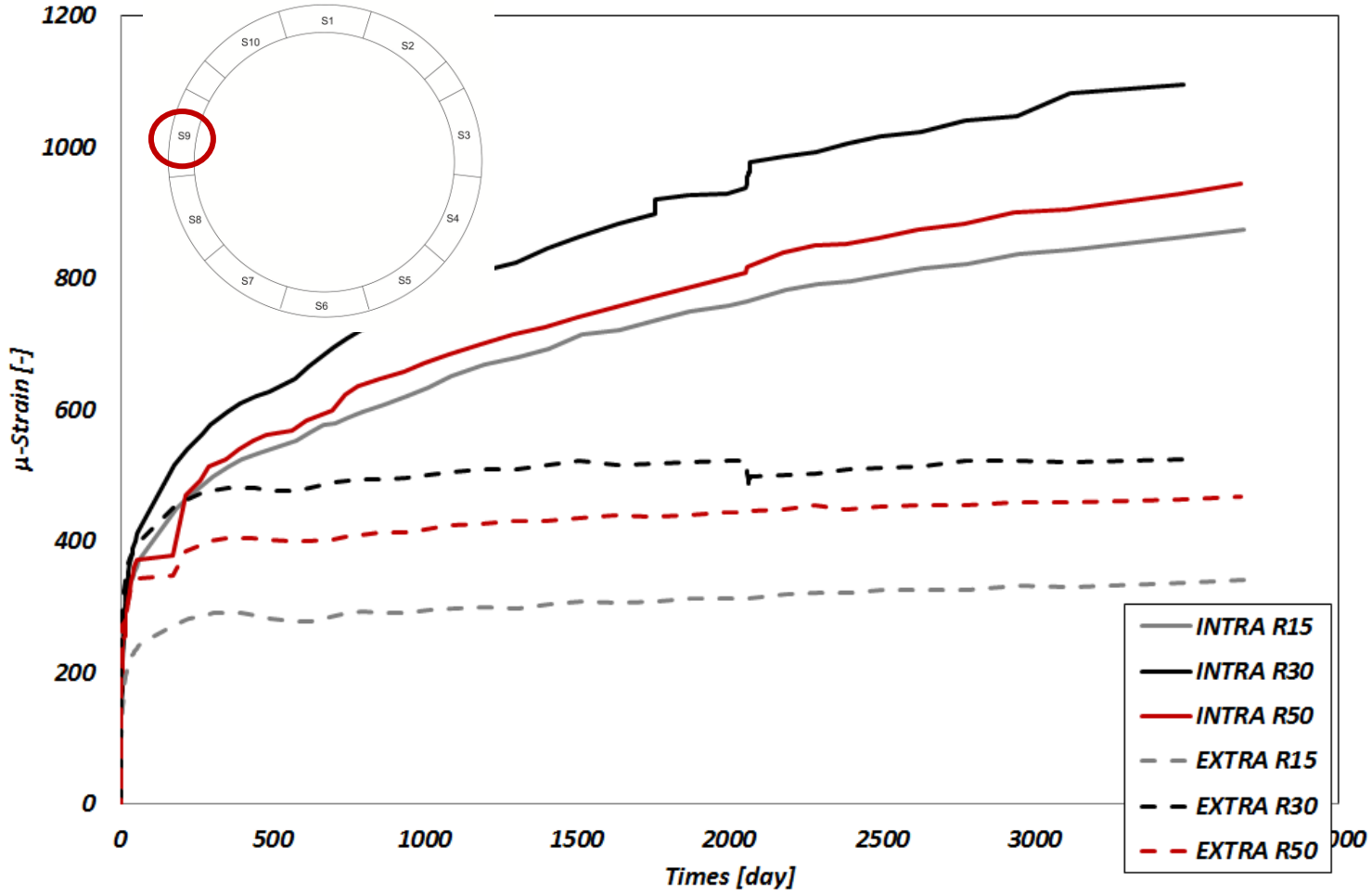
circumferential strain
- inside
- outside



Consistent strains measured along the three rings



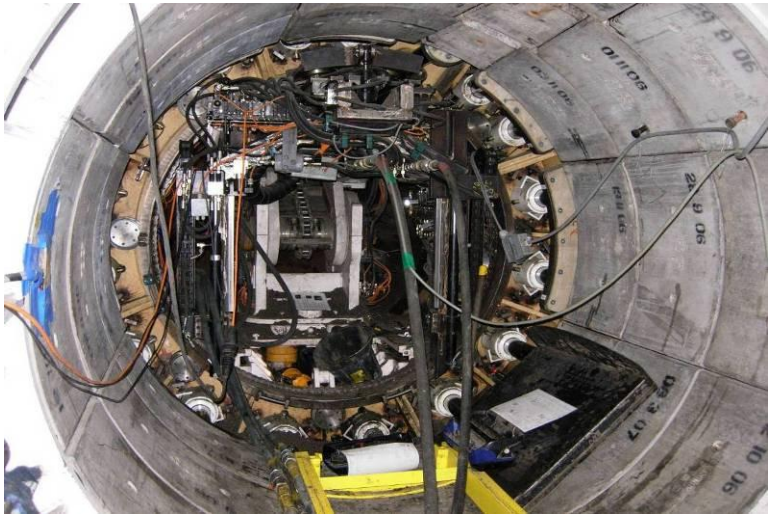
Bending (inner / outer strain) depends on position



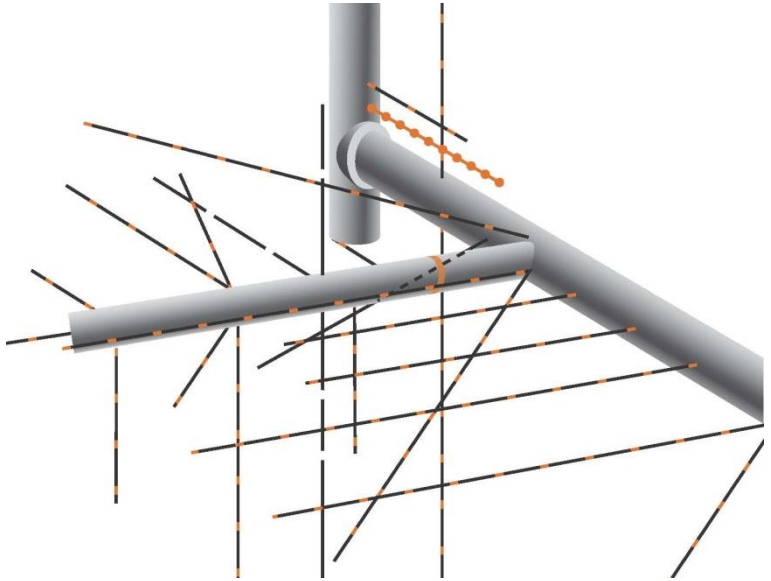
After 4 years in the host clay...

PRACLAY Gallery Excavation

excavation works (2007)



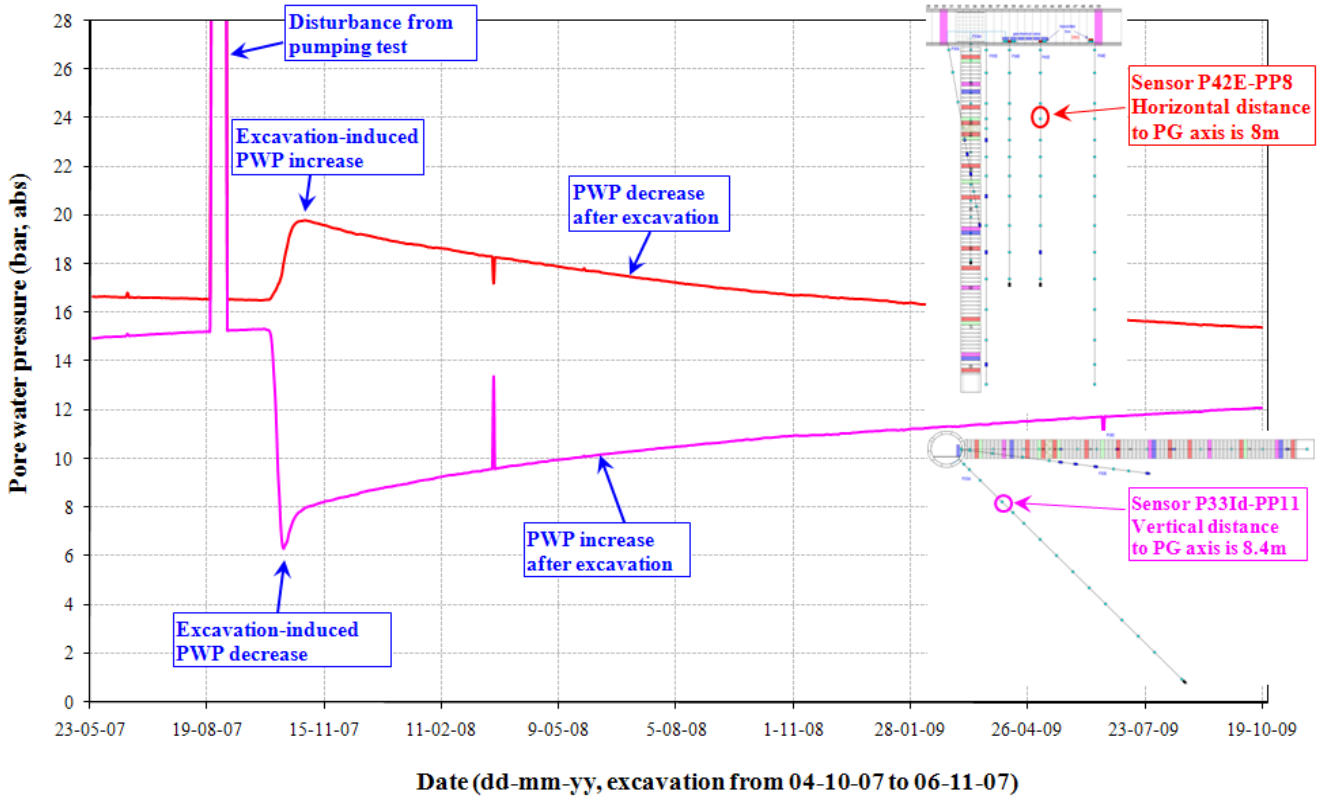
extensive monitoring network



Monitoring of PG excavation/construction

Confirmation of our understanding of CG phenomena

- highly coupled HM behaviour
- anisotropy, far extent of the hydraulically disturbed zone,…



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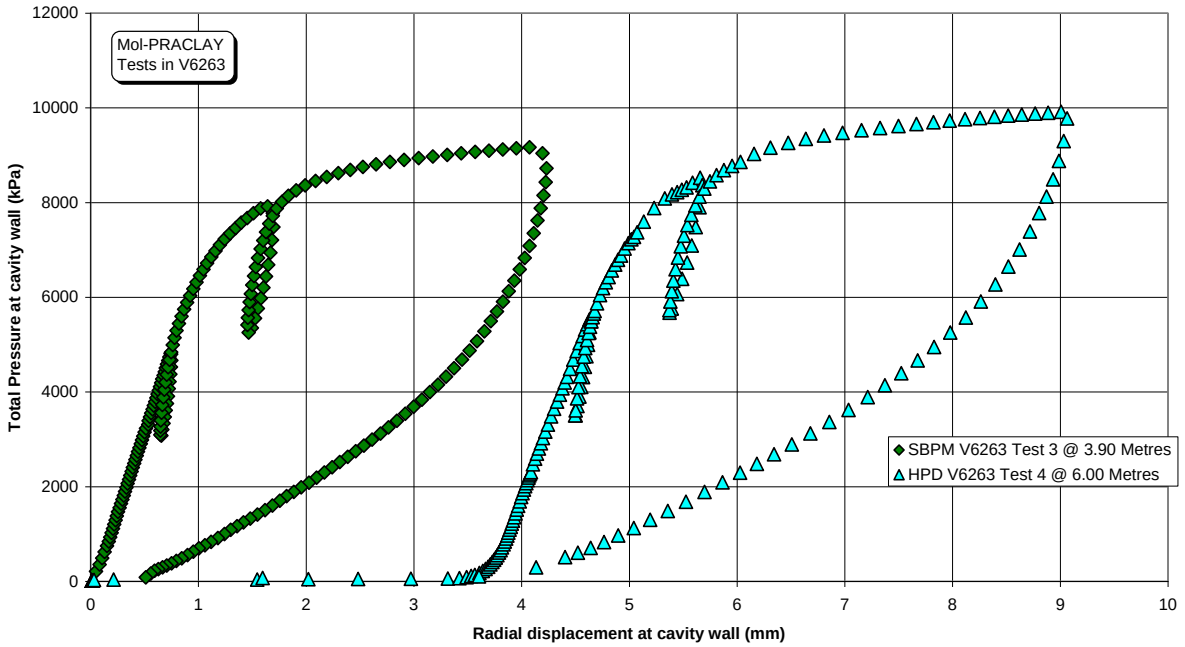
Field characterisation

Hydro-mechanical parameters

- (self-boring) pressuremeter / dilatometer / hydrofracturing to get better estimate of total pressure (in addition to other mechanical parameters)



Model validation

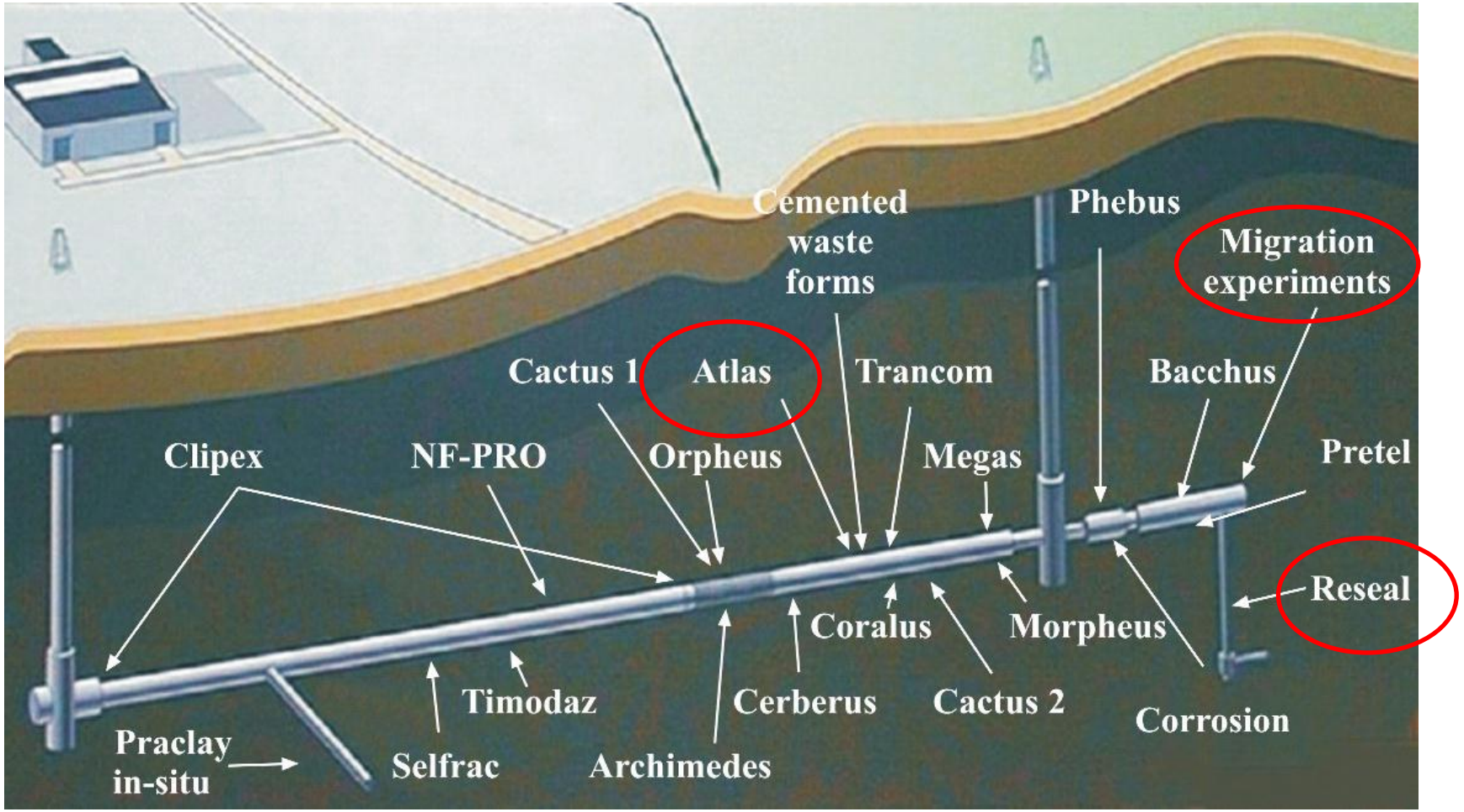
THM coupling phenomena

- related to excavations + long-term follow-up
  - e.g. reference piezometers in Connecting Gallery
- purpose built set-ups
  - ATLAS, RESEAL,...

Migration / solute transport

- upscaling of lab results in time and space

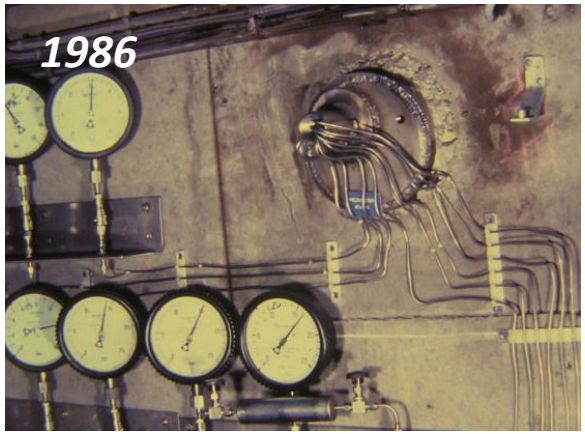
Experimental set-ups

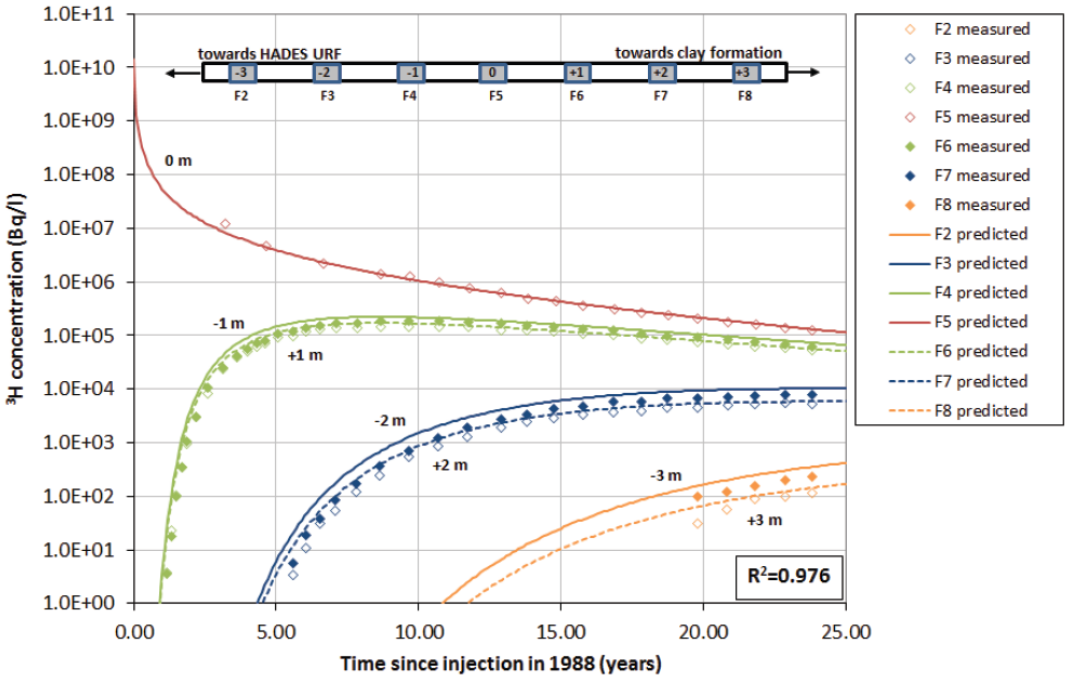


CP1 – long term monitoring

Concrete Plug 1 –long term model validation of solute transport

… also of the piezometer concept





E. Weetjens (2012)

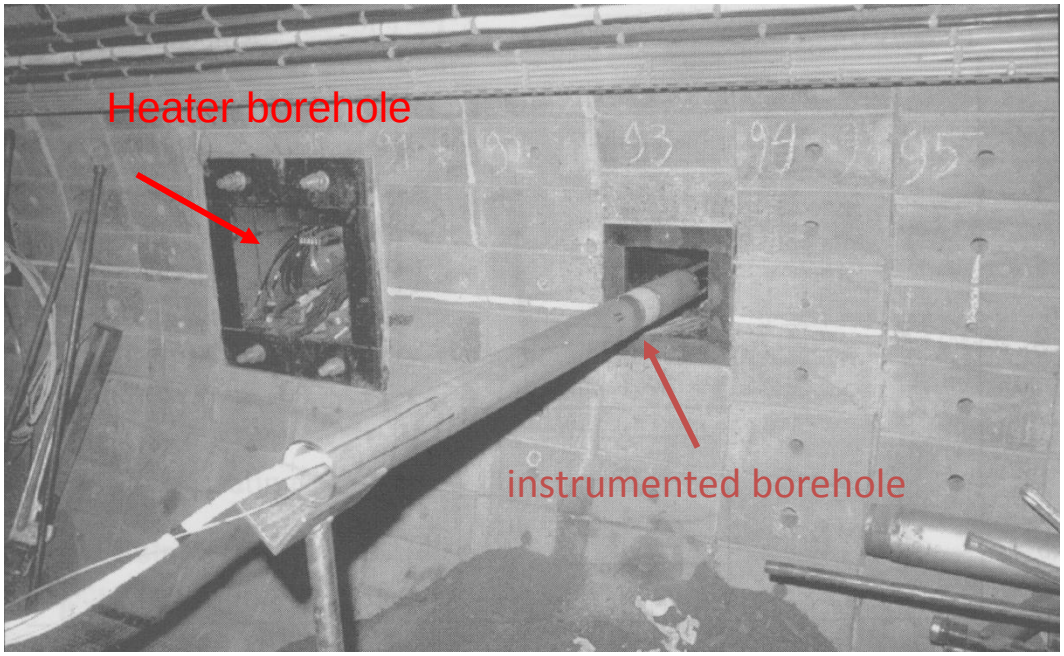
ATLAS – a “simple” T → HM test

Another 20 y old test set-up

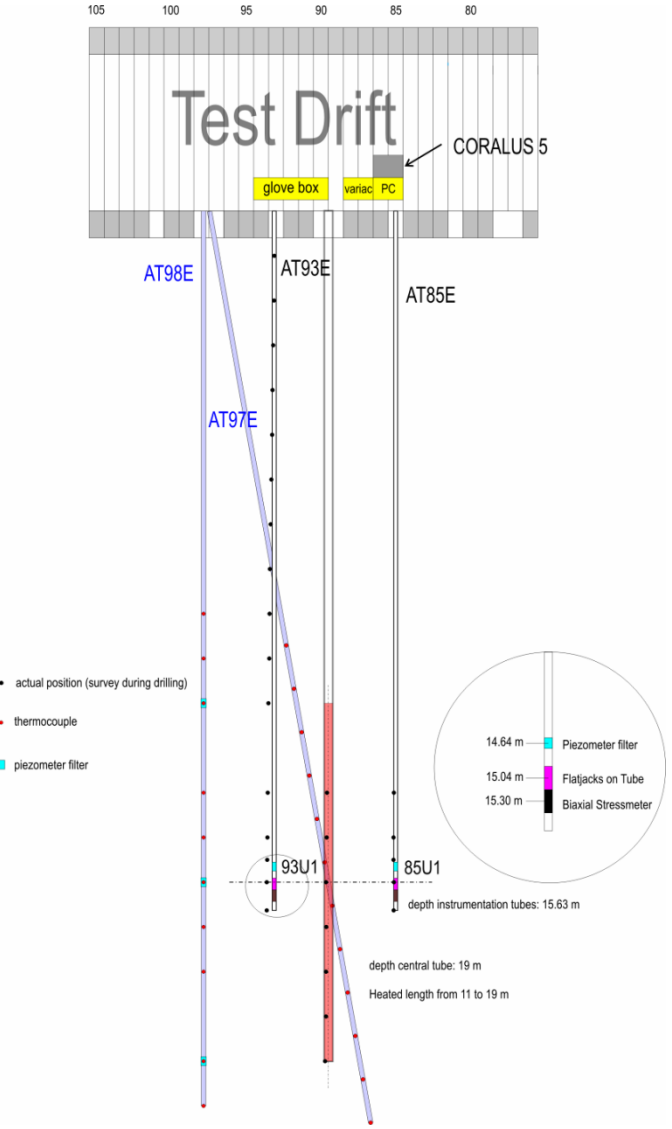
- Part of the EC INTERCLAY-II project (1990-1994)
- An experiment for modellers (blind predictions)
  - No radioactive source (CERBERUS)
  - No backfill material (BACCHUS)
  - Focus is on the behaviour of the Boom Clay
- Second life in 1996
- upgraded in mid 2005
  - to investigate anisotropy
- in total 4 test campaigns

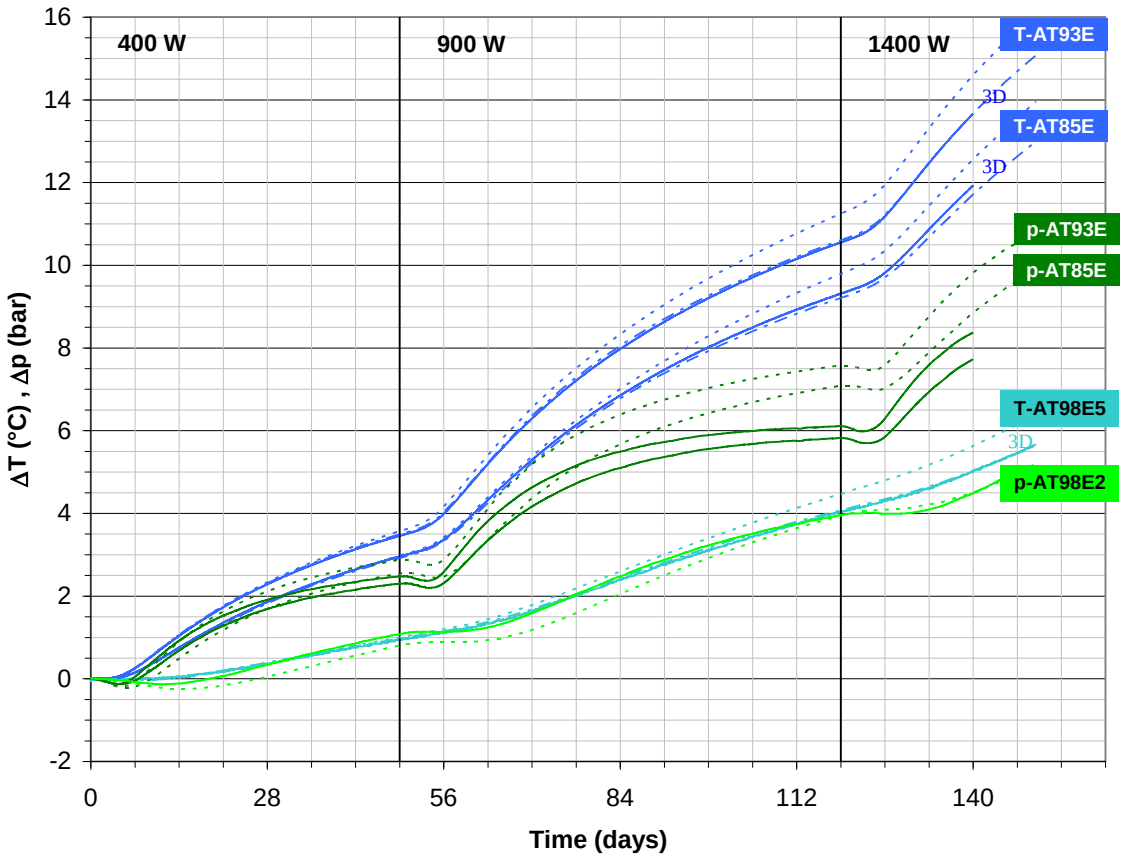
ATLAS – a “simple” T → HM test

Original test set-up (1992)



ATLAS – upgrade in 2007





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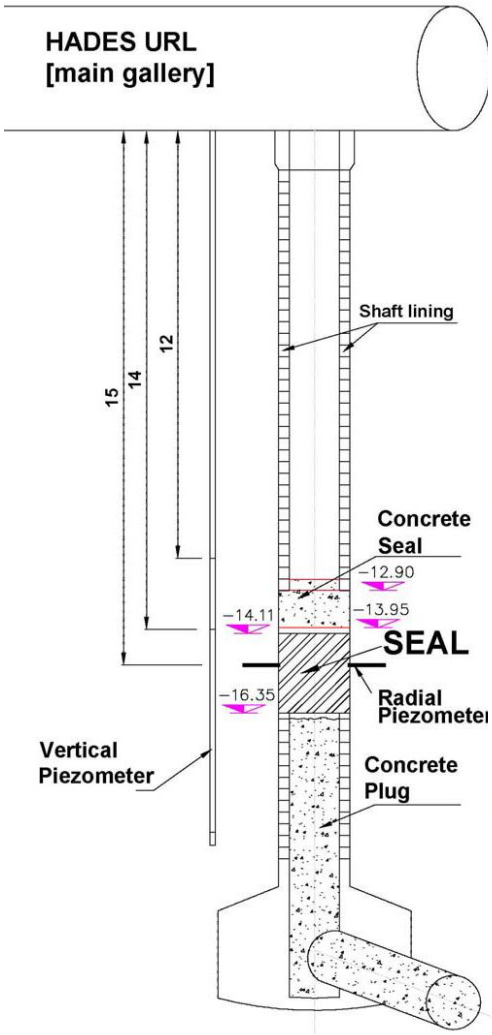
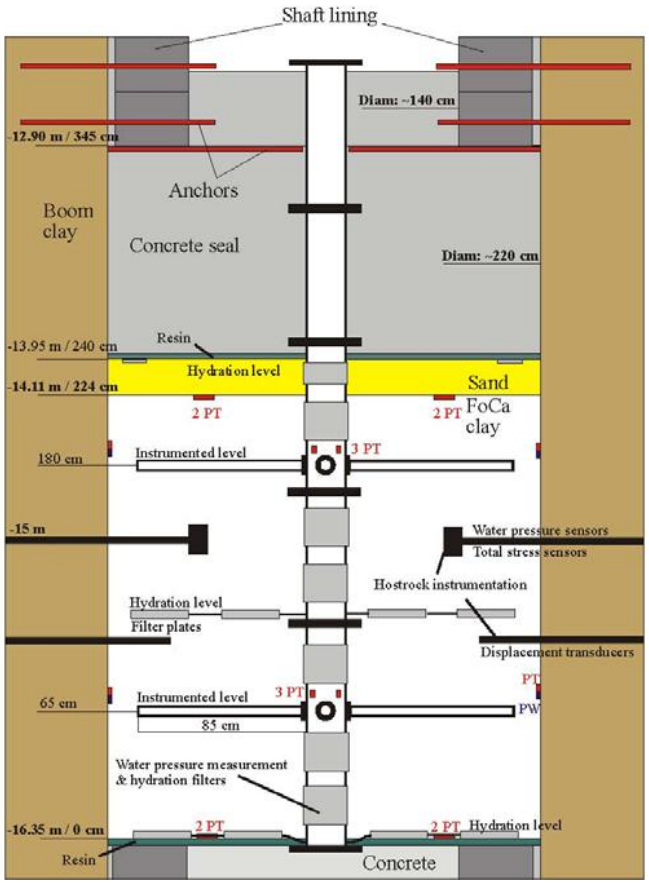
EBS instrumentation – RESEAL set-up





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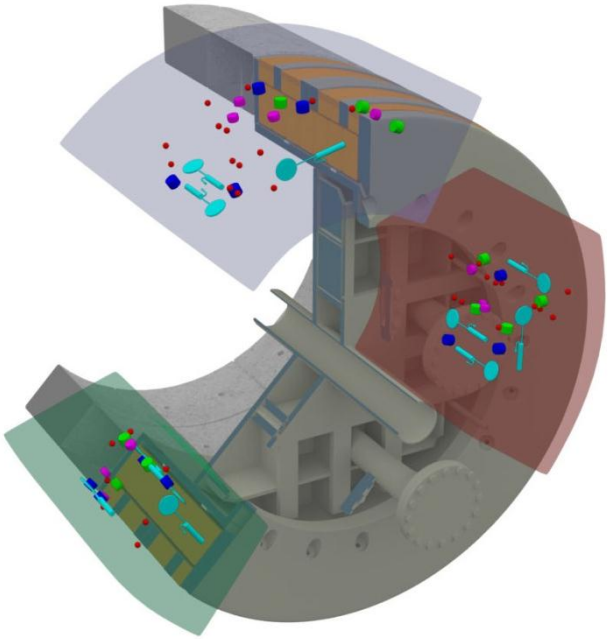
PRACLAY SEAL

total pressure cells and piezometer filters

- large surface might influence bentonite hydration…



Assessment of sensors according to parameter

- pore(water) pressure
- total pressure
- moisture content (suction/unsaturated materials)
- displacements
- mechanical strain
- physico-chemical phenomena
  - oxidation
  - corrosion

Pore pressure – most used parameter

Succesful deployment of multifilter piezometer

- installation adapted to Boom Clay characteristics
  - self sealing, no packers needed
- due to strong HM coupling – sensitive to many phenomena
  - short- and long-term anisotropic influence of gallery excavation on porewater pressures
- versatile instrument, also for “active use”

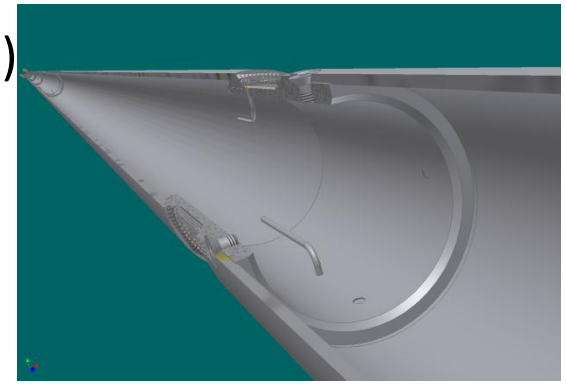
  sampling

  hydraulic parameters (permeability, storage)

  looping for on-line analysis

  migration / solute transport

  gas transport investigations
- allows for regular calibration



Total pressure

Performance of total pressure sensors depends on

- sensor characteristics (stiffness ↔ host formation)
- installation
  - borehole drilling alters the total stress field

Rather good results in backfill and at interfaces

- inside host clay formation: better approximation by combining different techniques, including active methods: (self-boring) pressuremeter, dilatometer, hydro-fracturing
- change in total pressure is often also a good indicator

Unsaturated state

Different methods for determination of hydration / saturation degree

- suction through RH
  - vulnerable for liquid water
- close to saturation: psychrometer / tensiometer
- direct moisture determination: TDR, n-γ probes
- indirect methods: thermal properties

Important for bentonite EBS performance

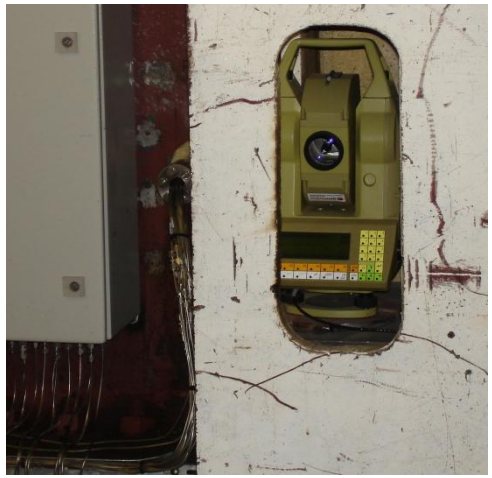
- much experience (being) gained

Different techniques for displacement monitoring

direct optical methods

⟶ most reliable but require access

- total station
  - manual borehole survey
  - automatic total station



inclinometer

- e.g. CLIPEX example – excavation of Connecting Gallery

extensometer

- MPBX : anchoring problem in clay boreholes
- magnetostrictive devices (RESEAL)
- inductive transducers (PRACLAY Seal)
- fiber-optic long-base gauges (around PRACLAY Gallery)

Experience gained after 30 y of monitoring

Succesful implementation depends on adapting available (sensor) technology to the environment

Monitoring : more than instrumentation and sensor technology

- visual observations (routine and ad-hoc)
- clear understanding of the geo-environment and of the sensors helps us in a correct interpretation of the observations

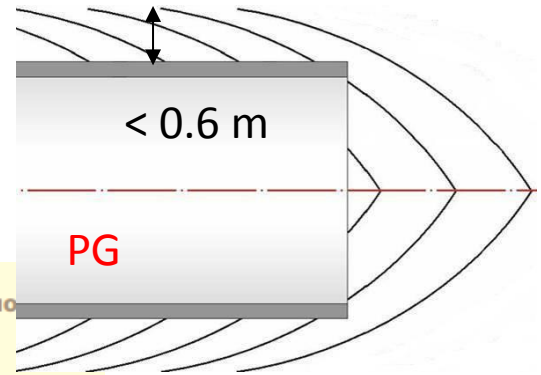
Knowledge management

- sensor expertise (technology, installation procedures,…)
- information technology
  - from mainframe and data storage on cassette tapes to Web-interface for data presentation

The power of observation

Important knowledge gained by field observations

e.g. fracture pattern around excavations



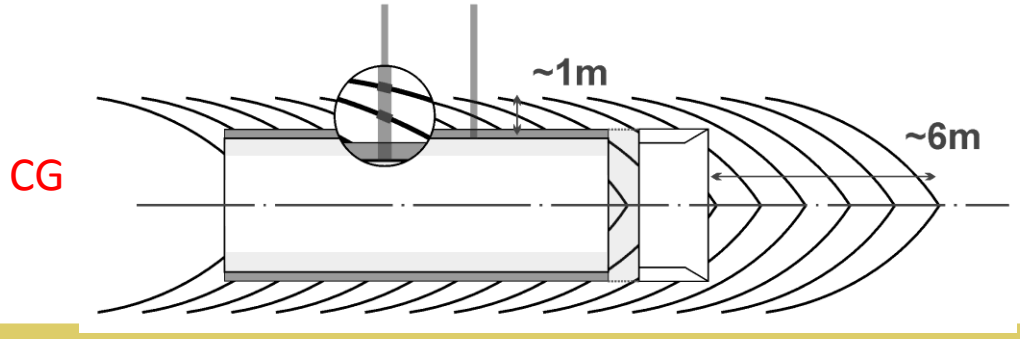
GEOTECHNICAL INSTRUMENTATIO

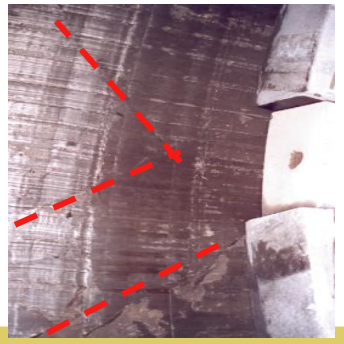
The Power of Observation

Ralph B. Peck

in winter, enough ore must be accumulated in the summertime to last through the winter. So every steel plant has an

consulted me, and that I had said the same thing. But then Terzaghi went on the say, "However, there may be some





Experience gained after 30 y of monitoring

Increasing confidence in monitoring by combining different observations ("redundancy")

- several sensors of the same type (spatial variability)
- different sensor principles for the same parameter
- different – coupled – parameters
  - stress – strain, H-M coupling
- point measurements versus geophysical techniques
  - "non-intrusive" (in the monitored zone)
  - to deal with spatial variability
  - confirmation of e.g. lab-derived parameters (e.g. elastic parameters through micro-seismic techniques)

Experience gained after 30 y of monitoring

As all field instrumentation engineers know…

“the devil is in the details”

“c’est le détail qui tue”

‘t zijn de kleine dingen die het doen….

→ enough resources to be planned for extensive (prototype) testing

→ baseline characterisation of sensor (determination of sensor characteristics in the field) to allow improved interpretation and diagnostics

Succes factors for monitoring

Technical aspects

- sensor robustness / adapted to field conditions
  - installation (construction site , watertightness, corrosion (oxidized zone, galvanic corrosion) ,…
- cabling
  - essential for sensor reliability
  - may affect environment / breaching of barrier
    - e.g. dam safety – sinkholes due to cabling from abandoned sensors
- data reduction / signal diagnostics
  - treatment of “wrong” / “unexpected” data
- do the sensor (and installation) alter the field conditions?

Management aspects

Success factors for monitoring

Technical aspects

Management aspects

- design/contracting/installation/follow-up
- record keeping / documentation / as built plans
- management of measurement data

  ! access to monitoring data

  ⟶ automated monitoring: follow-up?

  “increased data ≠ improved data”

  ⟶ GSIS project
- response plan: what if measurements/observations indicate deviation from “expected” value?

The Golden Rule

The golden rule is: **The people who have the greatest interest in the monitoring and instrumentation data should be given direct responsibility for obtaining the data.** Or put another way, who has the motivation to do these nit-picking tasks with enough care?

Dunniclif, 2011

Challenges for repository monitoring

Long term monitoring

- reliability/recalibration/ (powering)
- data management / record keeping
- nothing is happening …
  - transient phenomena (temperature, porewater pressures, oxidation,…)

Environmental conditions

- radiation
  - less an issue with SuperContainer design
- chemical (corrosion)
- thermal
  - although no suffering from diurnal or seasonal variations
- hydraulic

Challenges for repository monitoring

Inaccessible sensors

Minimal invasive cabling

Geological environment – spatial variations

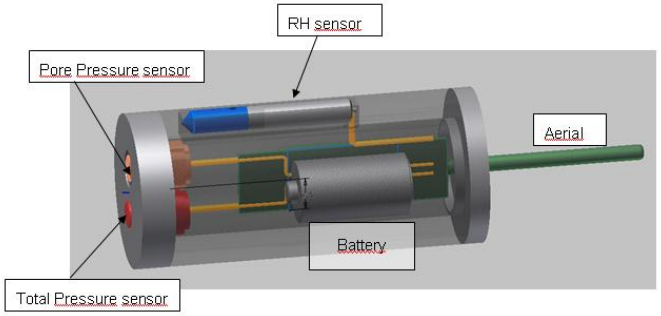
Sensor market – niche

- customized versions, limited production, prototypes
- take advantage of technical developments elsewhere
  - e.g. consumer electronics (VW sensors and MP3 players, Kinect® sensor for scanning excavation fronts…
  - fiber optic technology based on developments for data communication

Perspectives for repository monitoring

Sensor and monitoring technologies

- fibre optics
  - also alleviates cabling issues
- MEMS / miniaturisation
- wireless techniques
  - autonomous power (thermo-electric generation)
- geophysical techniques
  - numerical capabilities allow increase techniques (tomography)



wireless sensor prototype developed by AITEMIN

Conclusion

Broad experience gathered in the field of

- sensor technology and availability
- implementation (installation techniques)
- instrumentation and data management

Successful monitoring programme also depends on a clear framework regarding

- design / specification / manufacturing
- testing and installation
- follow-up (maintenance, reporting)

Sensor expertise needs to be secured for longer term

- knowledge management
- sharing of sensor experiences at international level