Institut français
des sciences et technologies
des transports, de l'aménagement
et des réseaux

13 décembre 2018 :
Journée technique multisectorielle :
des femmes à l'honneur
Participez à cette journée, une 1ère dans la profession !

CND du béton :
focus sur des recherches en cours en France

Odile ABRAHAM
PRECEND, 15 décembre 2018

IFSTTAR

Lmdc Toulouse · LMA · I2M Bordeaux · IFSTTAR · Centrale Lille · ISTerre

Introduction

Civil infrastructures are the basis of socio-economic wealth for modern societies

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Concrete is the most used material

in volume in the world

Increasing demand for housing, water, energy, mobility

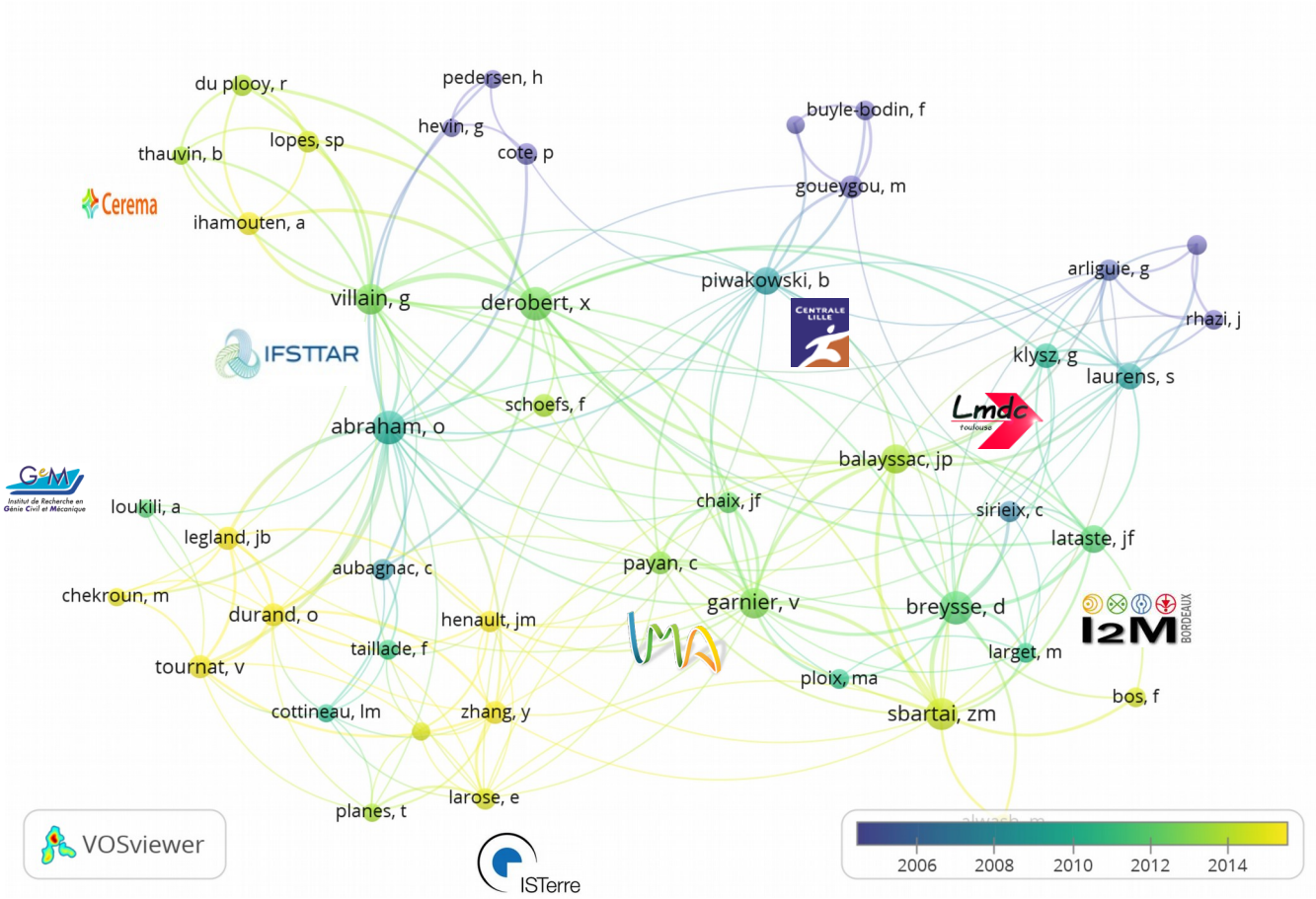
Traffic increase

Climate change

CO_2 emission

Introduction

French research laboratories involved in concrete NDT



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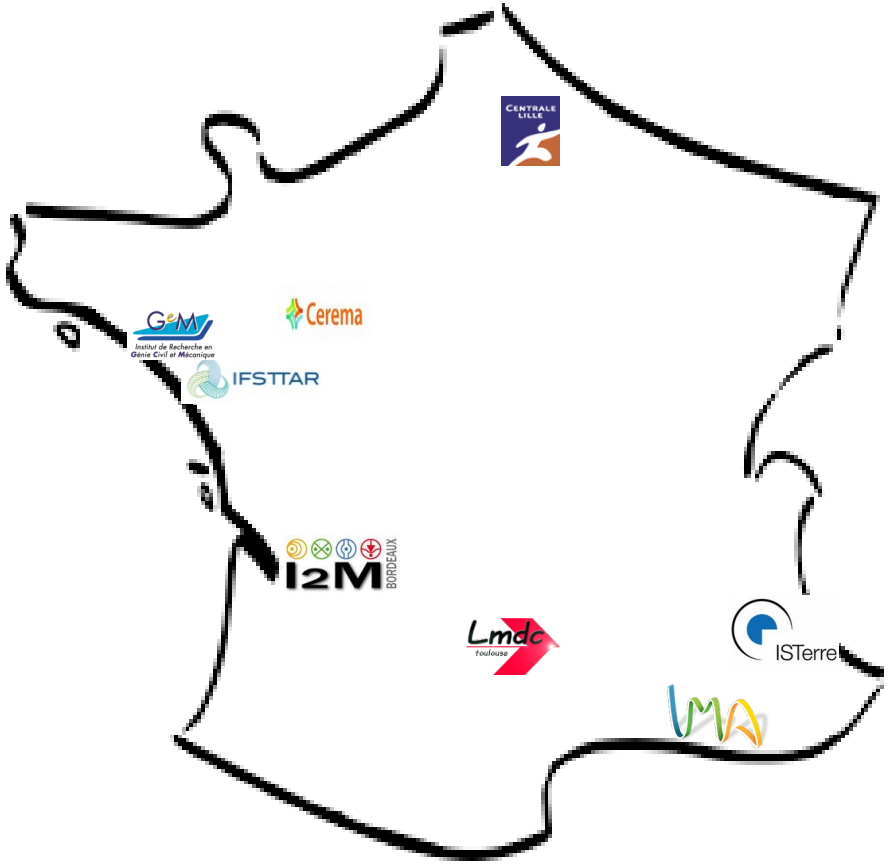

General frame

Research is focused on **reinforced concrete** with the aim to recover **quantitative informations** on the **material properties**

Outline

- **Context**
  - Summary of the methodology/philosophy (recently finished projects)
- **Some ongoing research work**
  - PIA ENDE Project
  - Increase NDT methods TRL (Technology Readiness Level)
  - Numerical and physical modeling
  - Gradient
  - Embedded sensors
  - Monitoring
- **Conclusions**

Outline

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Some ongoing research work

PIA ENDE Project
Increase NDT methods TRL (Technology Readiness Level)
Numerical and physical modeling
Gradient
Embedded sensors
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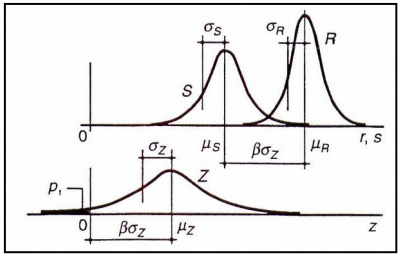
Conclusions

Context

NDT can be an alternative way for the assessment of concrete properties
→ non intrusive and repeatable with reasonable cost

Usual assessment of concrete properties
→ destructive testing on cores

Significant variability of concrete properties
→ the use of probabilistic models requires the assessment of this variability (cores↑)



Most of the structures are very large
→ coring is prohibitive/impossible

Context

But… Concrete properties have conjugated effects on NDTs

→ How to separate these effects?

French built heritage:

- 100000 important bridges
- 55 nuclear plants
- 350 electric dams
- Many buildings

Expected properties:

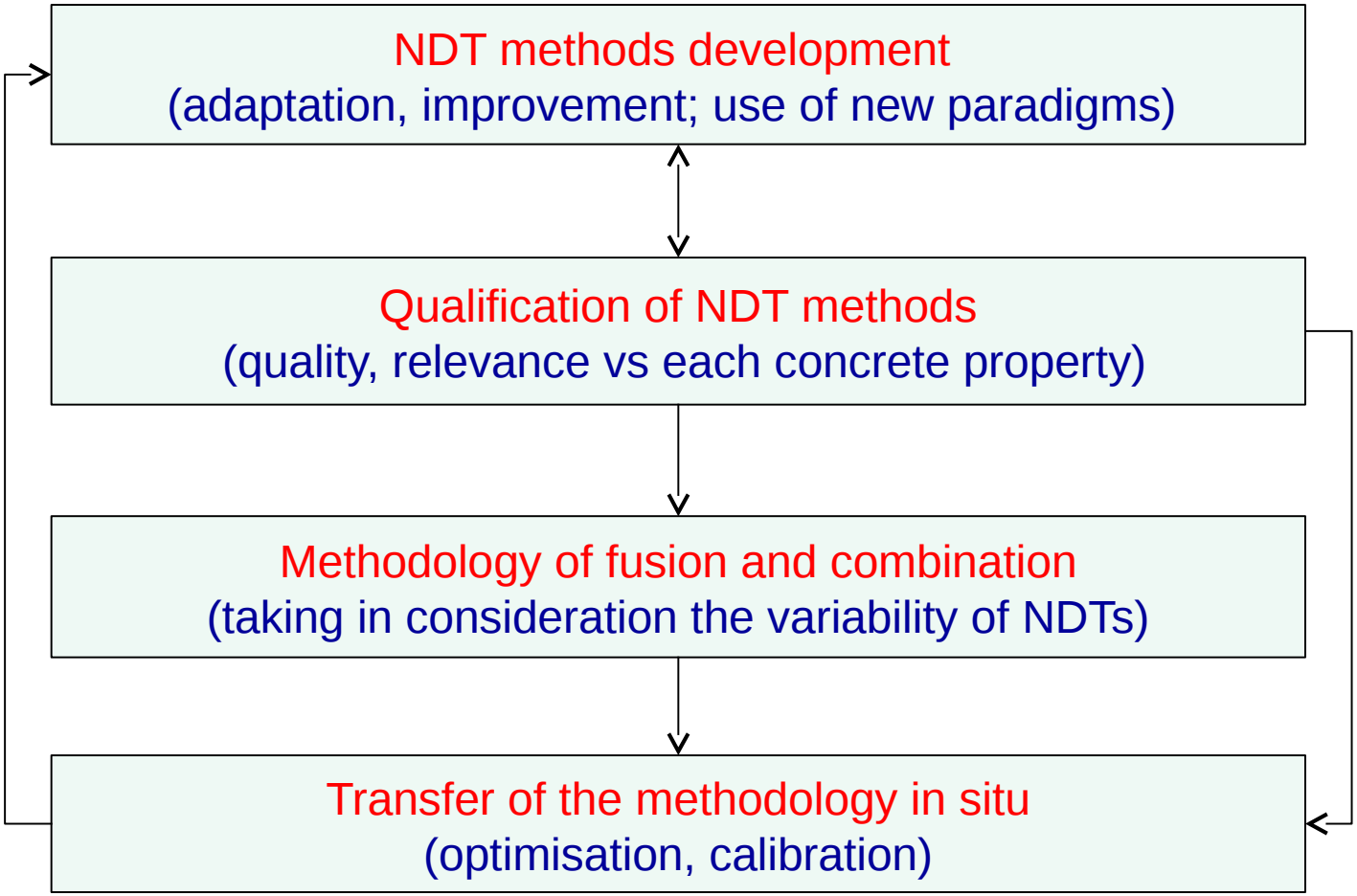
- E-modulus
- Porosity
- Moisture
- Chloride content
- Carbonation

- Thermal damage
- Stress

Several NDT methods are sensitive to these properties but the relationships between them are not direct

Both mean values and variability are necessary to assess

Methodology



NDT techniques involved

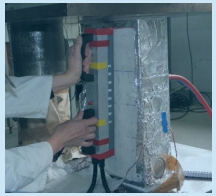
surface

radar

capacitive

resistivity

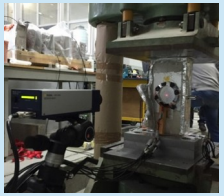
permeability



surface wave
dry coupling

surface wave
air coupling

diffuse wave
DAET, ATME



TREND

NDT techniques involved

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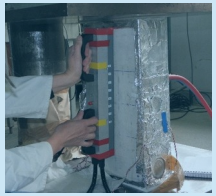
capacitive

resistivity

permeability



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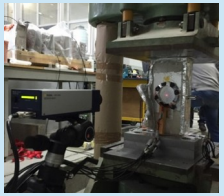


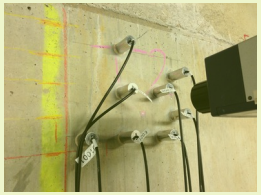
TREND

volume

ultrasonic
transmission

ultrasonic
pulse echo

impact echo



(Nonlinear) coda
wave interferometry

NDT techniques involved

surface

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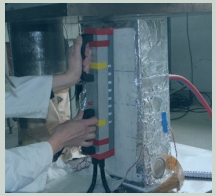

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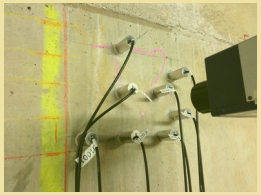


(Nonlinear) coda
wave interferometry

acoustics

NDT techniques involved

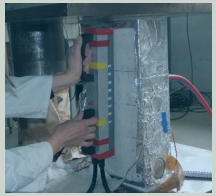
surface

radar

capacitive

resistivity

permeability



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(Nonlinear) coda
wave interferometry

acoustics

Low TRL

NDT observables vs concrete properties

Laboratory benchmarks are designed for controlling concrete properties

Involved properties: moisture, porosity, E-modulus, carbonation, chlorides, thermal damage, stress

NDT observables vs concrete properties

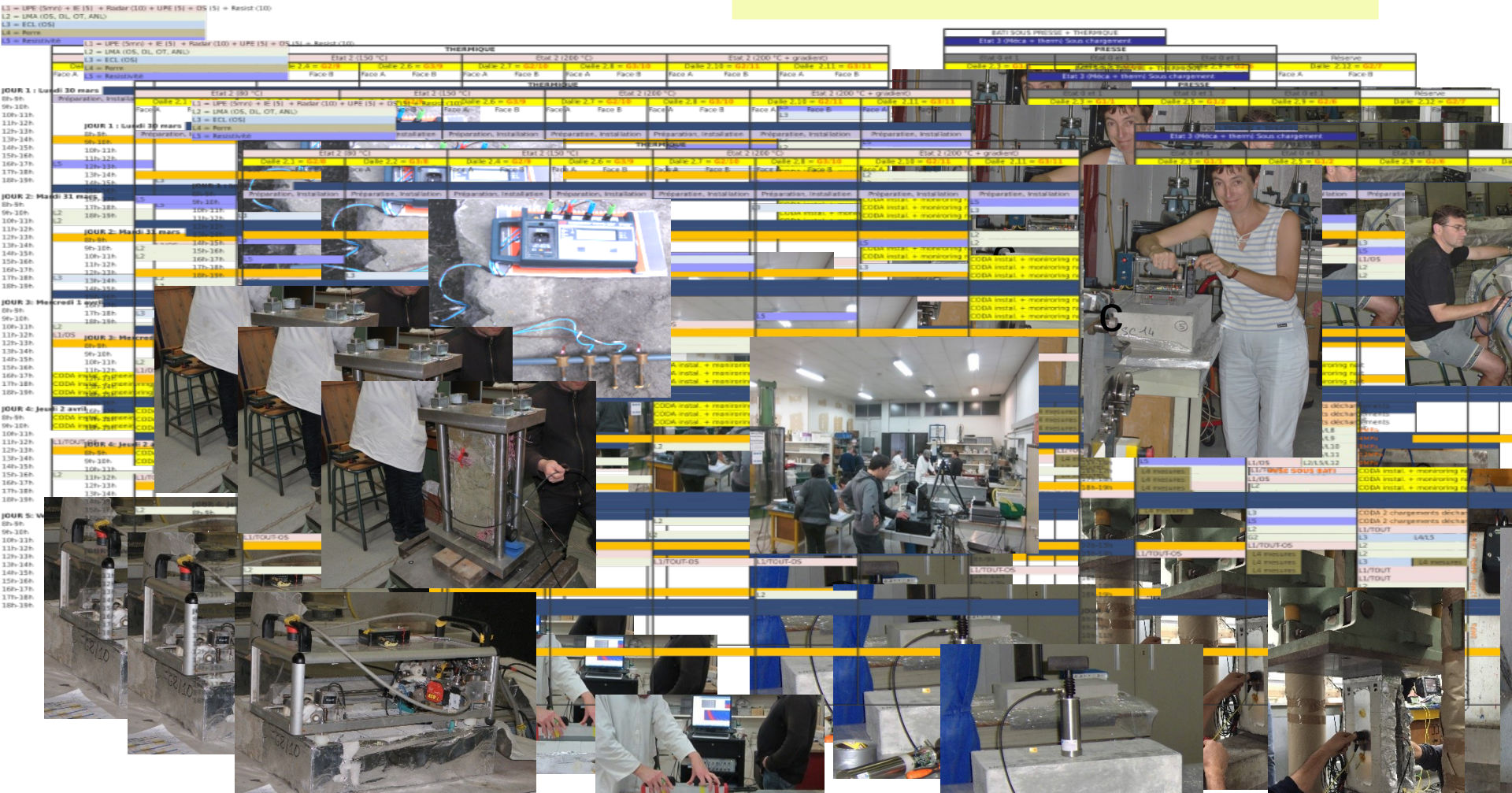
All the NDT measurements are performed at the same time

Measurement processing and extraction of **observables (features)** (velocity, attenuation, resistivity, etc)

NDT observables vs concrete properties

Variance of NDT observables is quantified at different scales

- Repeatability: V1
- In a same homogeneous sample: V2
- In a same batch: V3
- Between different concretes: V4



NDT observables vs concrete properties

Variance of NDT observables is quantified at different scales

- Repeatability: V1
- In a same homogeneous sample: V2
- In a same batch: V3
- Between different concretes: V4

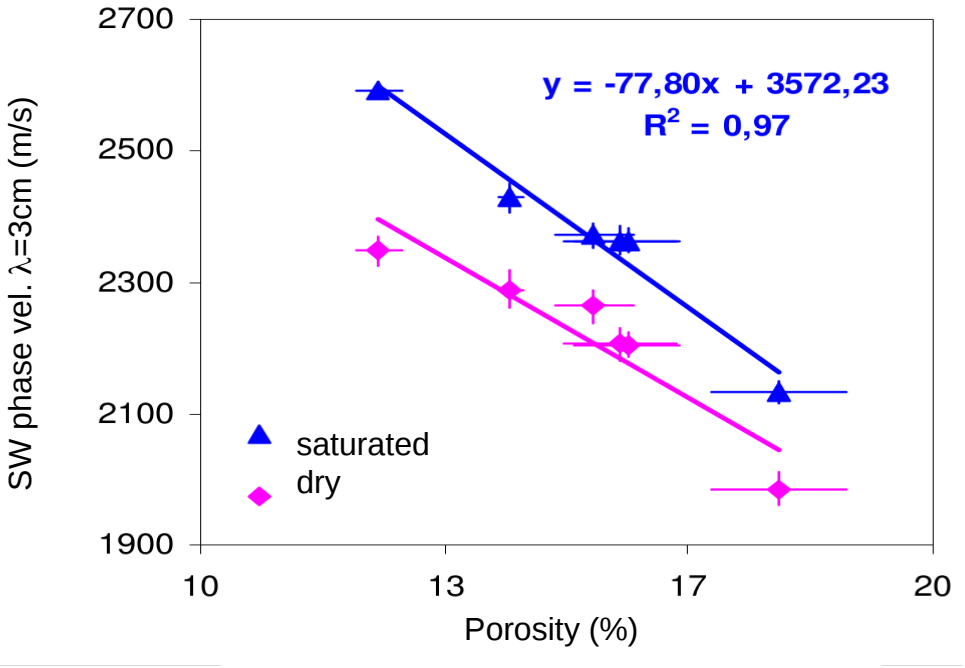
- **Strong incentive to increase the NDT methods Technology Readiness Level (TRL)**

Technology Readiness Levels as adapted by the CloudWATCH2 project

NDT observables vs concrete properties

But… Concrete properties have conjugated effects on NDTs

→ How to separate these effects?



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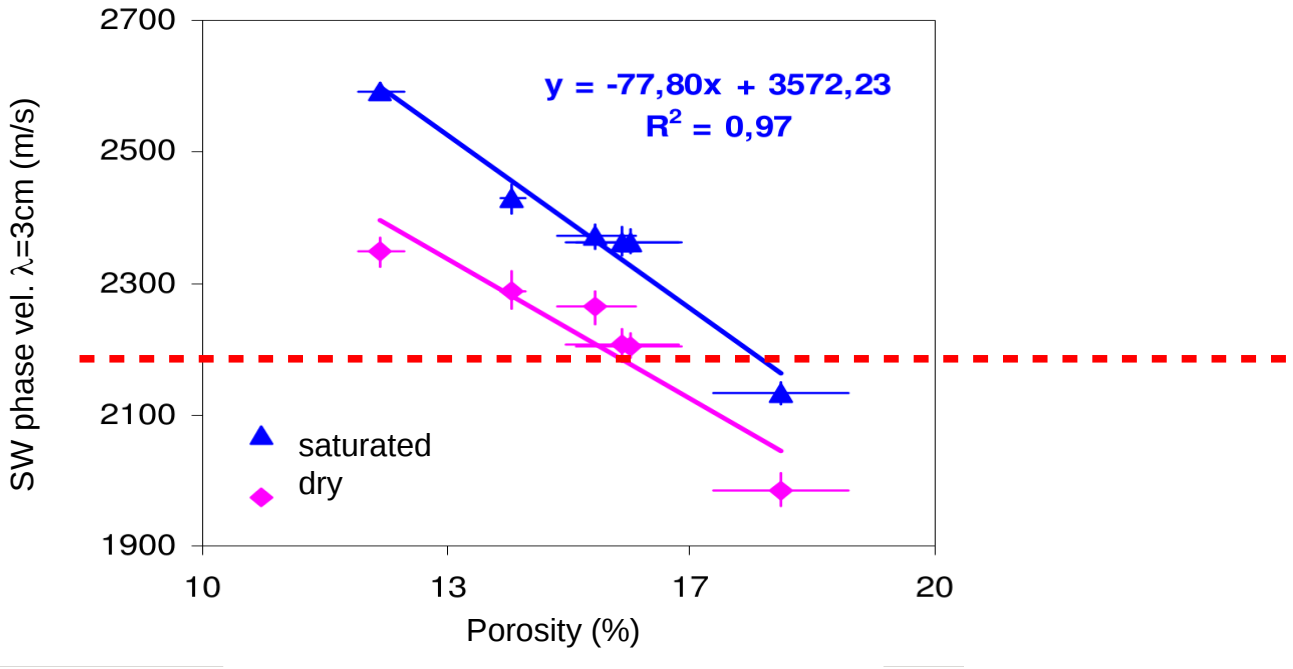

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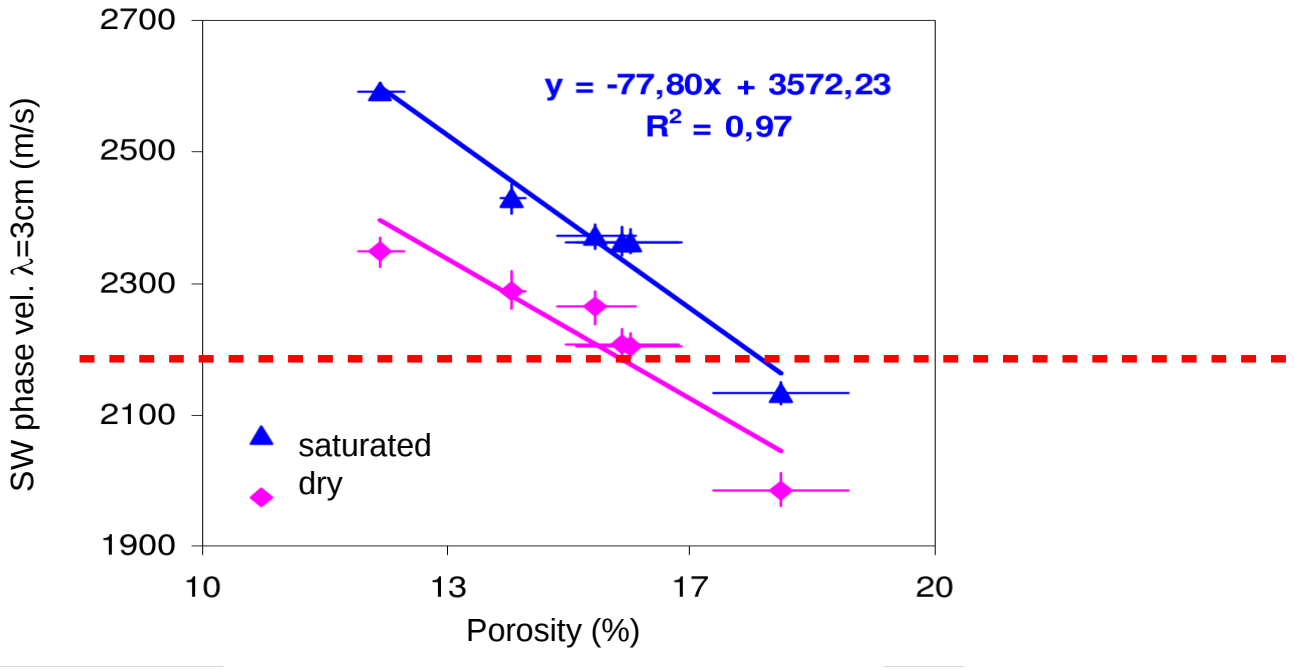
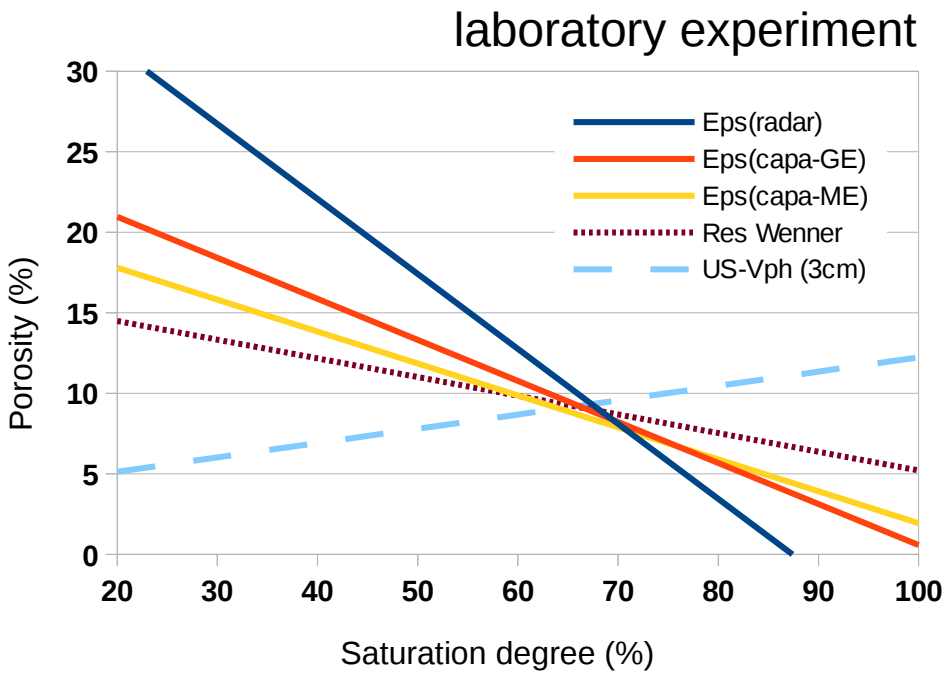


Linear regression models between NDT observables (Obs) and two concrete properties (cp_1 and cp_2)

$$Obs = A.cp_1 + B.cp_2 + C$$

NDT observables vs concrete properties

Combination of techniques



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NDT observables vs concrete properties

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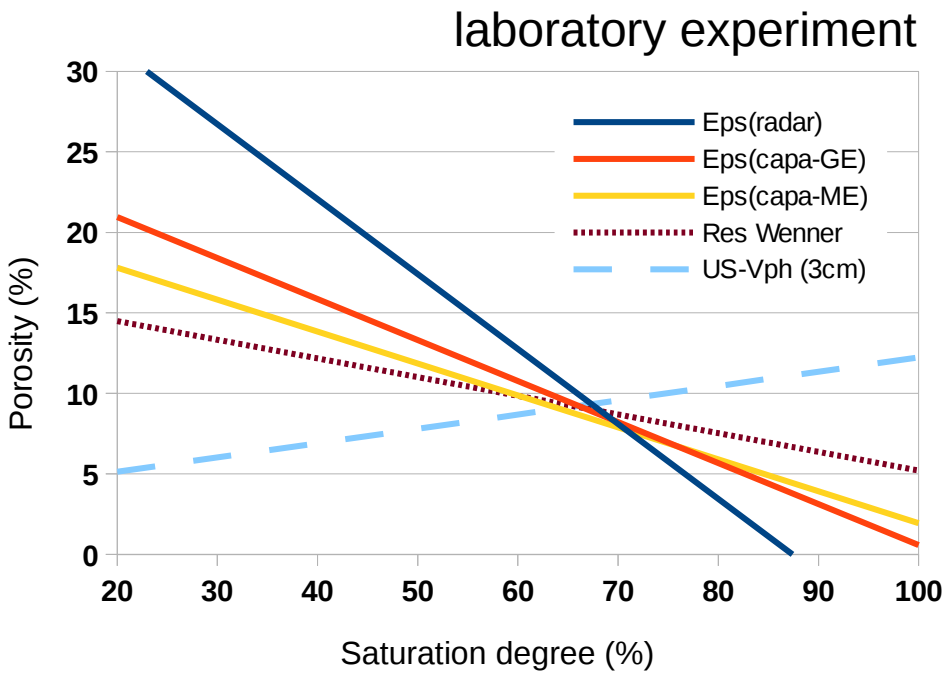
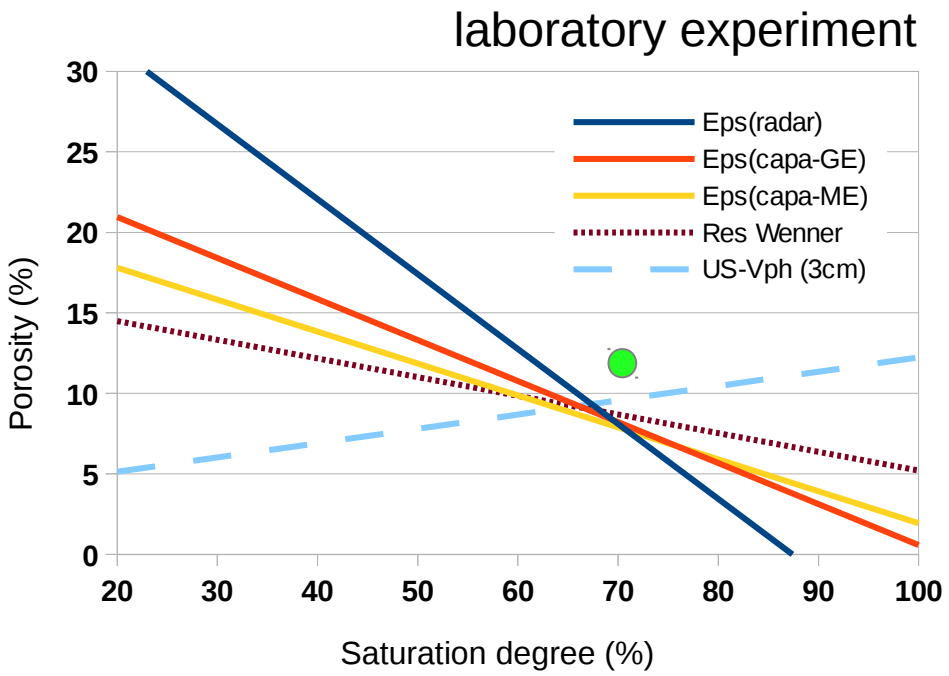


But… Concrete properties have conjugated effects on NDTs
→ How to separate these effects?

→ Which methods? → How to combine them?
→ With which confidence?

NDT observables vs concrete properties

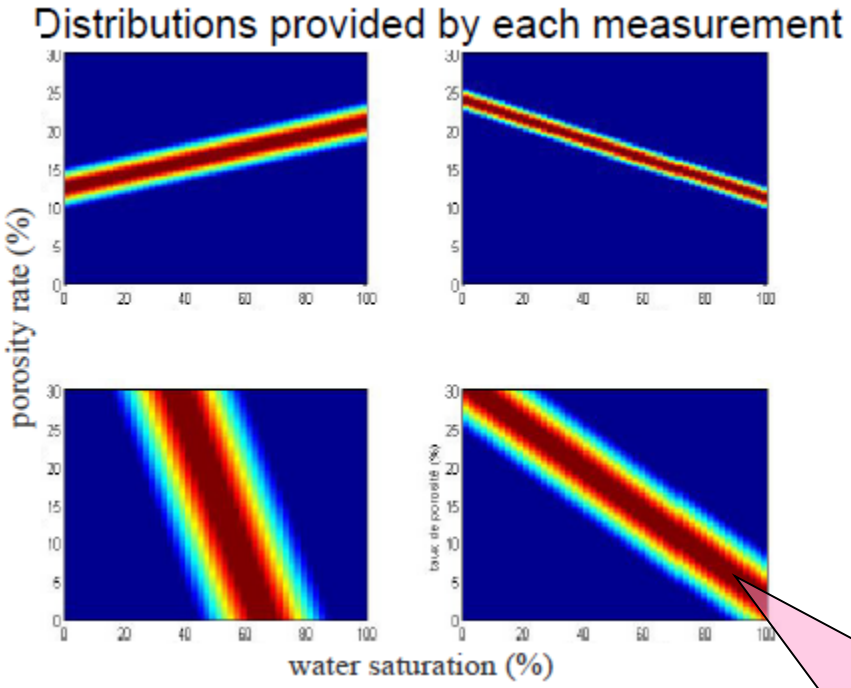
Combination of techniques



But… Concrete properties have conjugated effects on NDTs
→ How to separate these effects?

→ Which methods? → How to combine them?
→ With which confidence?
→ How to transfert on site this methodology ?

Data fusion



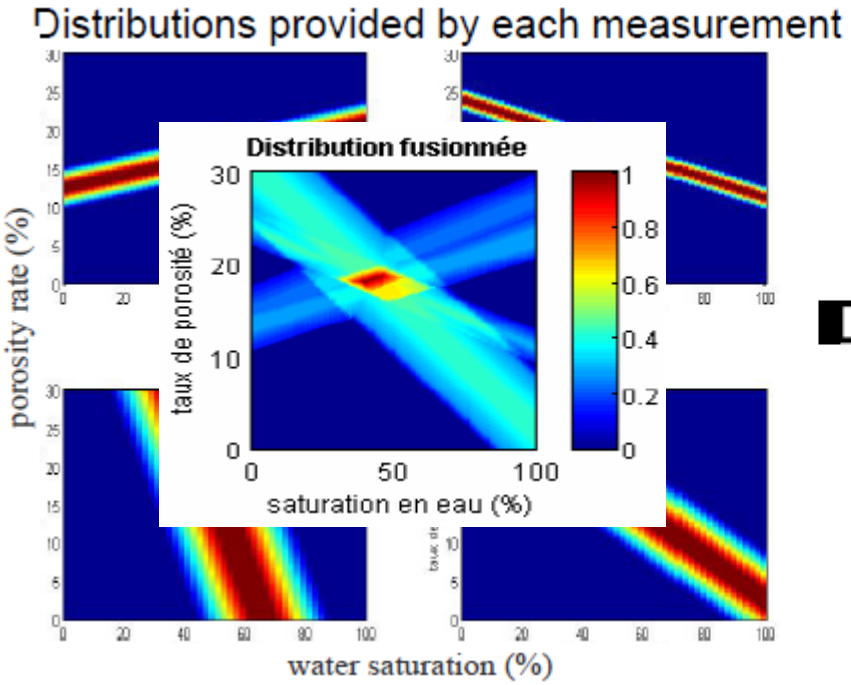
General aim:

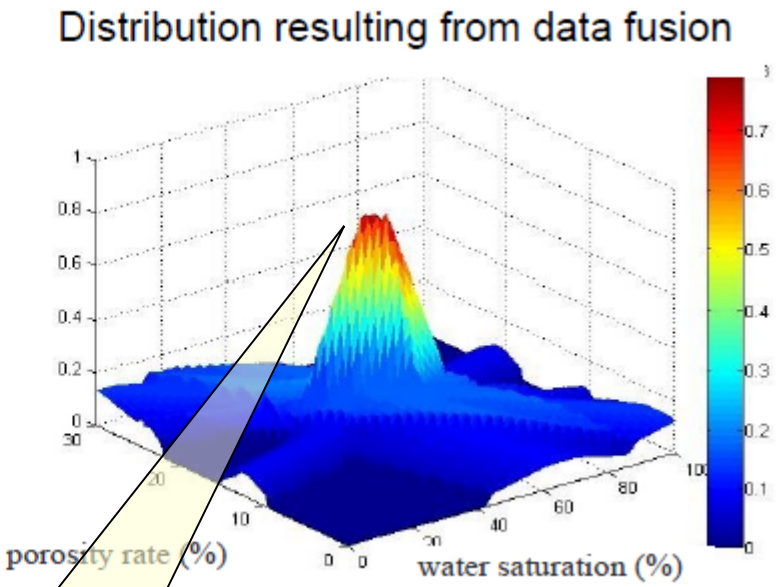
- to collect and combine information from different sources to provide more precise and reliable information
- to deal with uncertain and imprecise data

$$Obs = A.cp_1 + B.cp_2 + C$$

Distribution of possibilities is linked to the quality and relevance of the measurements

Data fusion





The solution corresponds to the higher degree of possibility

Higher is the cone, higher is the fusion quality

Data fusion

- **The methodology has been extended to on site NDT**

Data fusion

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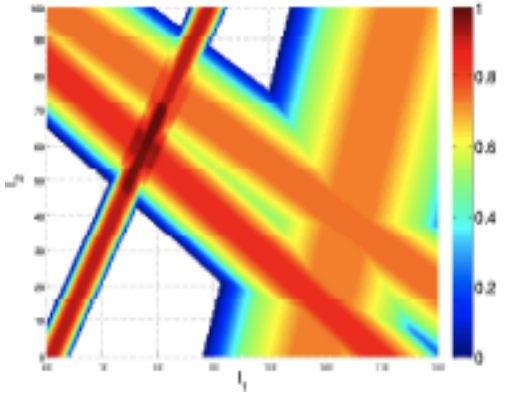

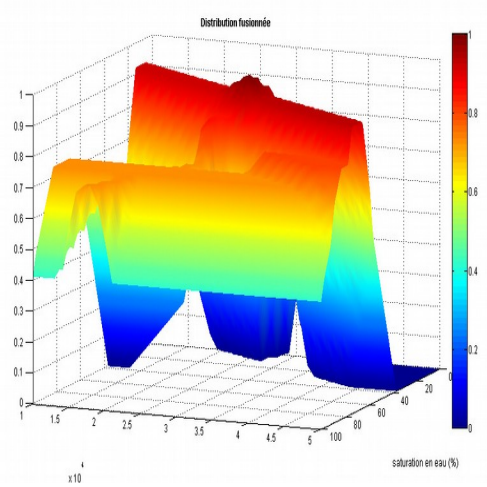

Data fusion

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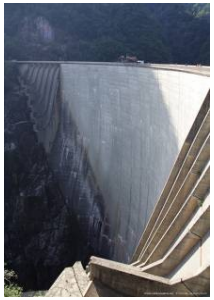
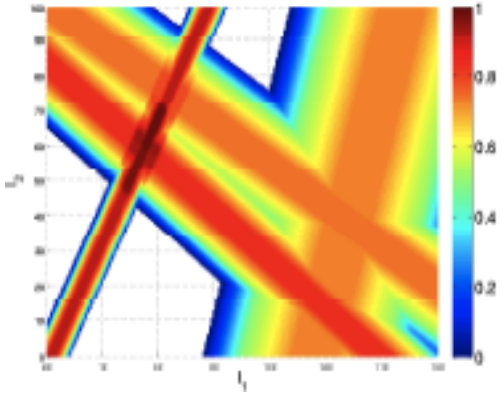
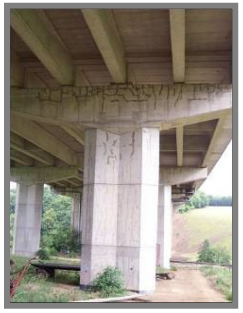


Chemistry Mechanics

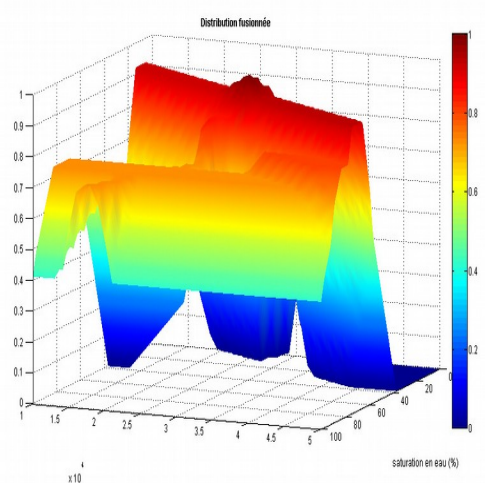


Composition

Environment



History



Need corrections and readjustments to adapt in the context of on site NDT

Data fusion

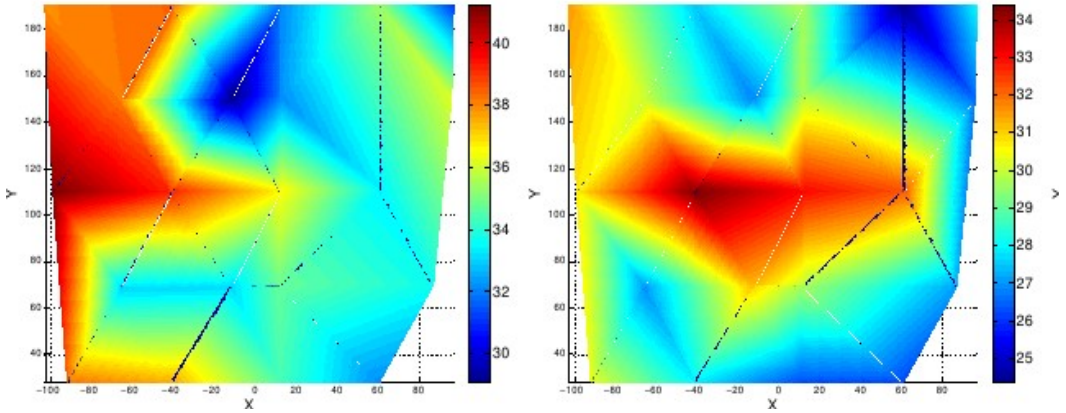
- **The methodology has been extended to on site NDT**
  - Pre-auscultation with NDTs to discriminate extreme zones
  - Data fusion for a first estimation
  - Extraction of cores from the structure

→ **calibration procedure** of the fusion process by using DT results

Data fusion: exemple

Marly in the North of France

Before correction

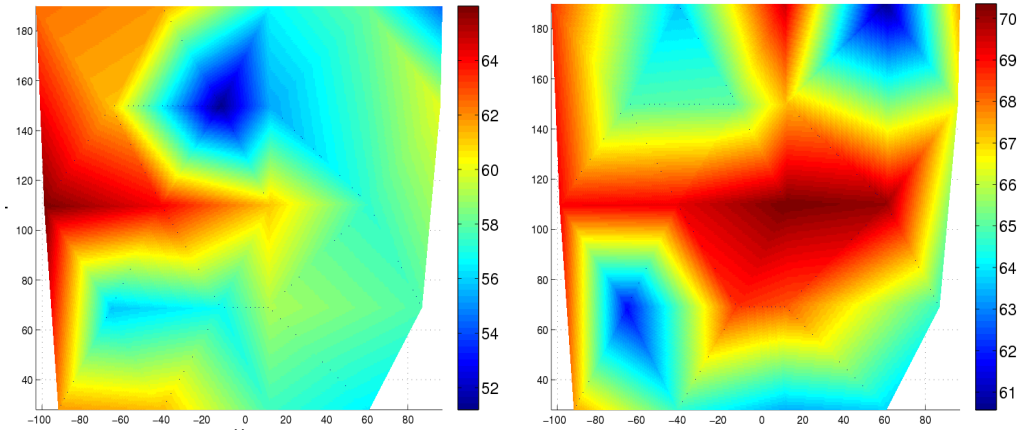


Degree of saturation (%) Compressive strength (MPa)

Mean Possibility = 0.12

Non-realistic results

After correction



Degree of saturation (%) Compressive strength (MPa)

Mean Possibility = 0.85

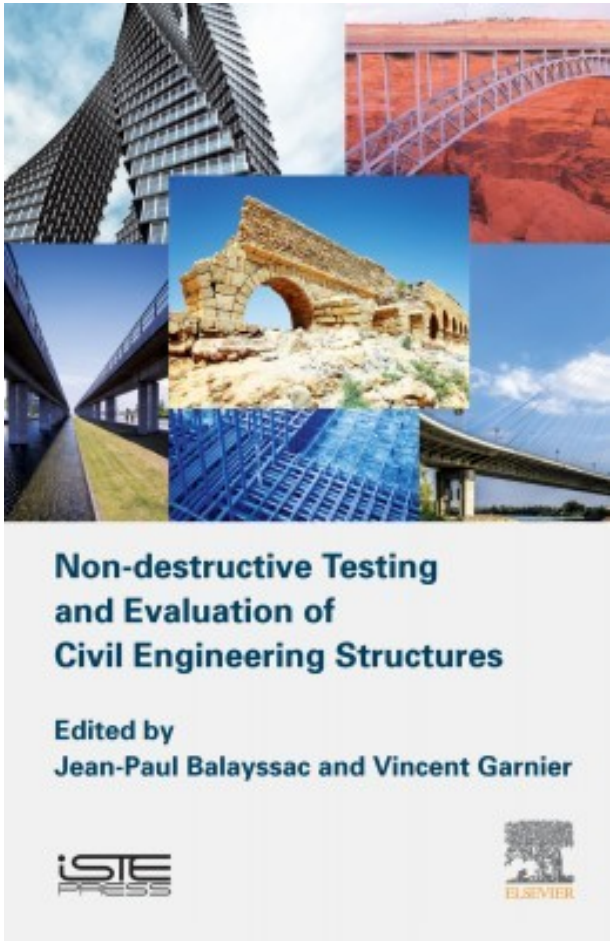
More realistic results

Methods:

US Velocity - Capacity

Impact Echo - Radar

French state of the art



http://www.iste.co.uk/book.php?id=1270

Content:

- Introduction
- Ultrasonic methods
- Electromagnetic methods
- Electrical methods
- Electrochemical methods
- Quality, uncertainties and variabilities
- Construction of conversion models of observables into indicators
- Assessment of concrete by a combination of NDT
- Applications in situ
- Methodological guide

JP. Balayssac

Lmdc toulouse

V. Garnier

Towards a new industrial sector

Creation mid 2016 of a “civil engineering” working group within the French Confederation of Non Destructive Testing (COFREND)

- Communication and federate
- Forecast and define needs (tools, methods, people, qualifications, ...)
- Qualify the techniques (guidelines, norms, application domains, practise, ...)
- Qualify the people (who, how many, benchmark, evaluation, teaching, ...)

cofrend

V. Garnier

The idea of creating a new sector (in civil engineering) has been accepted by the COFREND mid 2018

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summary of the methodology/philosophy (recently finished projects)

- **Some ongoing research work**

  – PIA ENDE Project

  Increase NDT methods TRL (Technology Readiness Level)

  Numerical and physical modeling

  Gradient

  Embedded sensors

  Monitoring

Conclusions

Project PIA ANR ENDE (2015 → 2018)

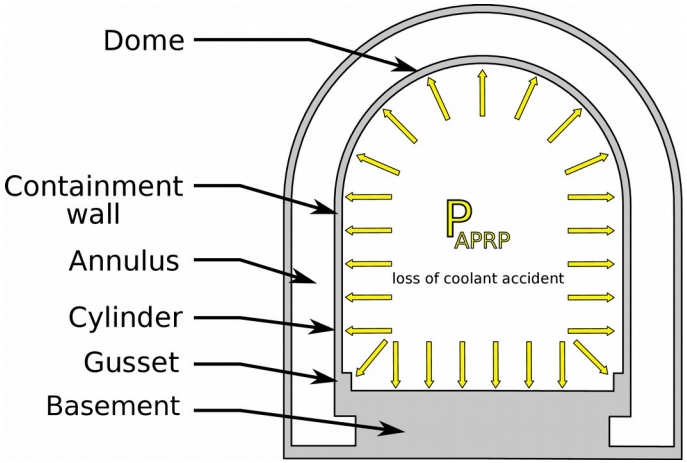
- **Nuclear containment plants = ultimate barrier in the event of an accident**
  - Resist internal overpressure
  - Prevent leakage
- **Aging of concrete**
  - Safety requirement
  - Life extension
- **No core → NDE (monitoring)**
  - Normal condition (pre-stressing 10-15 MPa)
  - Accident (pipe rupture in primary circuit): 5 bars and 180°C in 20 seconds
- **Several issues regarding the link between NDE observables and**
  - Durability indicators (elastic modulus, porosity, water content)
  - Tightness
  - Cracks (responsible for the leak)
  - Stress
  - Thermally damaged concrete
  - …

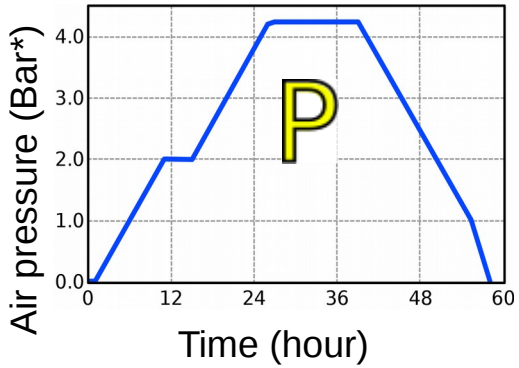
Project PIA ANR ENDE: on site experiment

- **2 steps process**
  - Experiments in the lab on slabs (50 cm x 25 cm x 12 cm)
    → calibration laws on the concrete mix of the on site concrete
  - Transfer to a real size structure (VeRCoRs mock-up)

- **VeRCoRs mock-up**
  - 30 m height
  - 16 m diameter
  - 0.3m thick wall
  - 5000 t of concrete
  - 700 sensors
  - 2 km of fiber optic

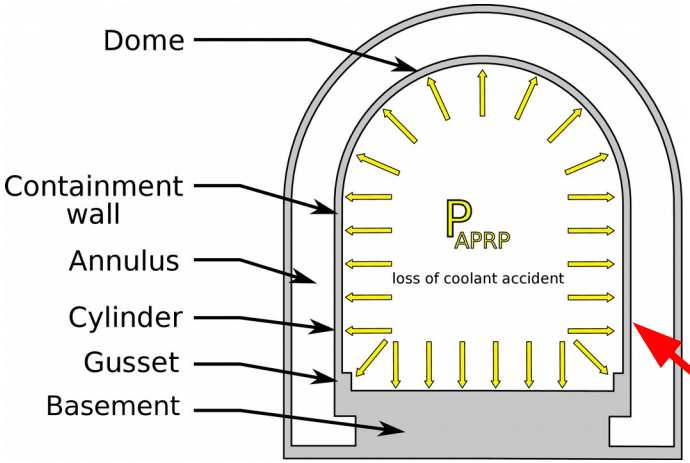
VeRCoRs mock-up

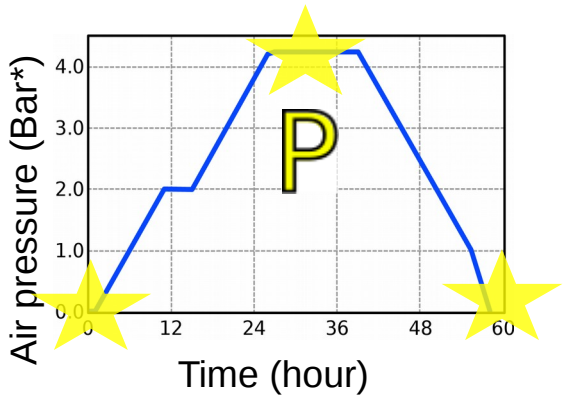


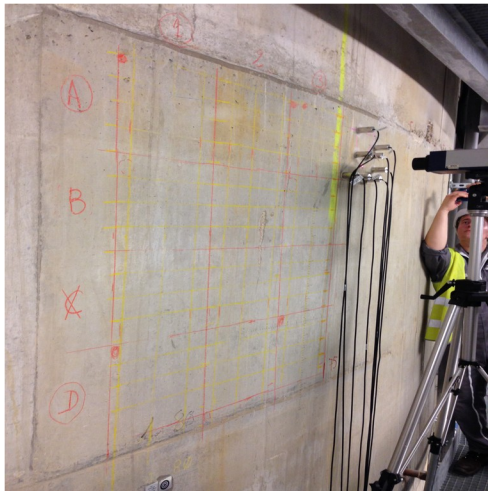


*1 Bar = 0.1 MPa = 14.5 psi

VeRCoRs mock-up







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Conclusions

IFSTTAR

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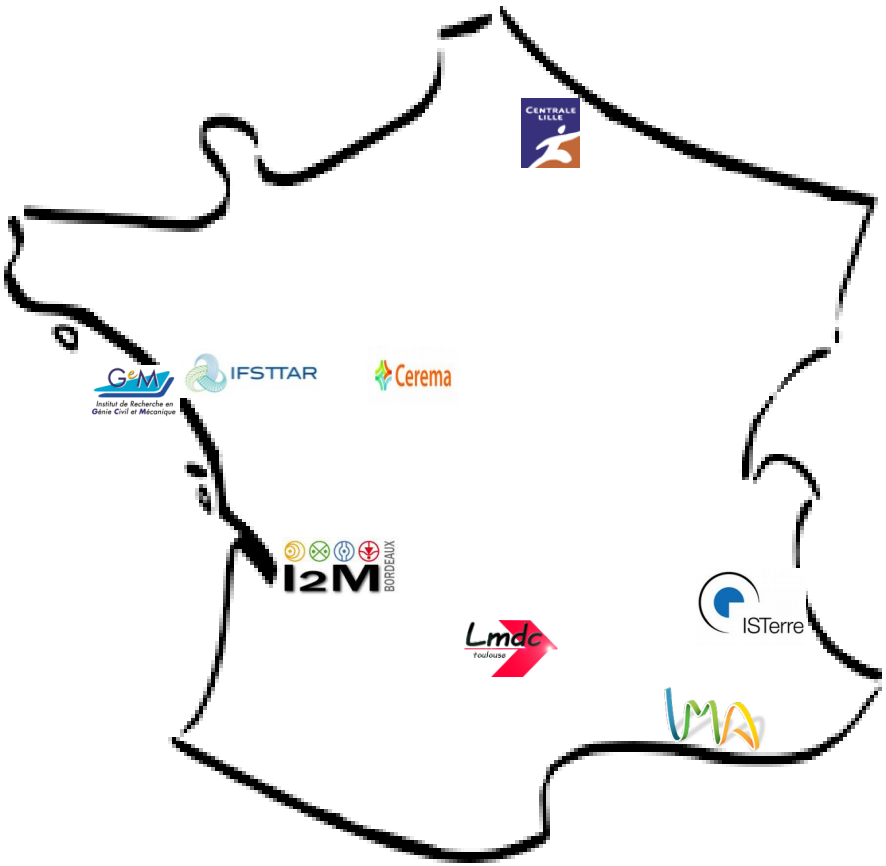


Gradients

surface waves
electromagnetic waves
resistivity
coda wave (N)CWI

↑ TRL

Embedded sensors

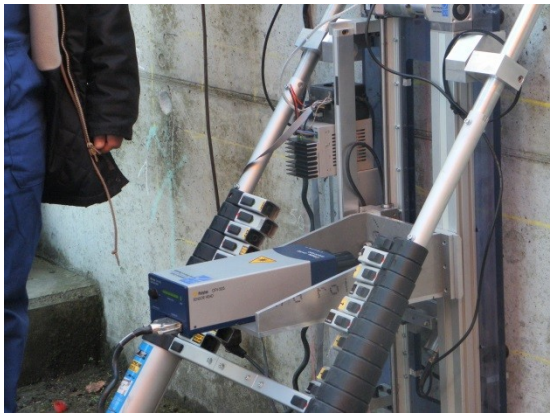
Monitoring

Increase the methods TRL

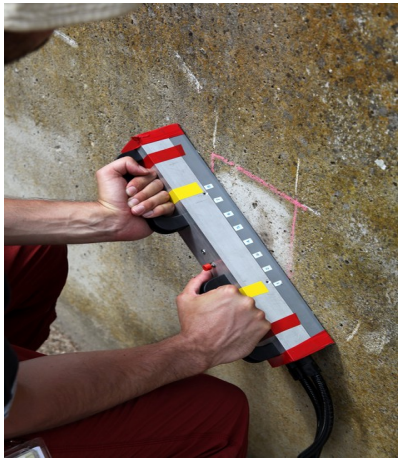
Surface waves

- Increase the measurements speed (no couplant)

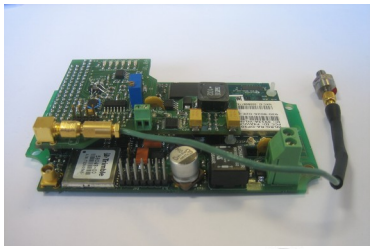
Laser vibrometer (2006):
-Surface waves
-Emitter with contact
-Automatic moving of the laser

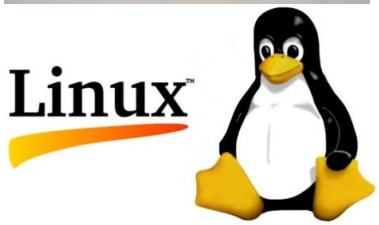


Multi-sensors probe (2015):
-Very light, easy to handle
-Very quick
-No couplant



Ungoing (2018):
-Development of a portable electronic
-Reduce the cost
-WIFI, internet (monitoring)





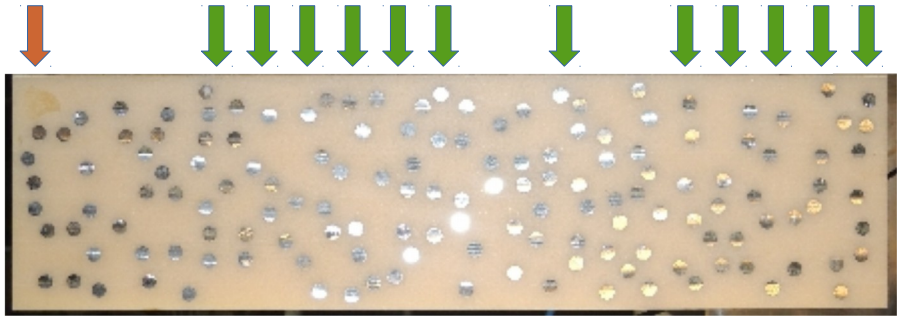
Pegase 3

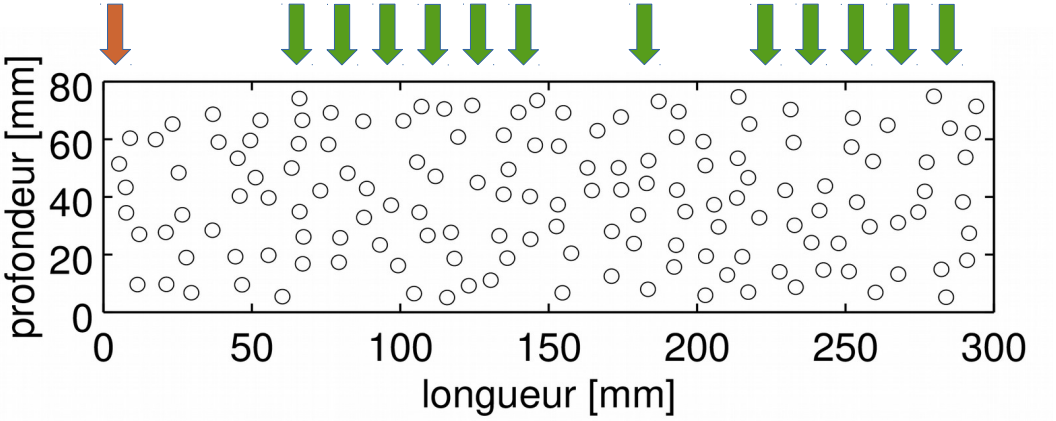
Gradient in cover concrete

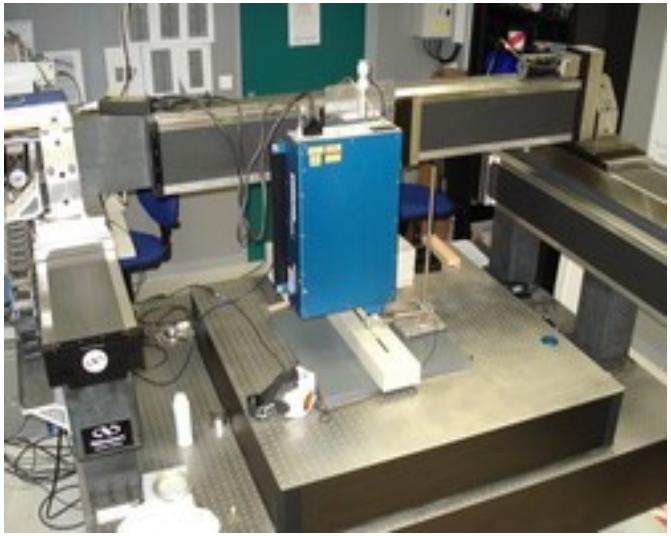
Surface waves

– Modelisation

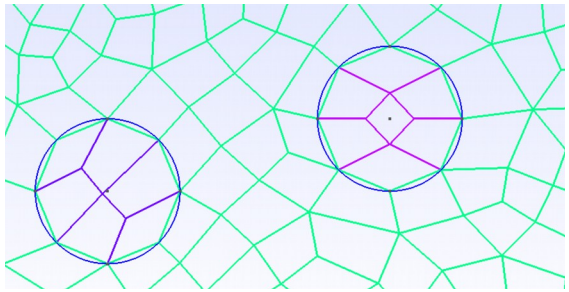
numerical & experimental



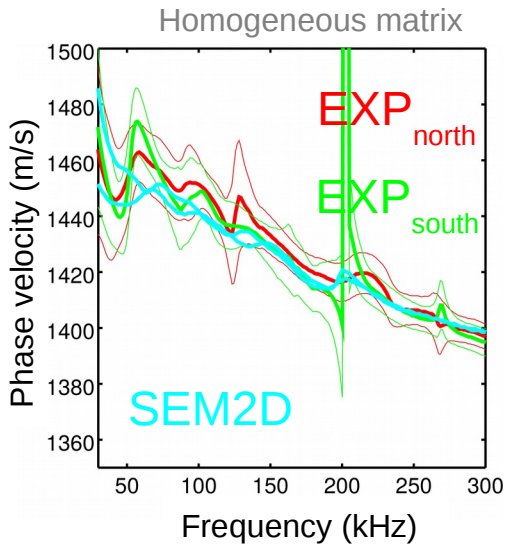




Spectral element method (SEM2D)



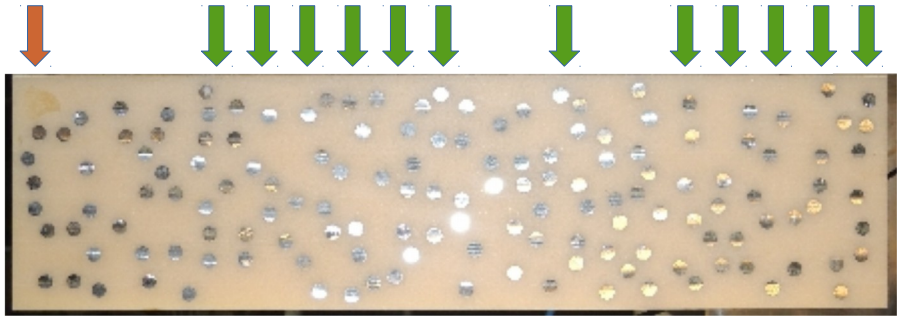
Gradient in cover concrete

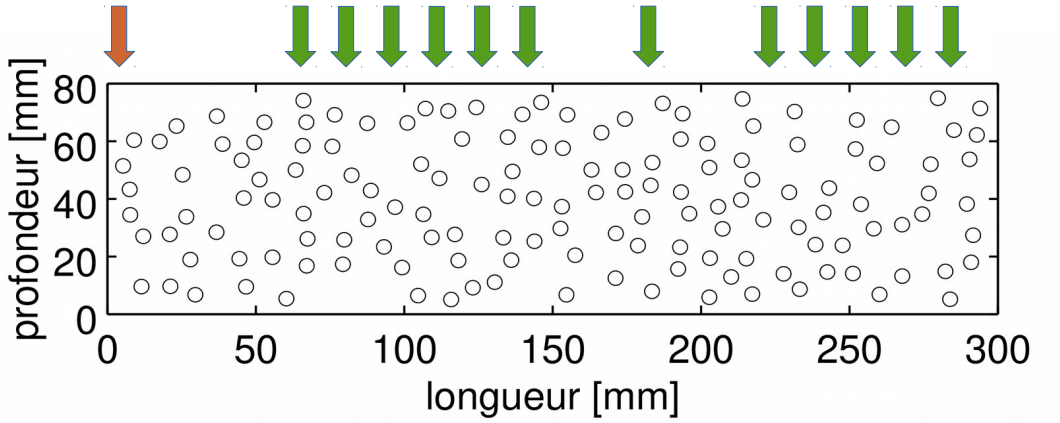


Surface waves

– Modelisation

numerical & experimental





numerical averaging on disorder

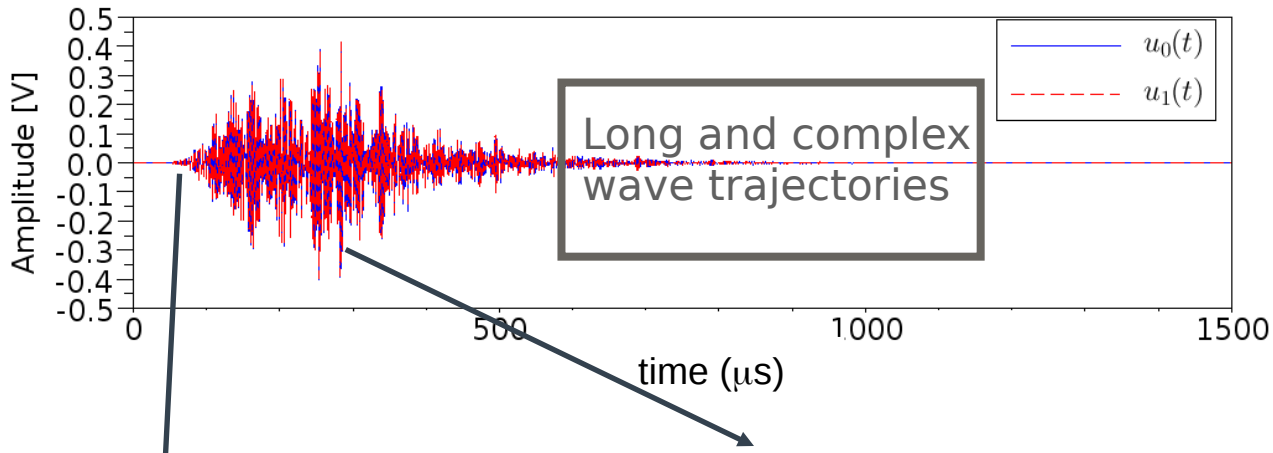
test/validation of homogenization **hypothesis**

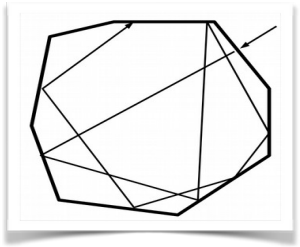
new forward modeling embedded in inverse problem for matrix gradient

requested for a precision of
1 (point,%) on porosity (heterogeneity not negligible)

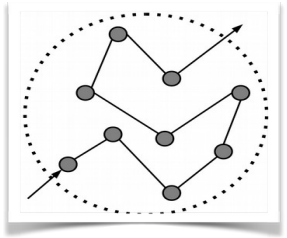
Coda waves

Multiple reflexions



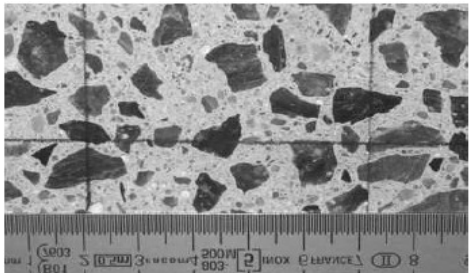


Scattering

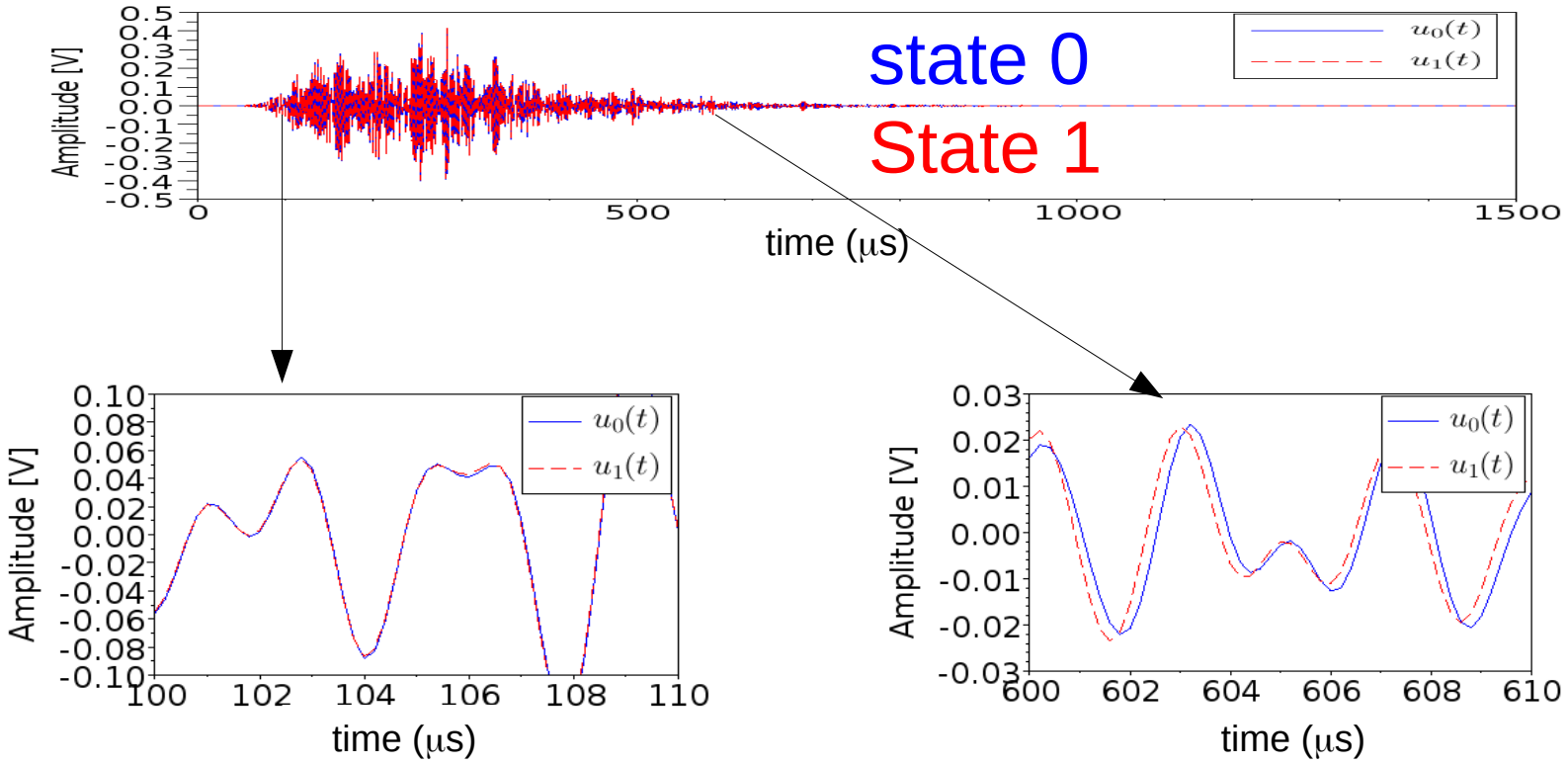


Body waves
Surface waves

Coda :
Reproducible
Sensitive



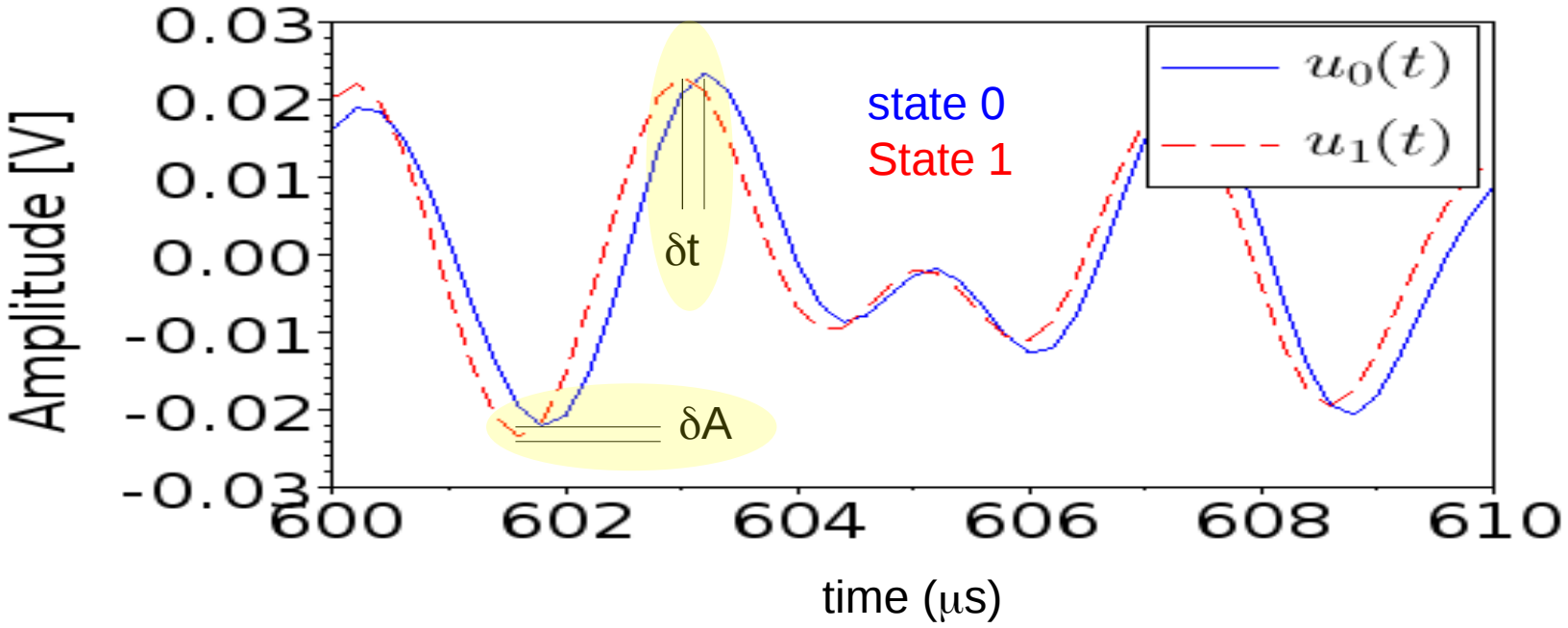
Coda waves



Body waves
Surface waves

Coda:
Reproducible
Sensitive

Coda waves interferometry: CWI

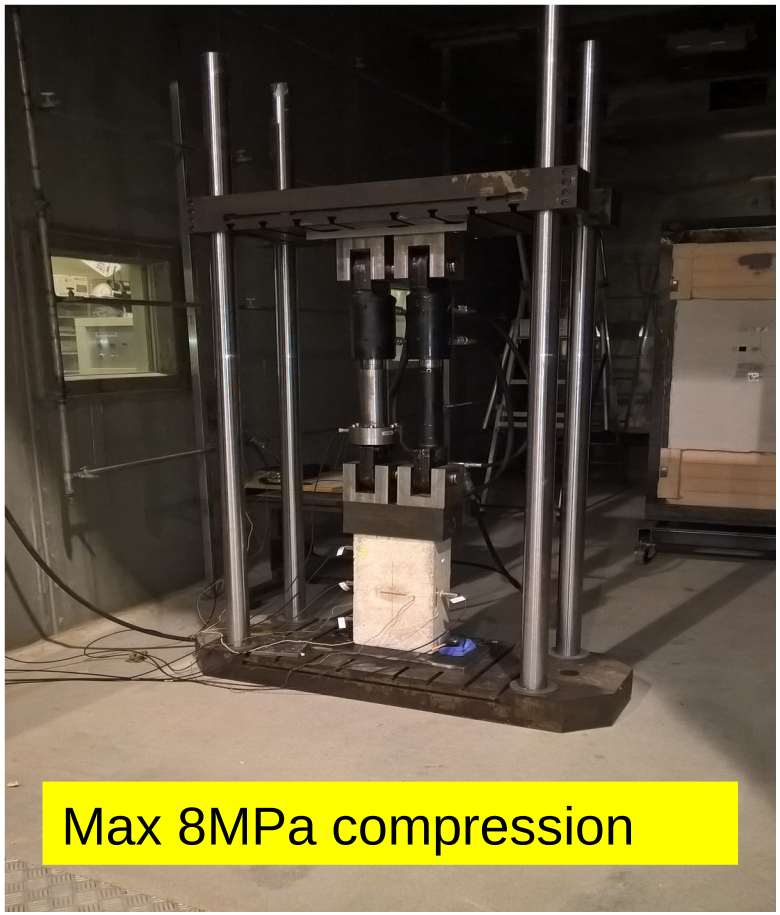


Coda:
Reproducible
Sensitive

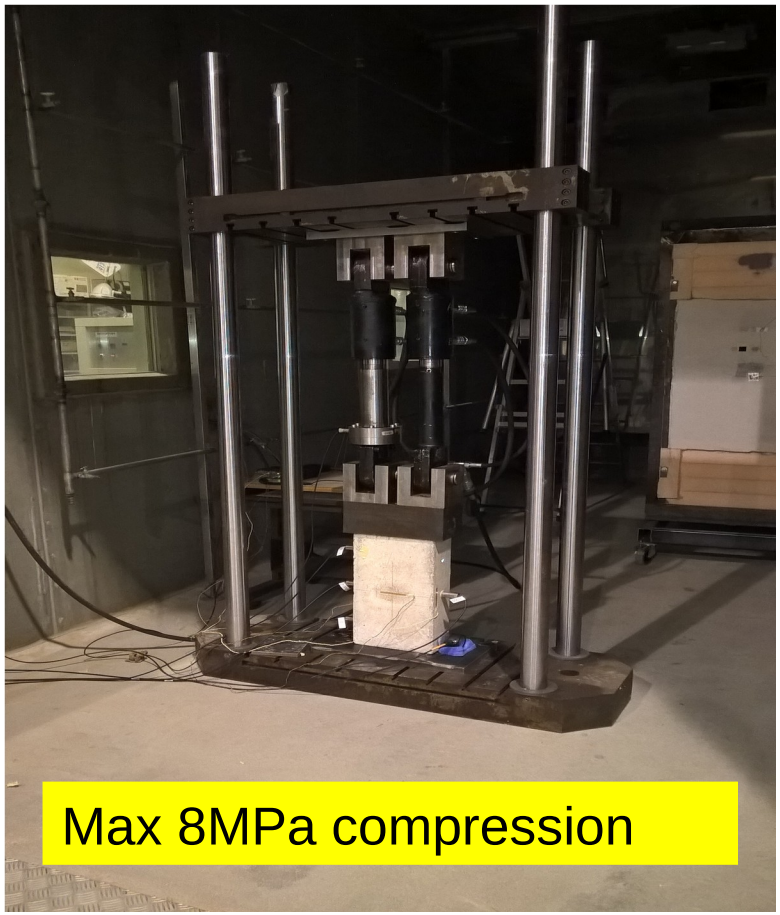
Observables:

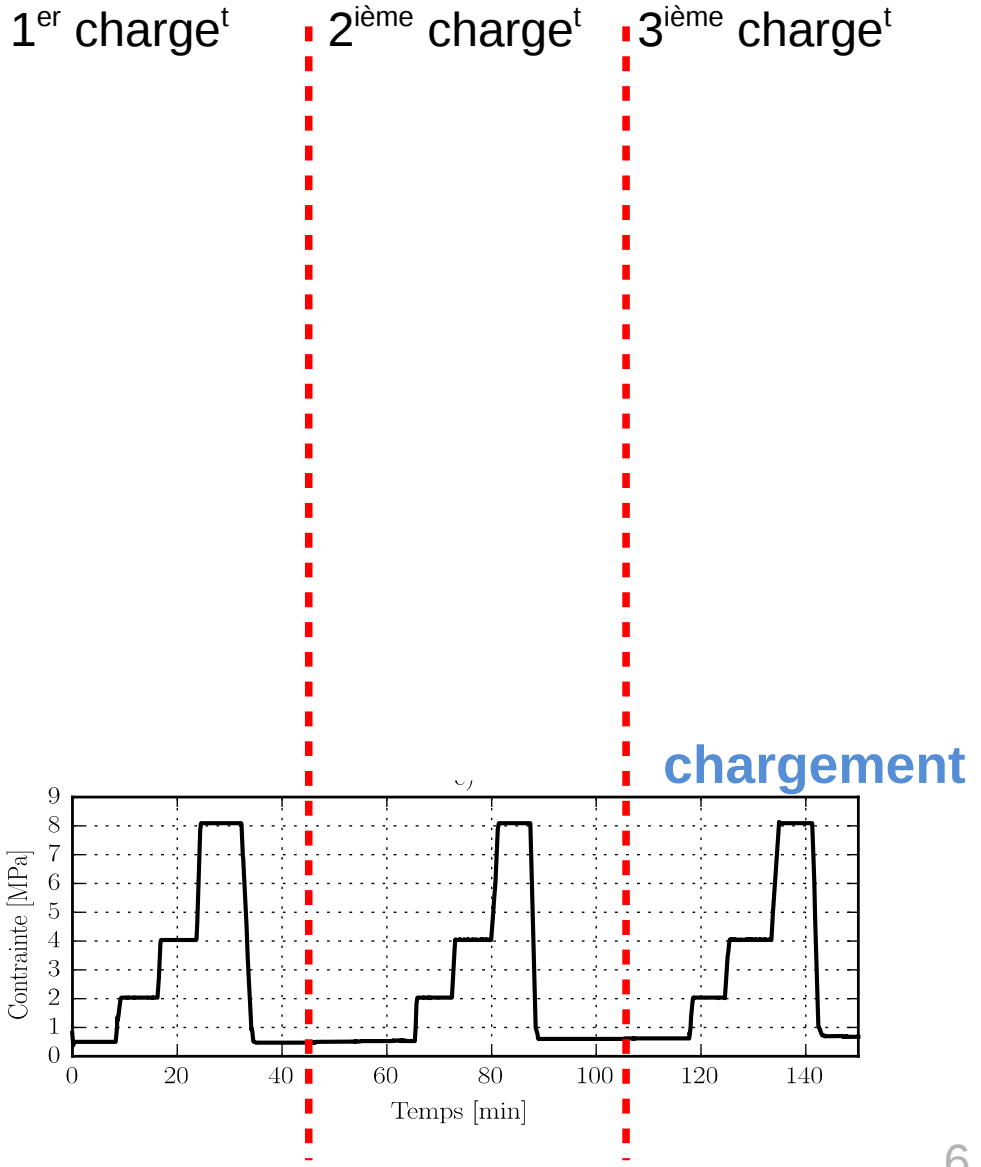
- velocity variation θ = **Δv/v**
- remnant decorrelation **Kd**

Coda waves interferometry: CWI



Coda waves interferometry: CWI





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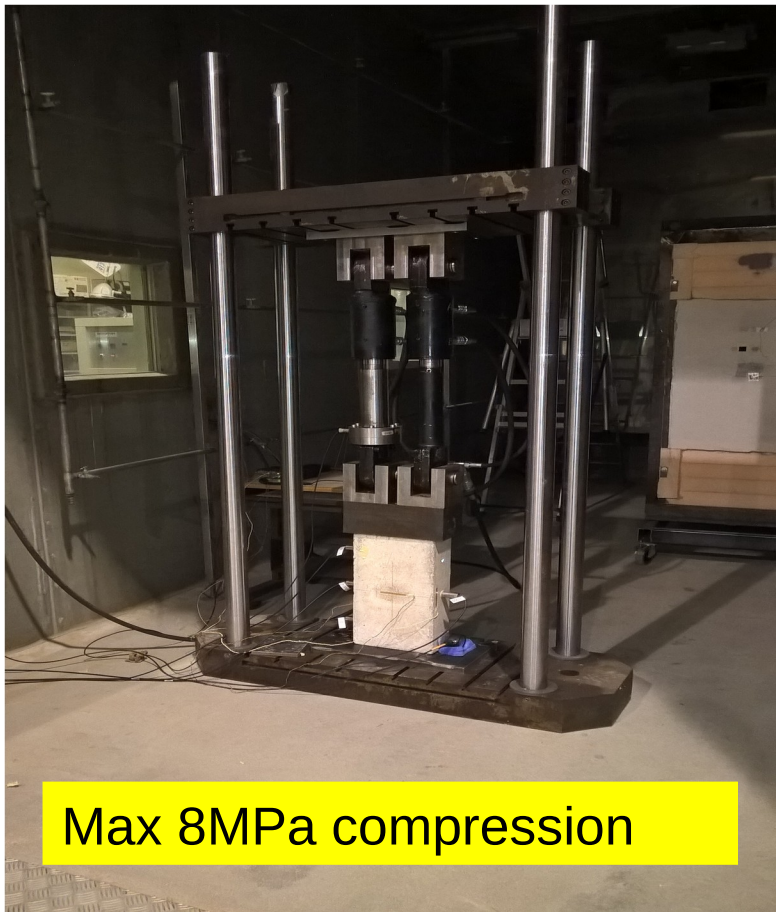


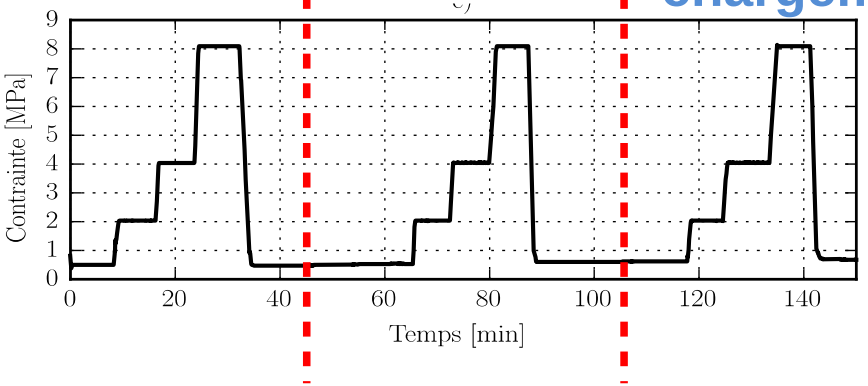
1er chargeᵗ | 2ième chargeᵗ | 3ième chargeᵗ

coda (CWI)

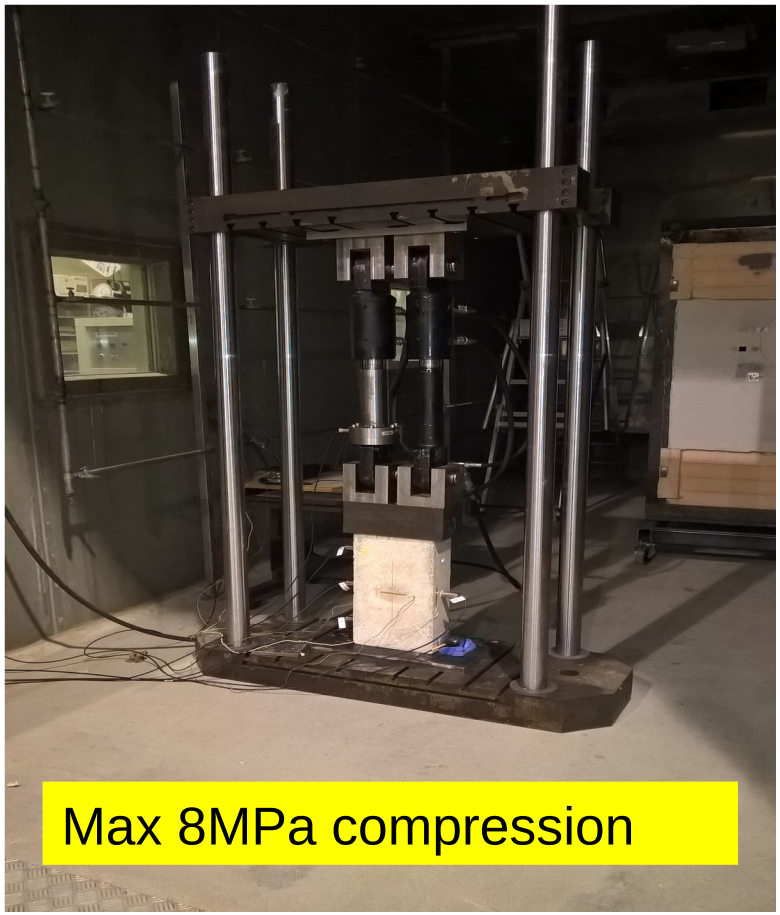
état 0 : 1er signal

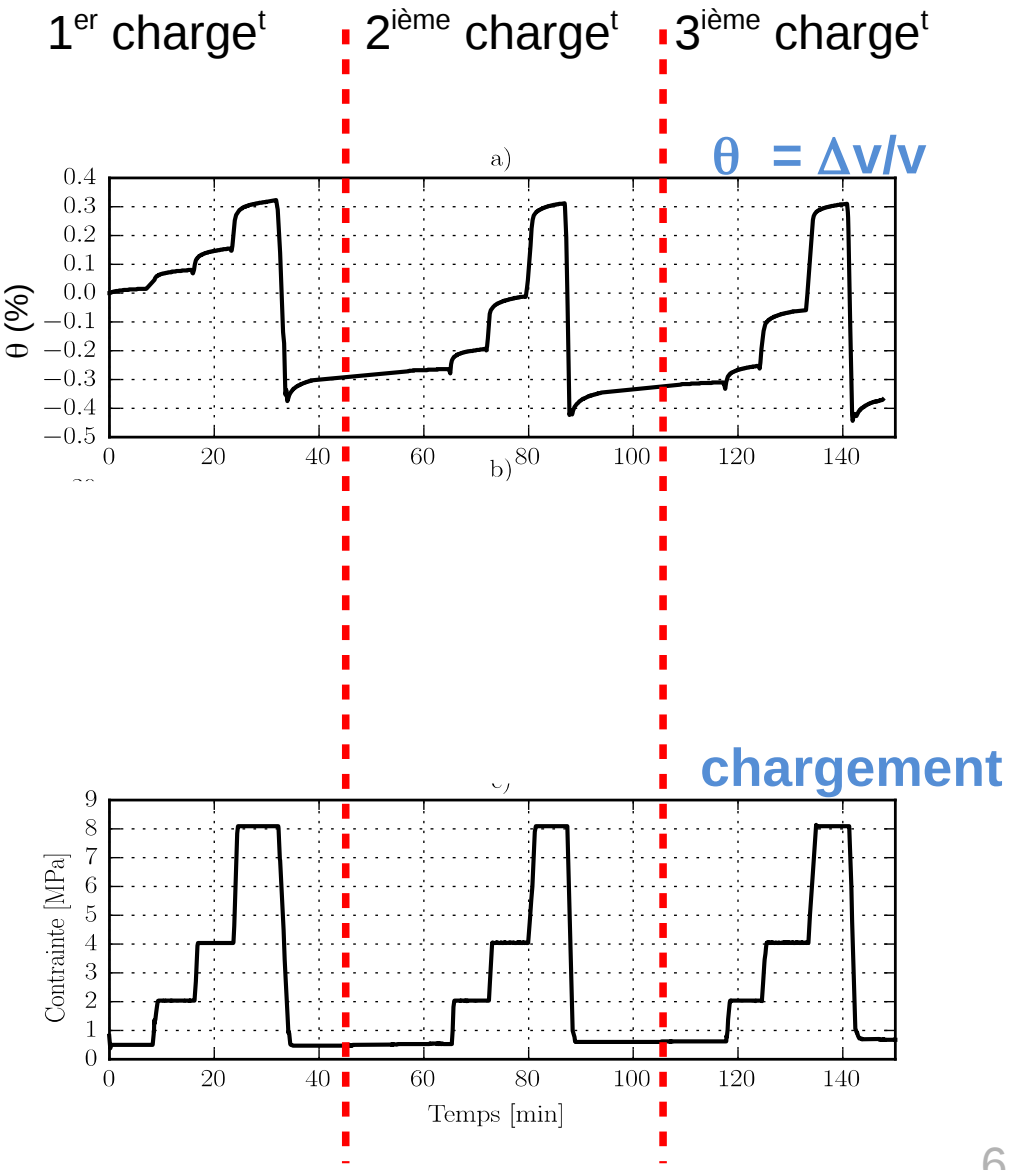
état 1 (i) : sous charge

chargement

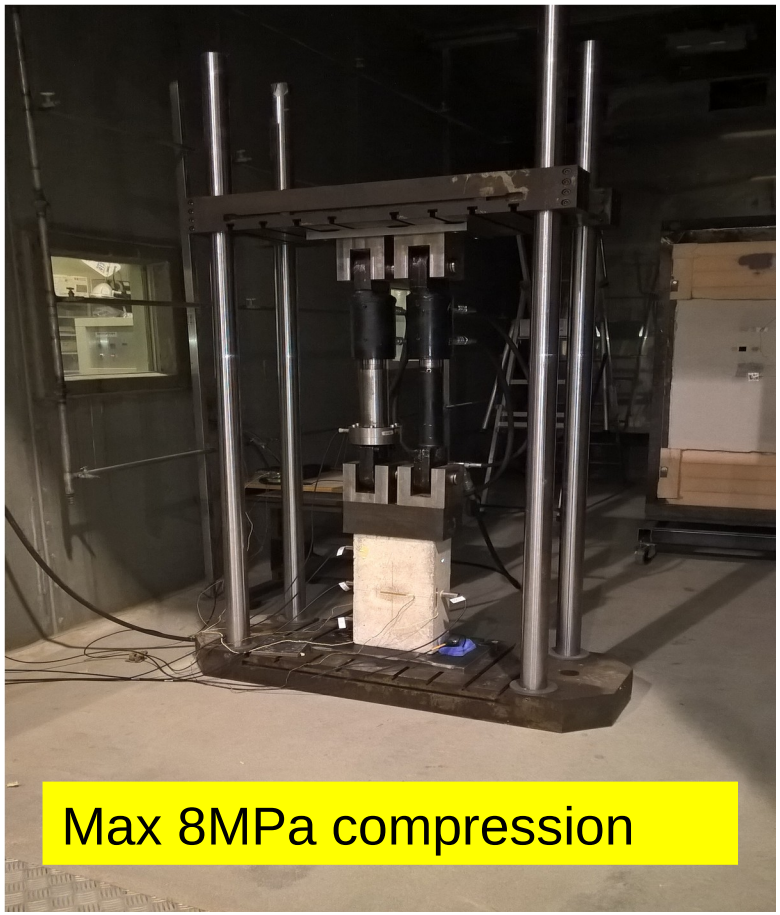


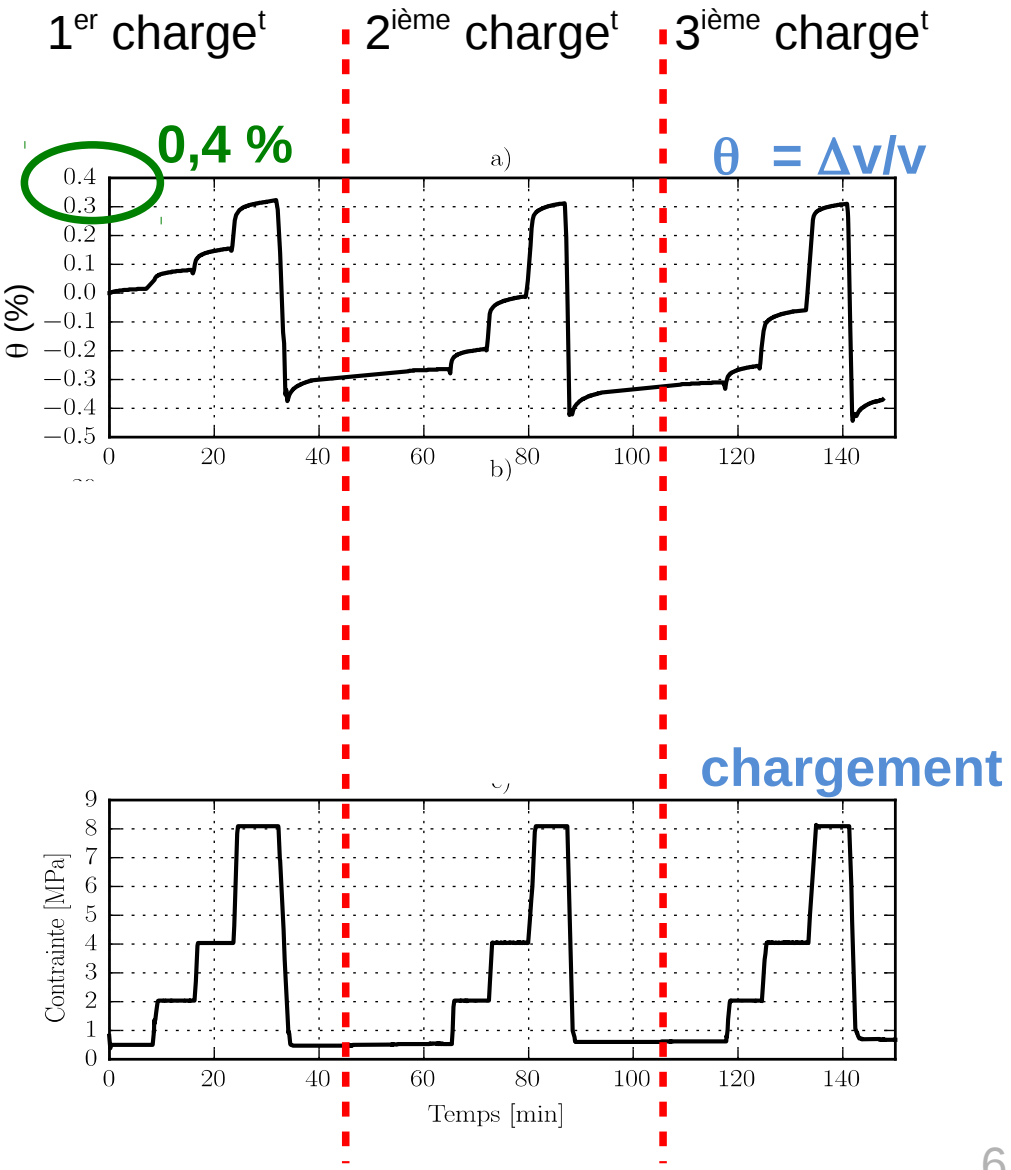
Coda waves interferometry: CWI



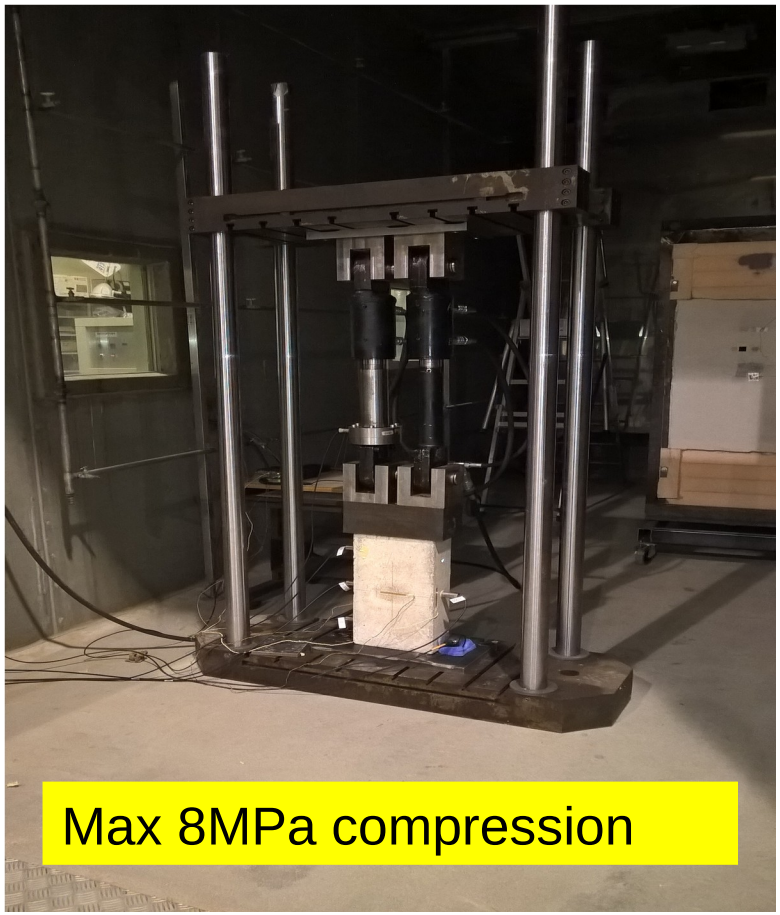


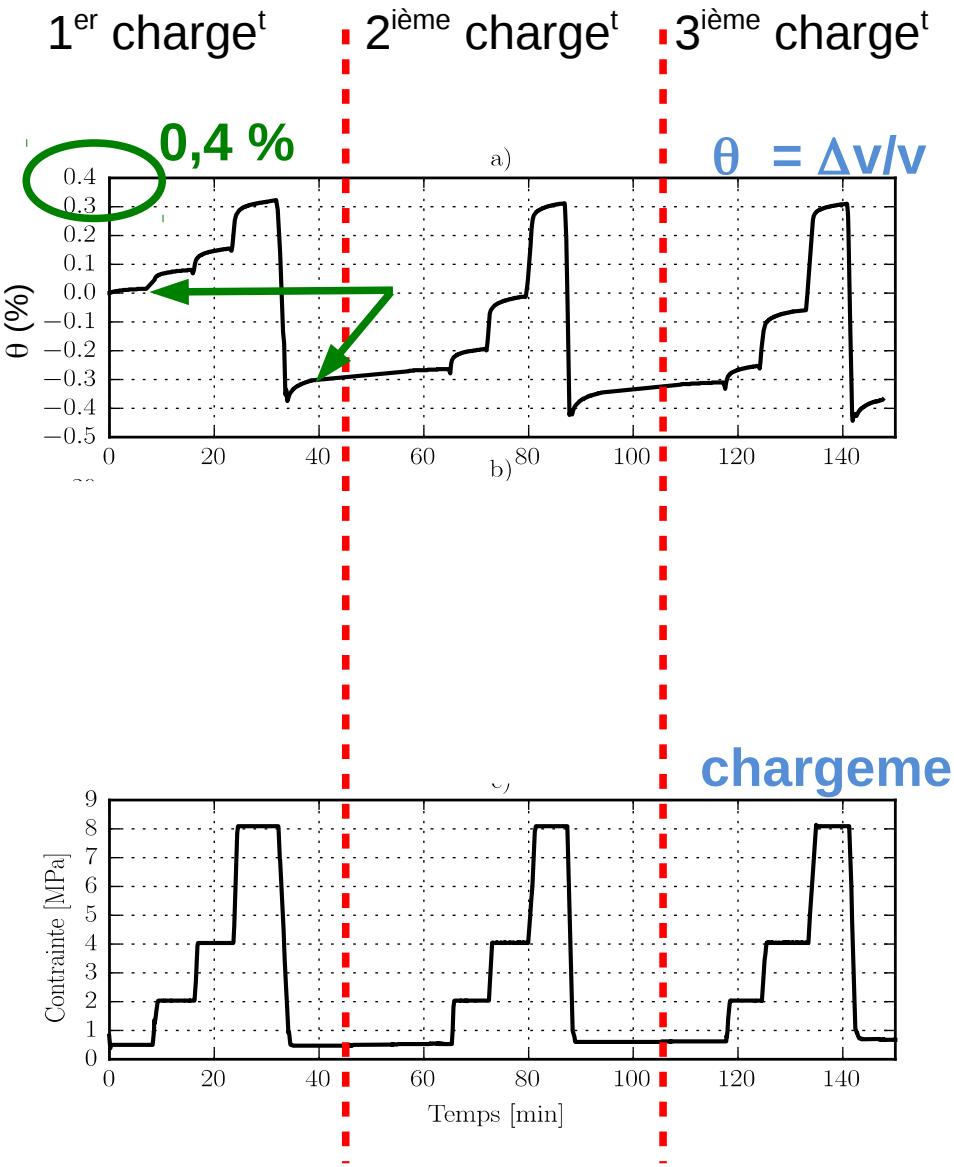
Coda waves interferometry: CWI



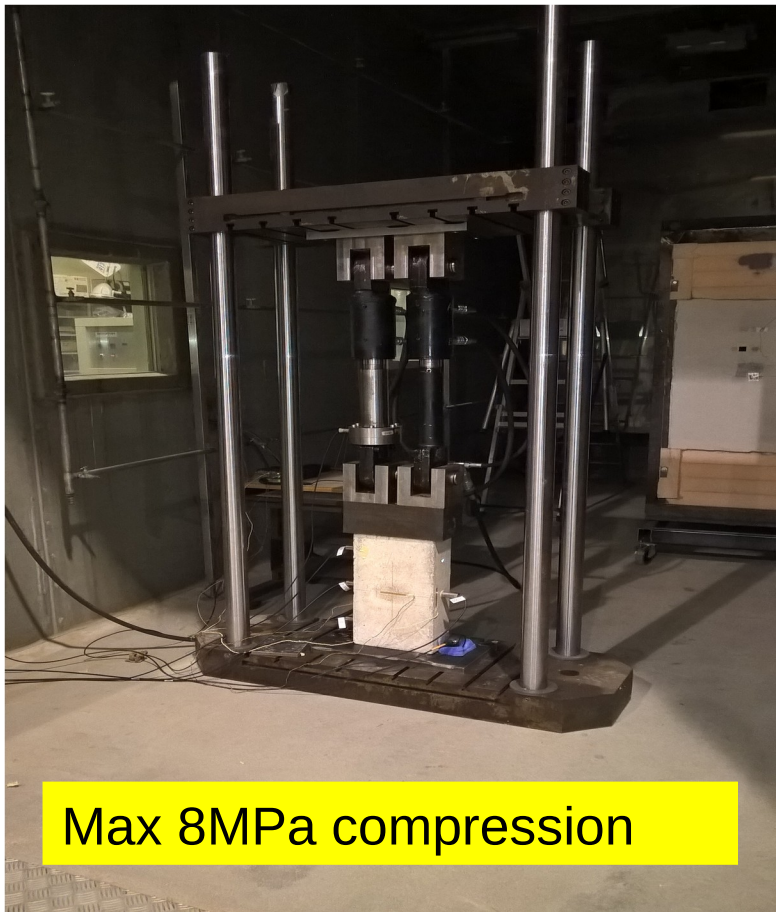


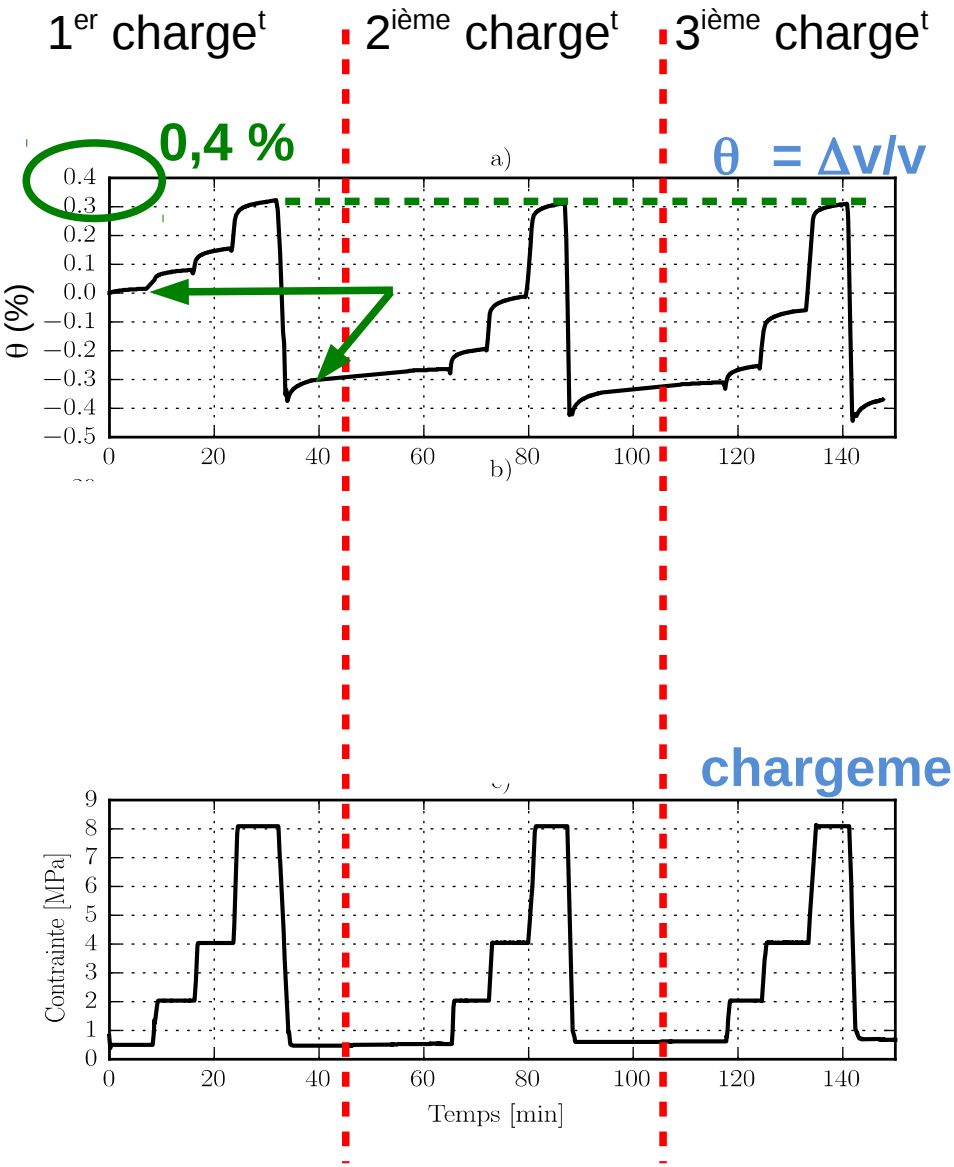
Coda waves interferometry: CWI





Coda waves interferometry: CWI

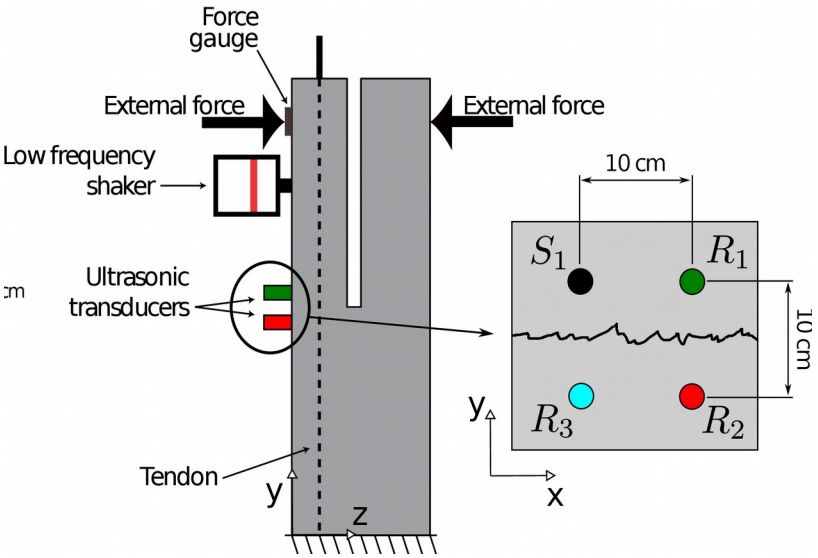


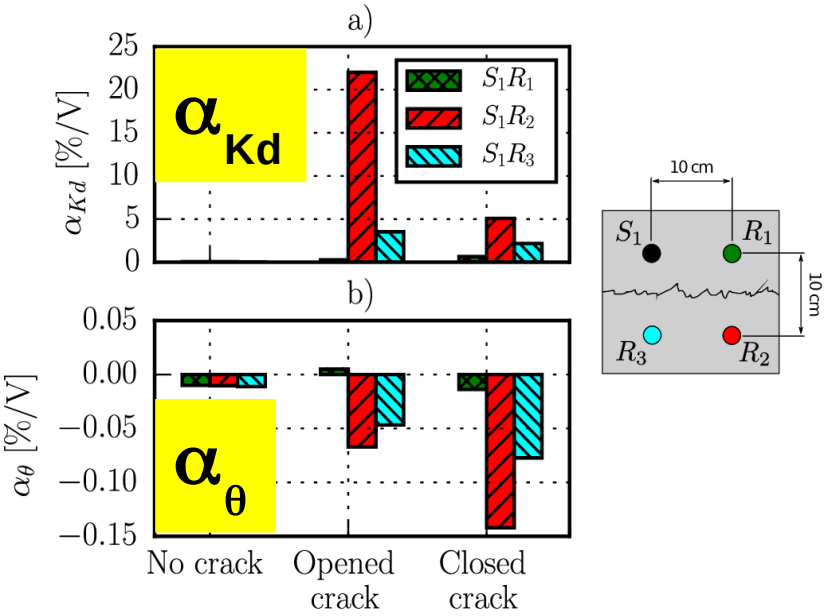


Nonlinear Coda waves interferometry: NCWI

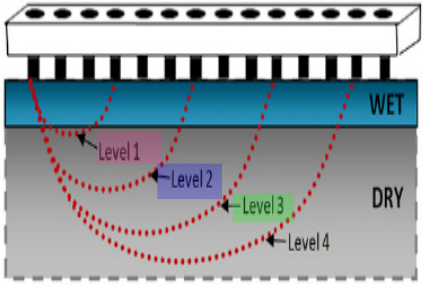
Closed crack

Pre-stressed concrete

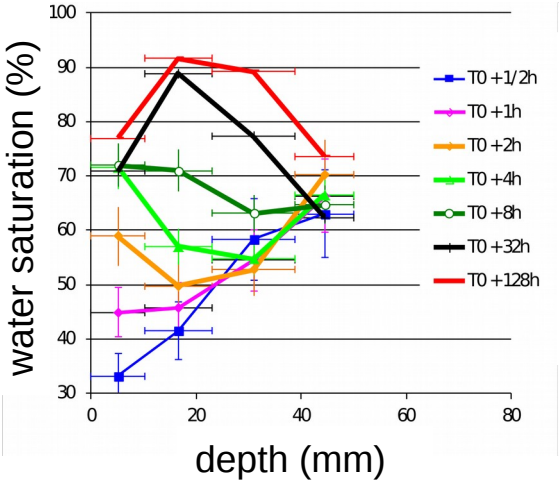


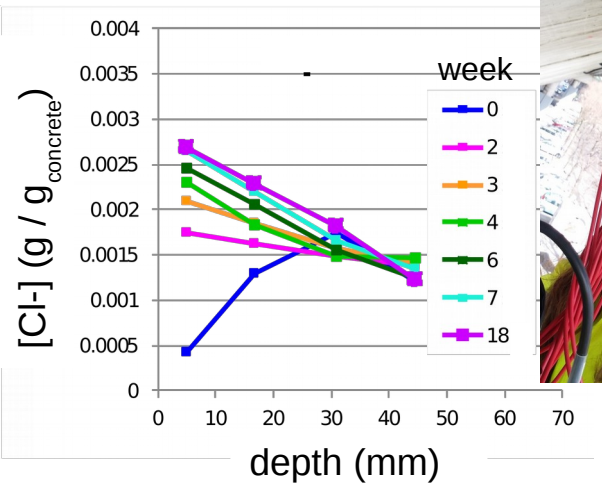


Embedded sensors - resistivity



Water and chloride profiles (including monitoring) → calibration + 1D inversion





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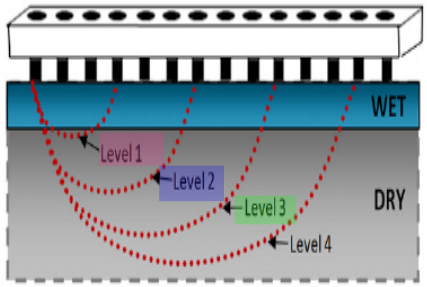
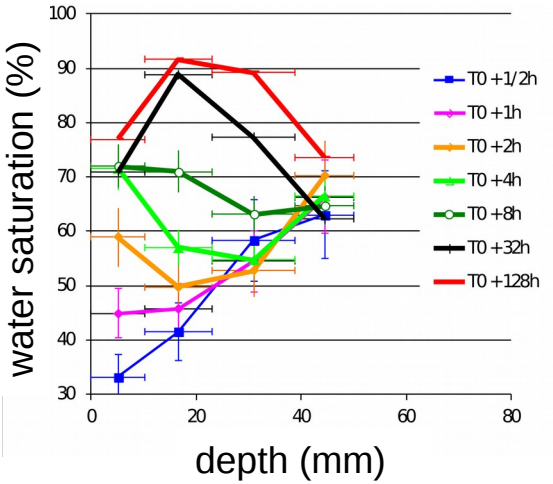
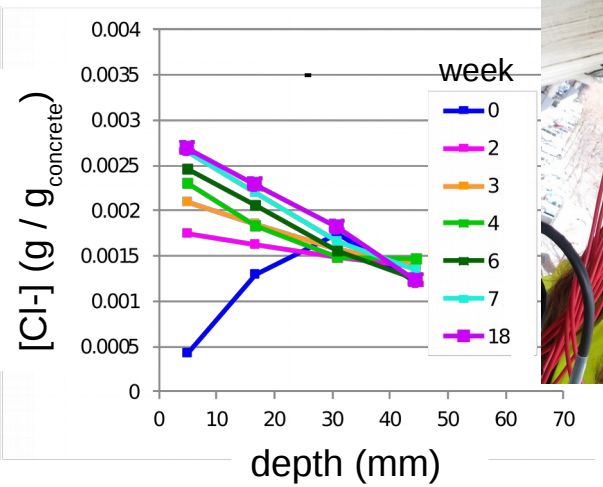
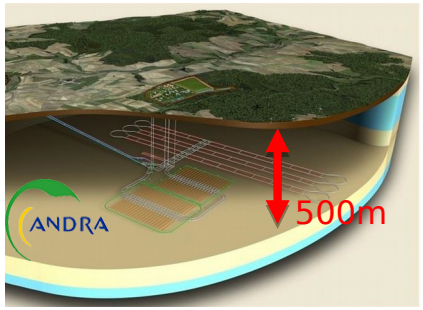
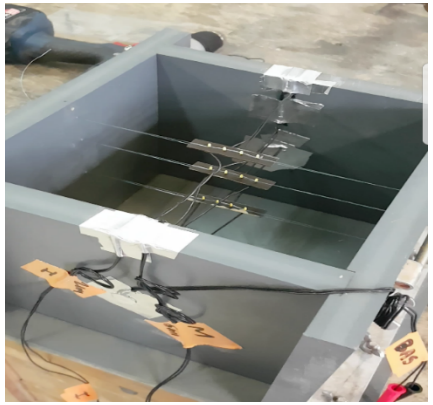
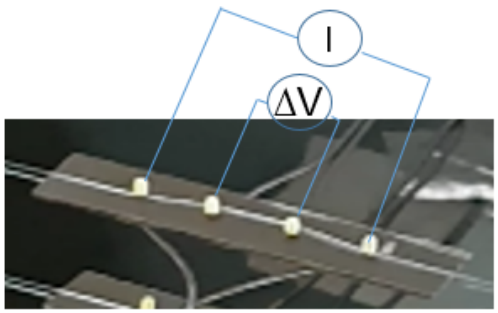




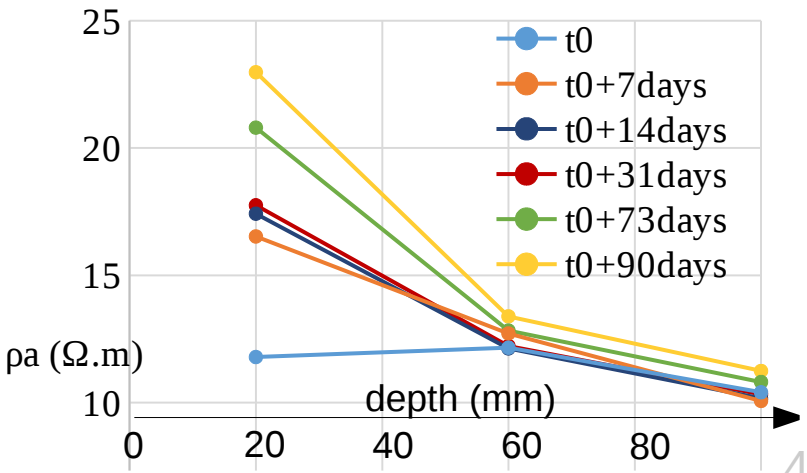




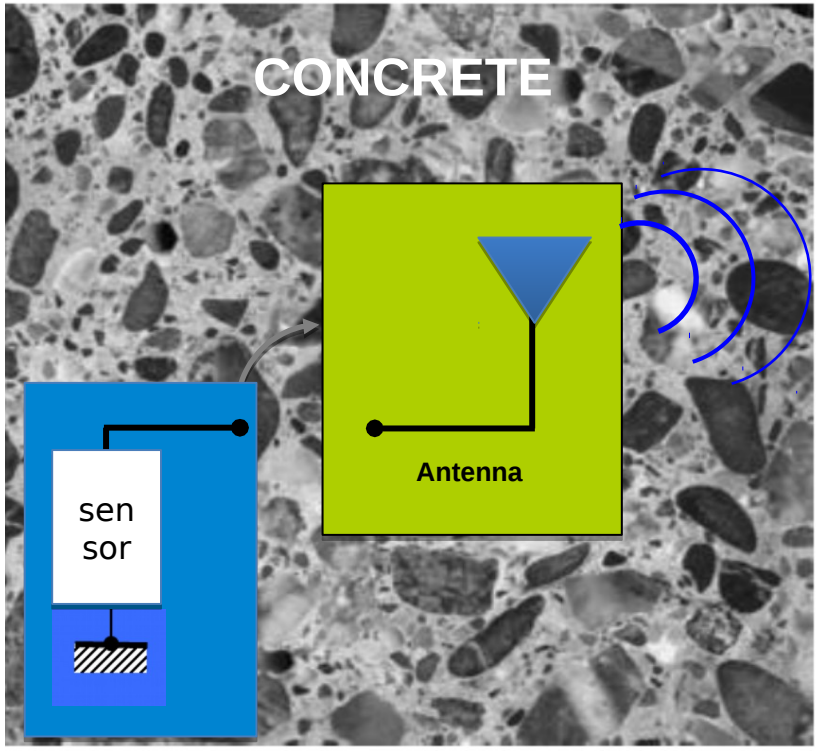




Design based on numerical modeling



Embedded sensors – electromagnetic HF



Antenna: not sensitive to concrete state (no frequency shift)

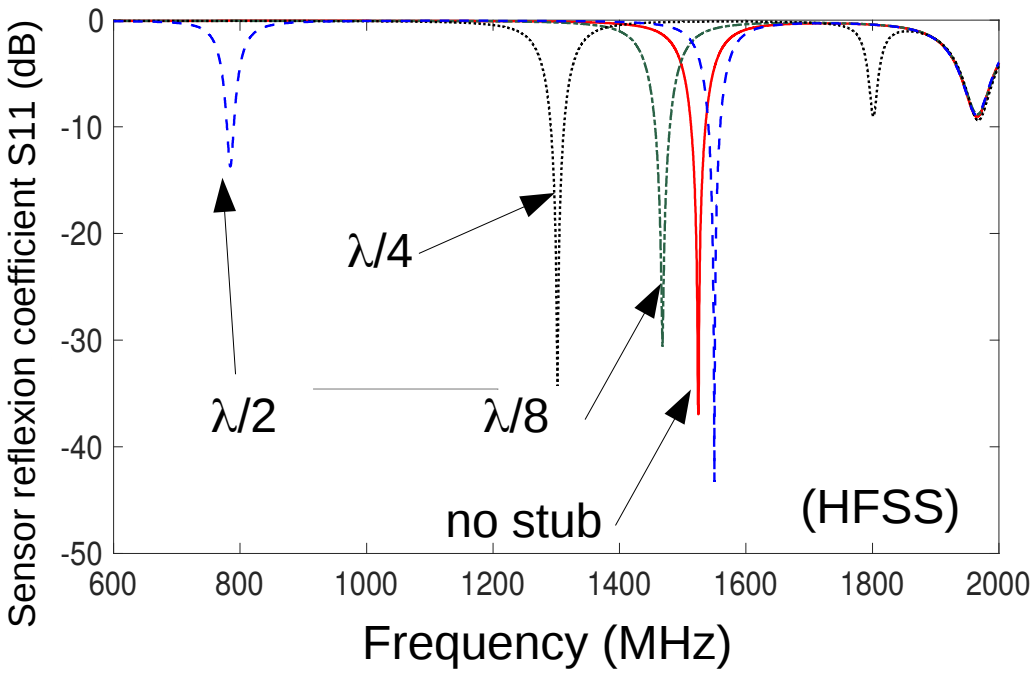
Passive stub: sensitive to chloride ingress (sacrificial stub)

Low cost

Emission from outside, reflexion from the sensor (antenna + stub)

Embedded sensor = (antenna + passive stub)

Embedded sensors – electromagnetic HF



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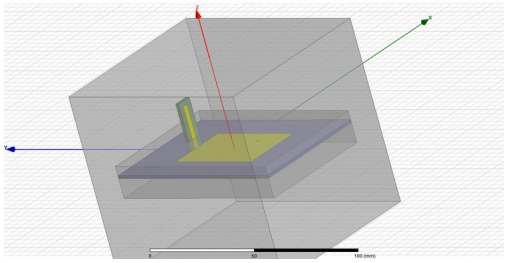
Low cost

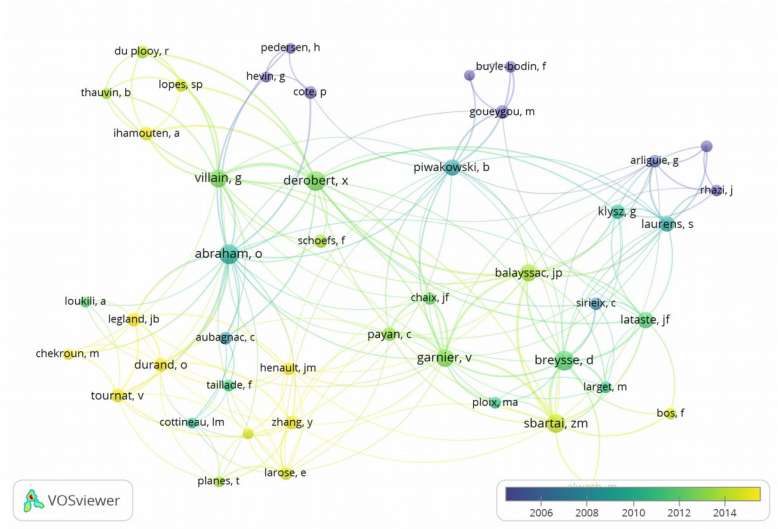
Emission from outside, reflexion from the sensor (antenna + stub)

Embedded sensor = (antenna + passive stub)
Antenna 3 to 5 cm below the surface



An many many more from all the other laboratories!

French research laboratories involved in concrete NDT



Conclusions

- **Quantitative evaluation of concrete properties**
  - Driving force to increase new NDT methods TRL
  - Requires combination/fusion of NDT observables
  - Raise the issue of investigation depth, gradients, ...
  - Requires calibrations (cores, baseline, T0, ...)

- **Damage ↔ Cracks (micro, macro)**
  - Non linear acoustics
  - Diffuse waves

- **Increasing involvement of NDT researchers in monitoring**
  - Embedded sensors (em, resitivity, us ↔ optic fiber, …)
  - Scanners, robots, ...
  - Time lapse inversion

- Modeling
  - Numerical modeling
  - Physical modeling

- **Physics**

- **Imagery**
  - Inverse problem
  - FWI

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Thank you for your attention