Coda waves, Surface Waves, Fiber Optics... Some challenges and results about the monitoring of concrete structures with ultrasonic waves

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GÉOPHYSIQUE ET ÉVALUATION NON DESTRUCTIVE

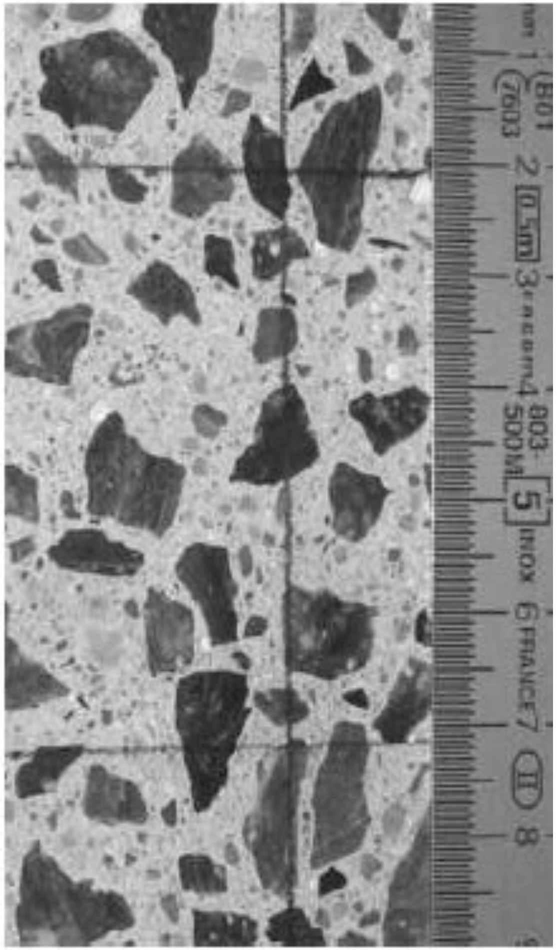
SPIN
MONITORING A RESTLESS EARTH

http://spin-itn.eu

Ludovic Bodet, Rabih Chammas, Mathieu Chekroun, Guangzhi Chen, Thibaud Devie, Olivier Durand, Jean-Baptiste Legland, Maximilien Lehujeur, Donatienne Leparoux, Vincent Métais, Pierric Mora, Shilin Qu, Géraldine Villain, Yuxiang Zhang
Jean-Paul Balayssac, Jean-François Chaix, Vincent Garnier, Benoit Hilloulin, Vincent Tournat, ...

CONTEXT/France Non Destructive Testing (NDE) of concrete

Research has been "recently" focused on
reinforced concrete
with the aim to recover **quantitative information**
on the **material properties**

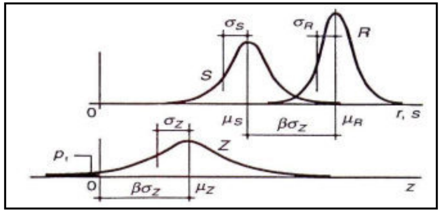


CONTEXT/France Non Destructive Testing (NDE) of concrete

NDE 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/France Non Destructive Testing (NDE) of concrete

But… Concrete properties have conjugated effects on NDTEs

→ 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 NDE methods are sensitive to these properties but the relationships between them are not direct

Both mean values and variability are necessary to assess

CONTEXT/France   Non Destructive Testing (NDE) of concrete

NDE methods development
(adaptation, improvement; use of new paradigms)

↕

Qualification of NDE methods
(quality, relevance vs each concrete property)

↓

Methodology of fusion and combination
(taking in consideration the variability of NDTs)

↓

Transfer of the methodology in situ
(optimisation, calibration)

NDE methods involved

surface


radar


capacitive


resistivity


permeability


surface wave dry coupling


surface wave
air coupling


diffuse wave
DAET, ATME


TREND

NDE methods involved

surface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permeability


surface wave dry coupling


surface wave air coupling

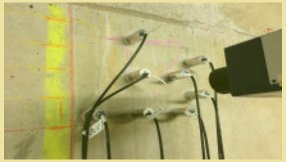

diffuse wave DAET, ATME


TREND

ultrasonic transmission


ultrasonic pulse echo


impact echo


(Nonlinear) coda wave interferometry

volume

acoustics

NDE methods involved

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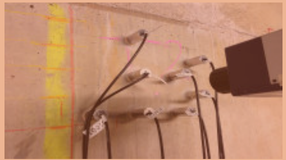


(Nonlinear) coda wave interferometry

acoustics

Low TRL

Outline

- Recovering some concrete material properties
    - fusion
- Focus on Surface Waves (NDE/SHM)
    - cover concrete
    - increasing TRL
- Focus on Coda Waves
    - monitoring
    - non linear
- Fibers Optics at ultrasonics frequency
    - project startings

Recovering some concrete material properties

Laboratory benchmarks are designed for controlling concrete properties

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

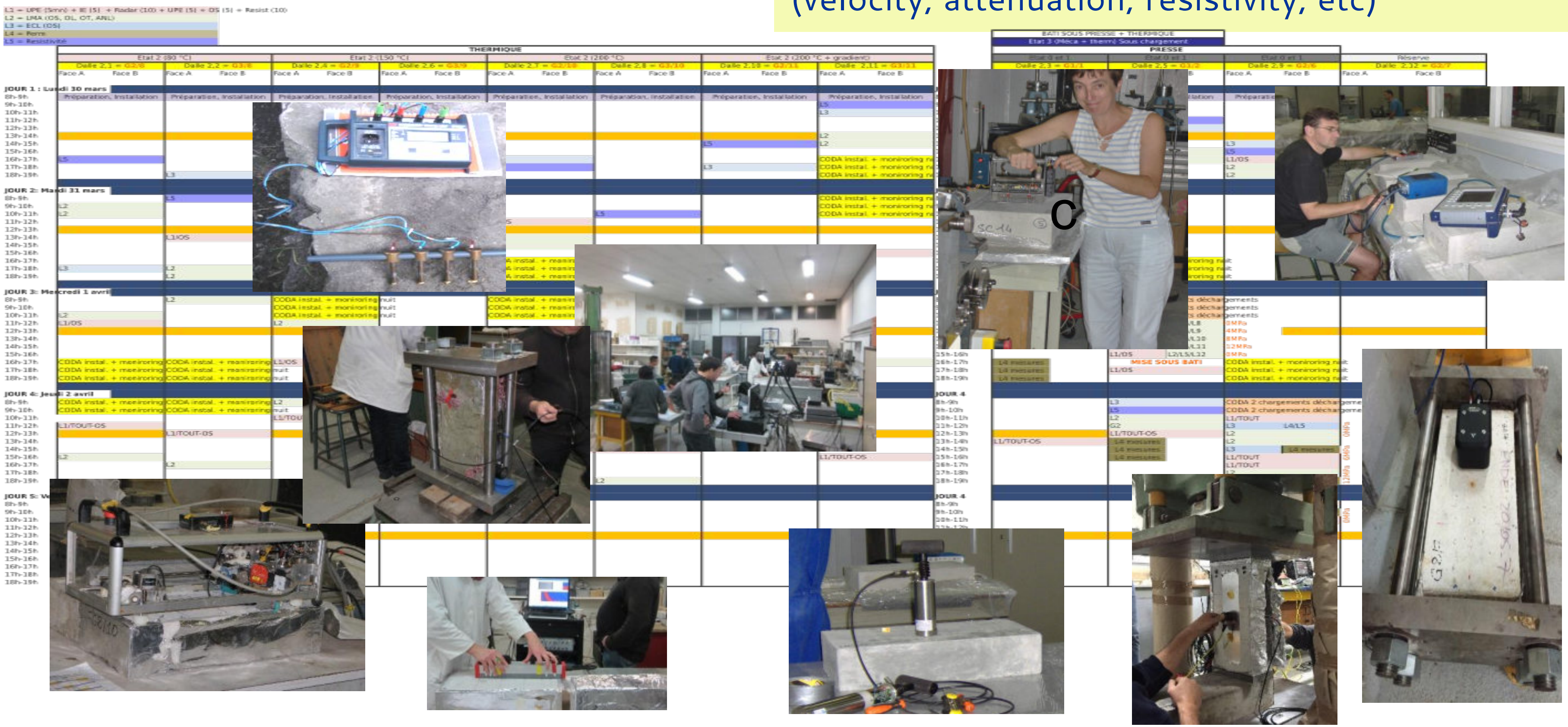
Concrete slab size:
50 cm x 25 cm x 12 cm

Recovering some concrete material properties

All the NDE measurements are performed at the same time

→

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



Recovering some concrete material properties

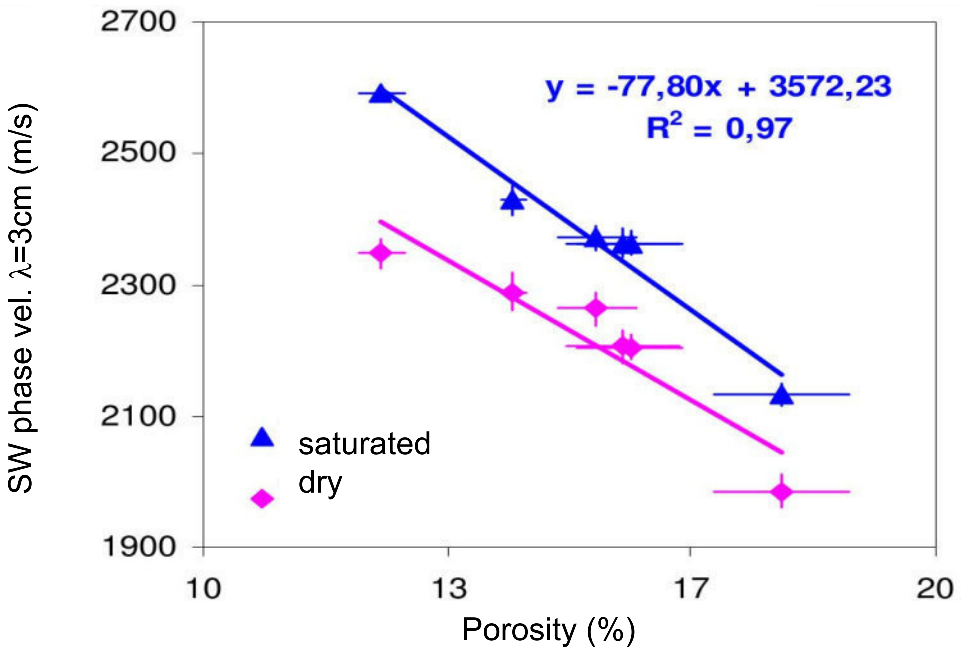
Variance of NDE observables is quantified at different scales

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

NDE observables/features vs concrete properties

But… Concrete properties have conjugated effects on NDTs

→ How to separate these effects?



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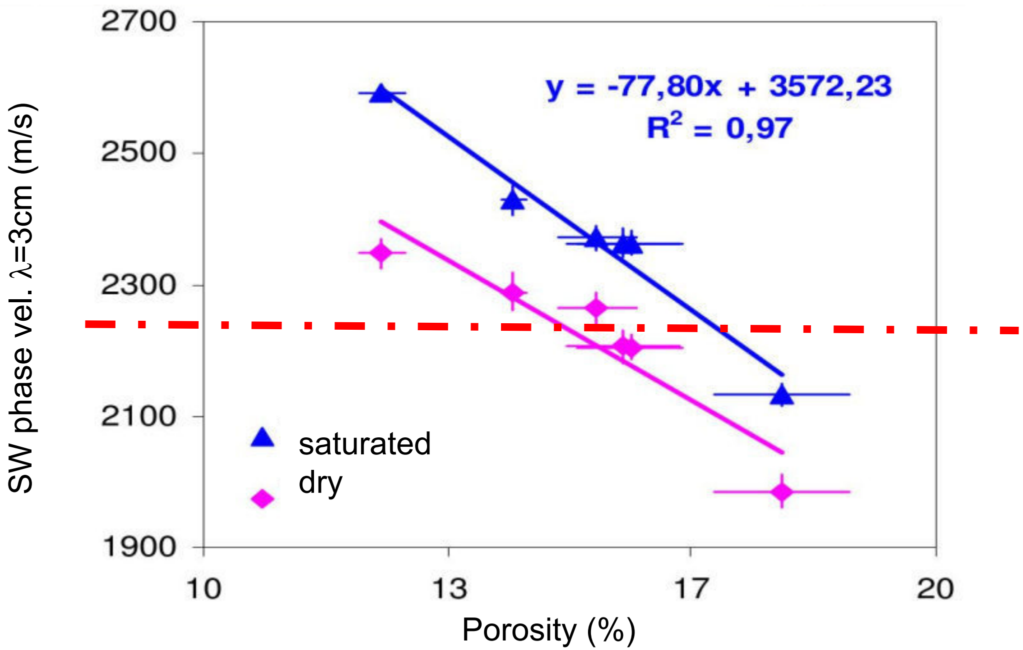

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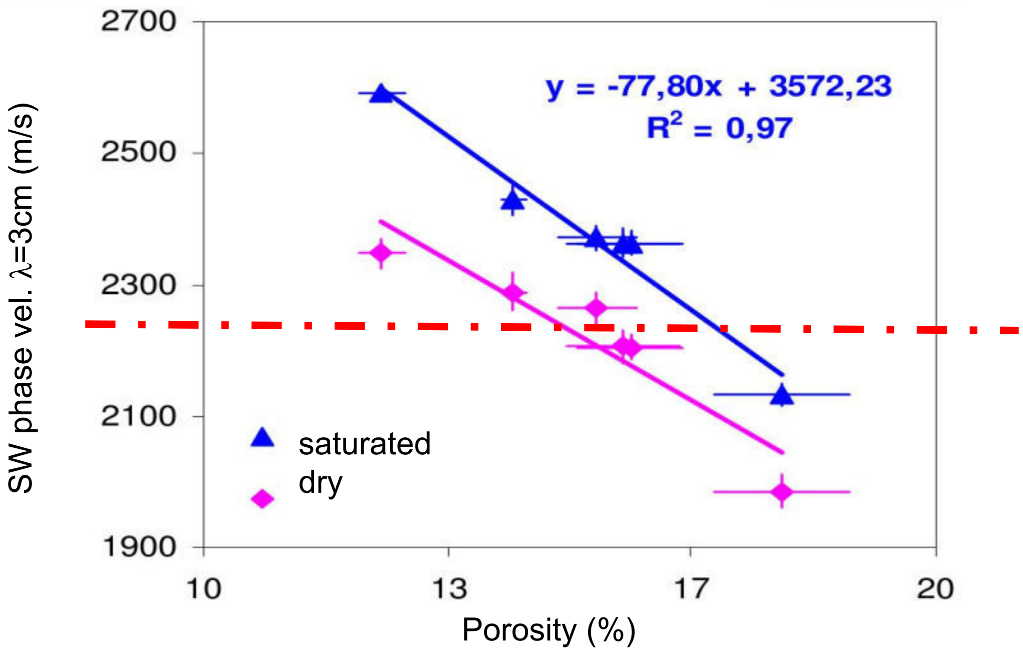

Linear regression models between NDT observables (Obs) and two concrete properties (cp_1 and cp_2)

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

NDE observables/features vs concrete properties

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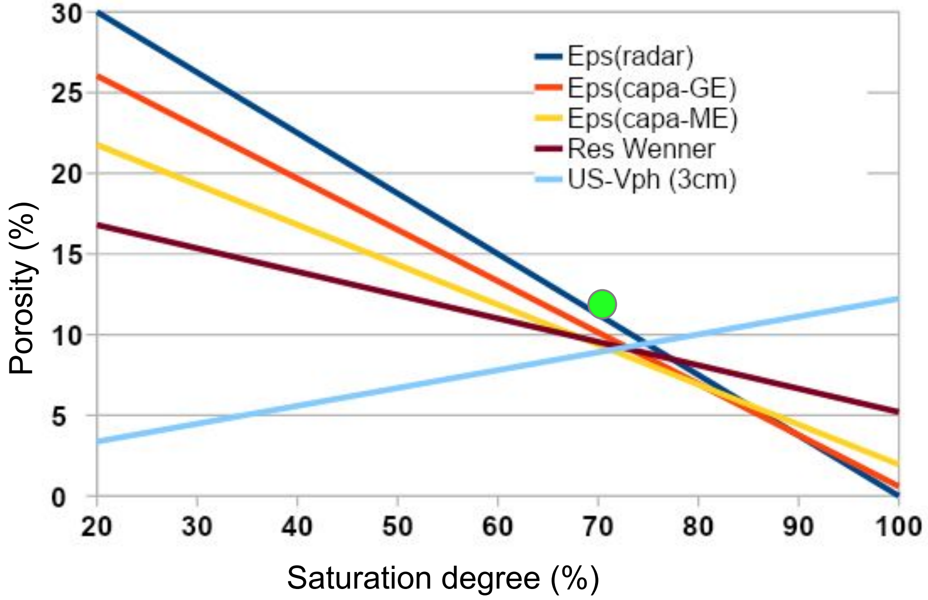
→ How to separate these effects?

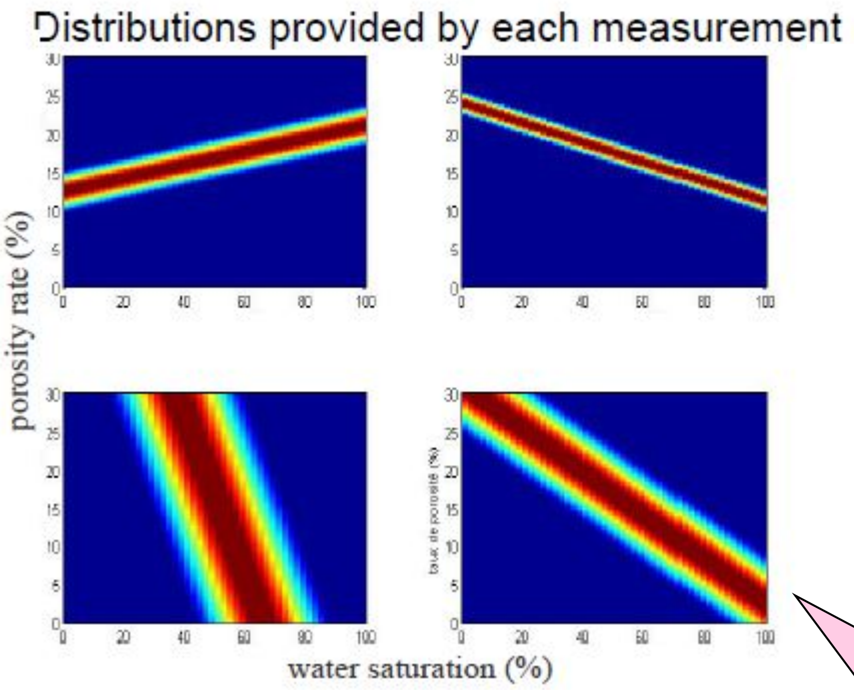
laboratory experiments



Combination of techniques

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

NDE observables/features vs concrete properties



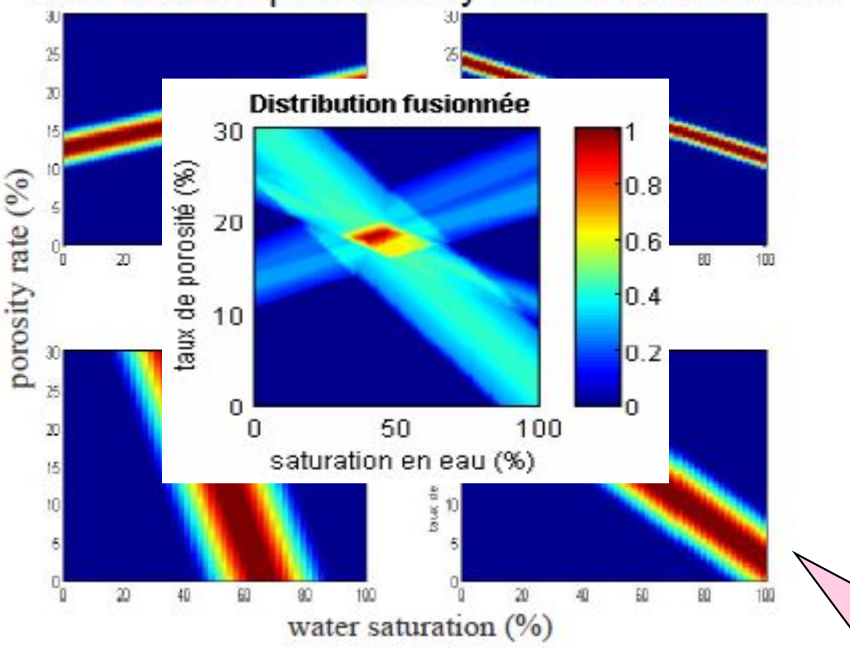
General aim (data fusion):

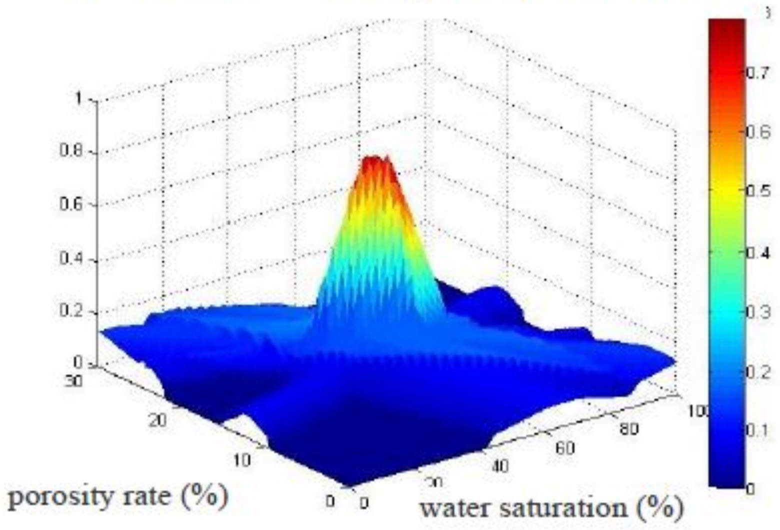
- to collect and combine information from different sources to provide more precise and reliable information
- to deal with uncertain and imprecise data

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

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

NDE observables/features vs concrete properties





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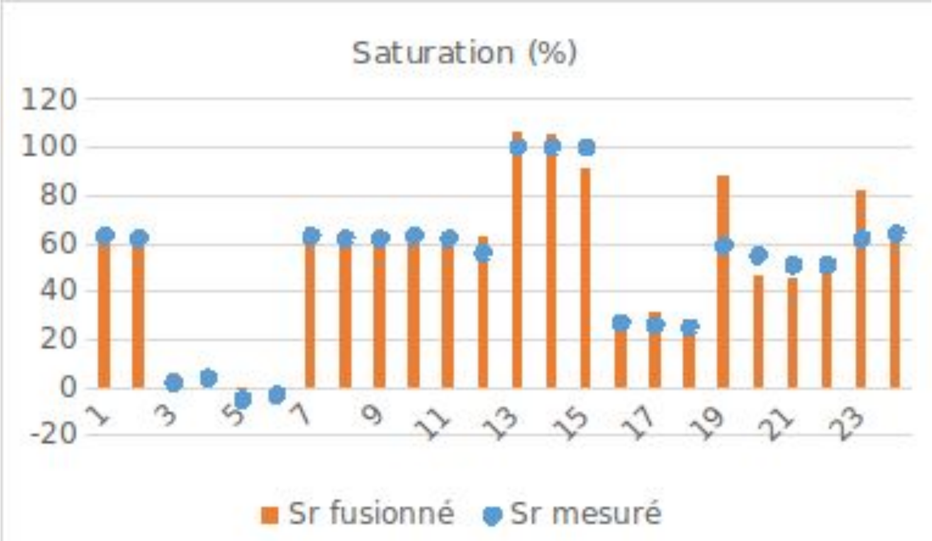
NDE observables/features vs concrete properties



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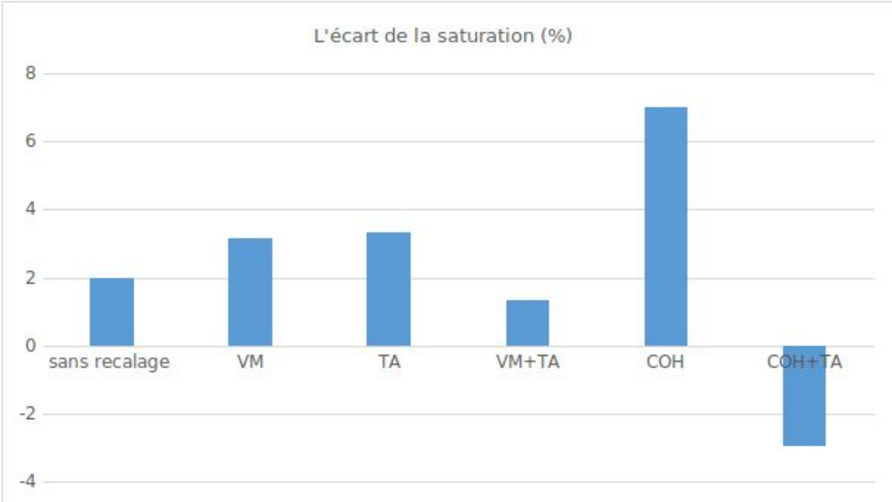
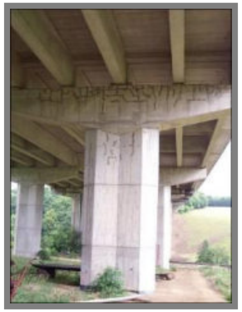


NDE observables/features vs concrete properties



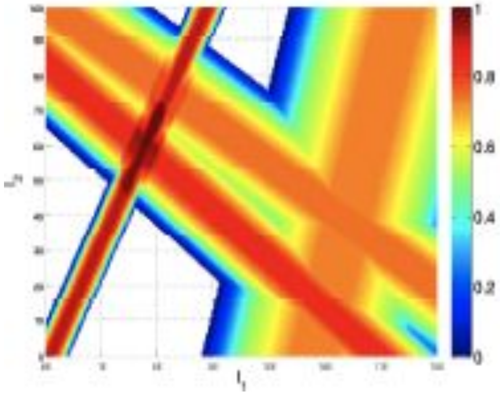
Chemistry

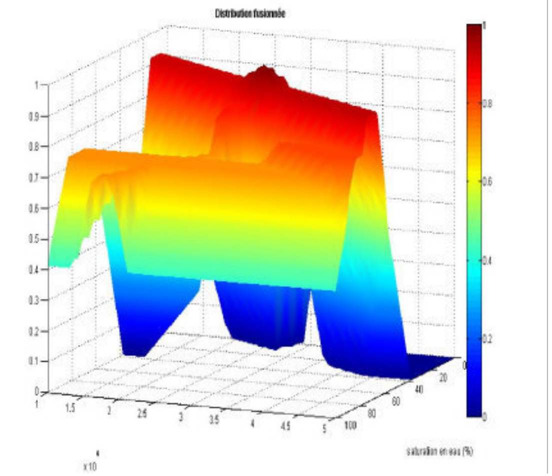
Mechanics

Composition

Environment

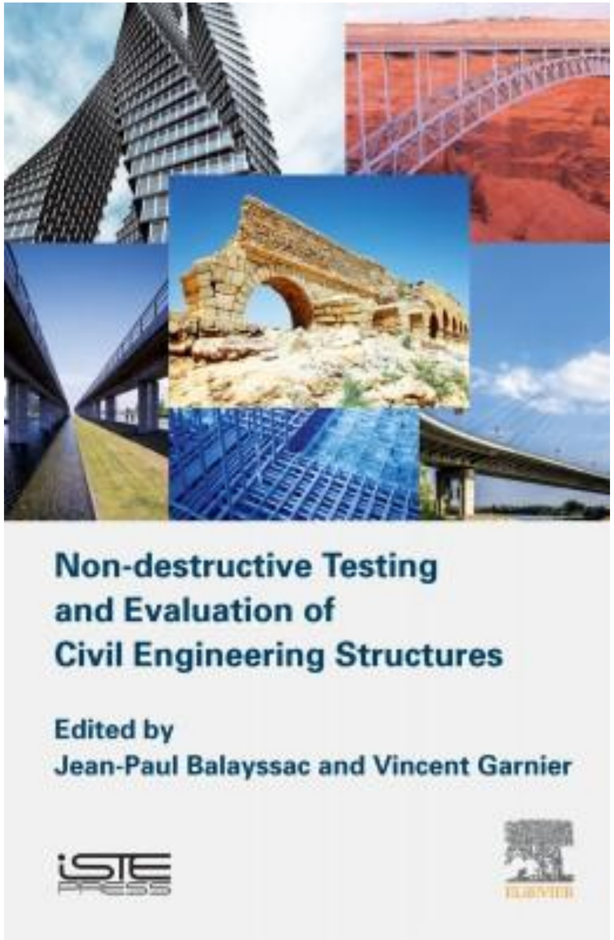
History





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

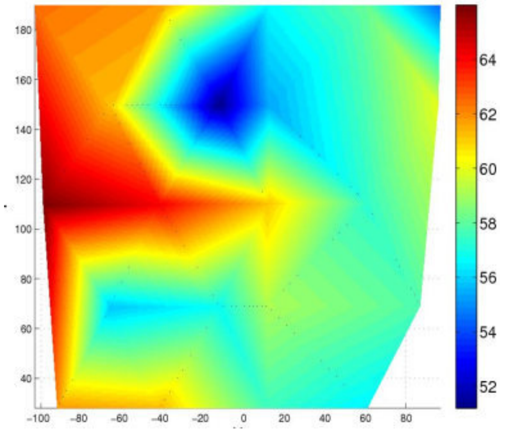
NDE observables/features vs concrete properties



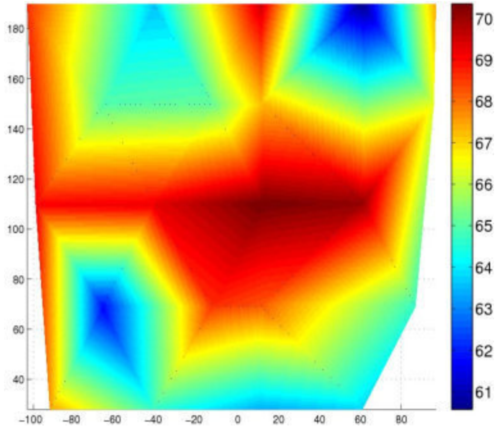
Methods:

US Velocity – Capacity

Impact Echo – Radar



Degree of saturation (%)



Compressive strength (MPa)

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  - fusion
- **Focus on Surface Waves (NDE/SHM)**
  - cover concrete
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  - monitoring
  - non linear
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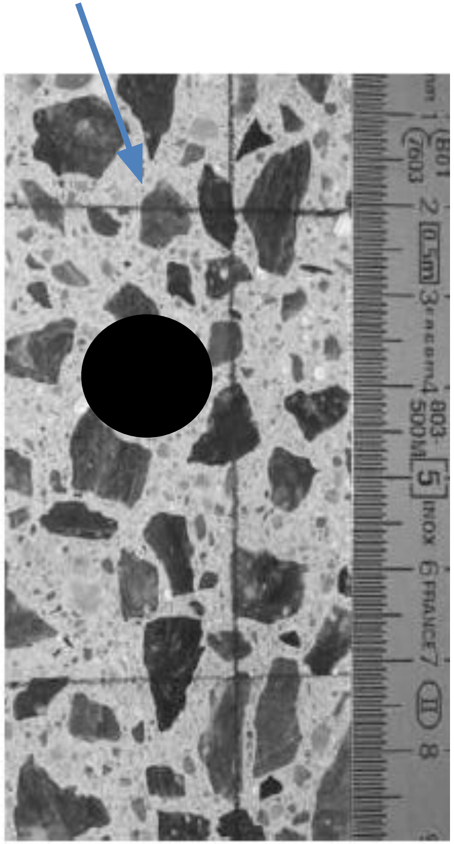
  - project startings

Focus on ultrasonic Surface Waves

CONTEXT: Cover concrete



Focus on ultrasonic Surface Waves

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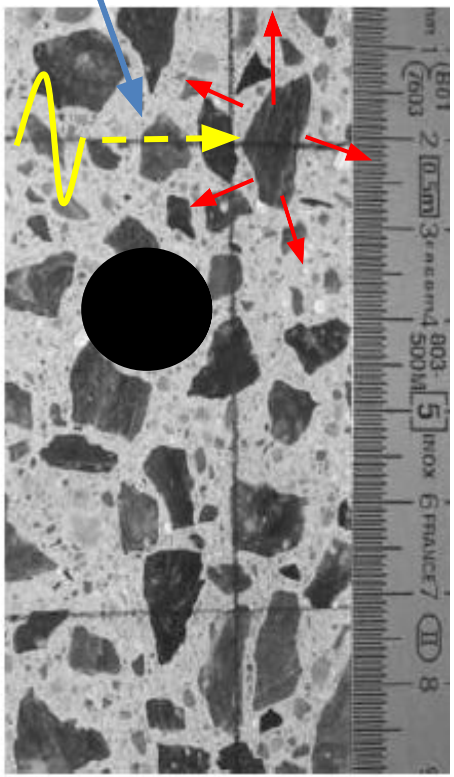
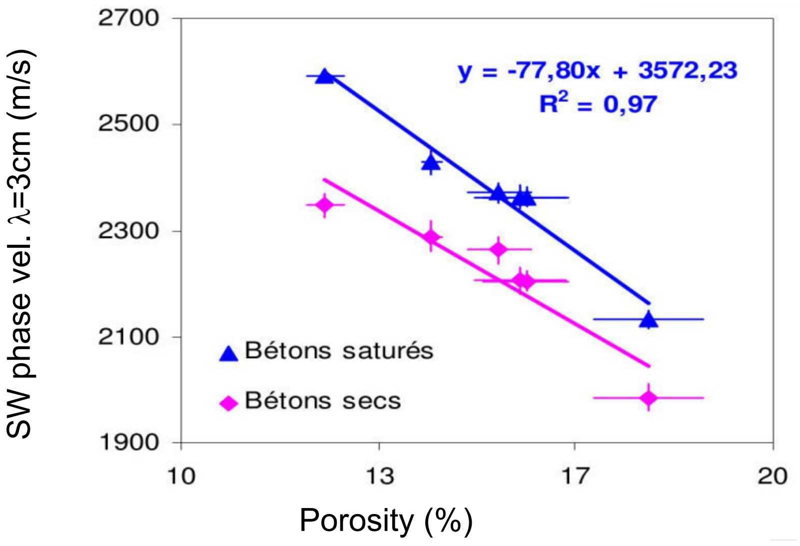


Investigation depth:
~3-5 cm
Depth resolution:
0,5 - 1 cm
Largest aggregate size:
~2-3 cm

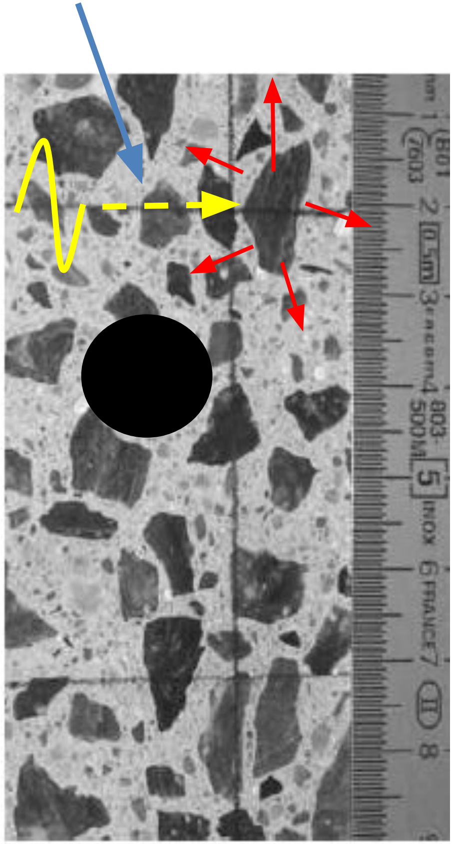


Can scattering be neglected ?

AIM: reach a precision of "0,5" on the estimated concrete porosity (expressed in %) thanks to SW phase velocity

Focus on ultrasonic Surface Waves

CONTEXT: Cover concrete

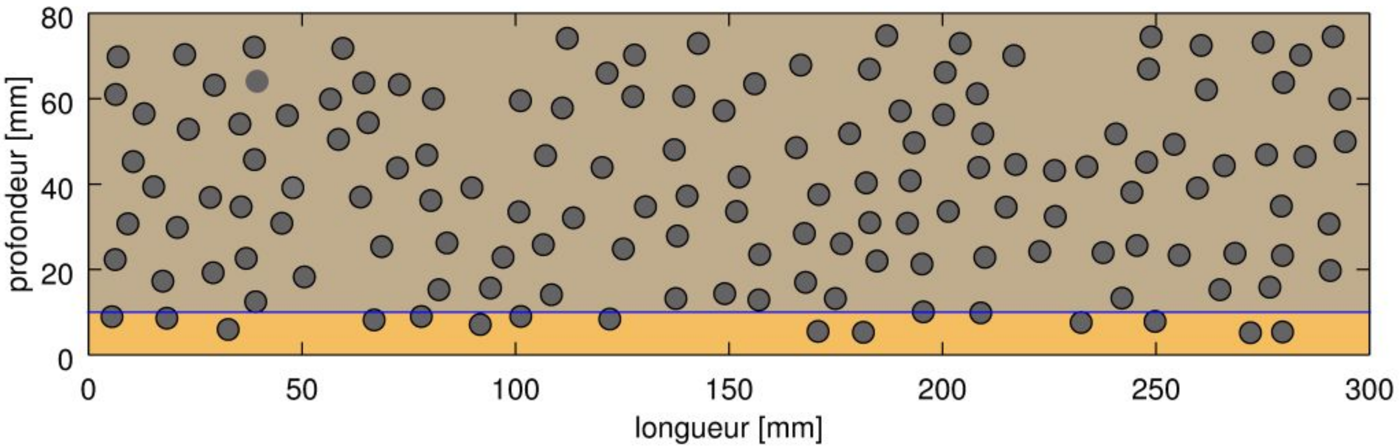


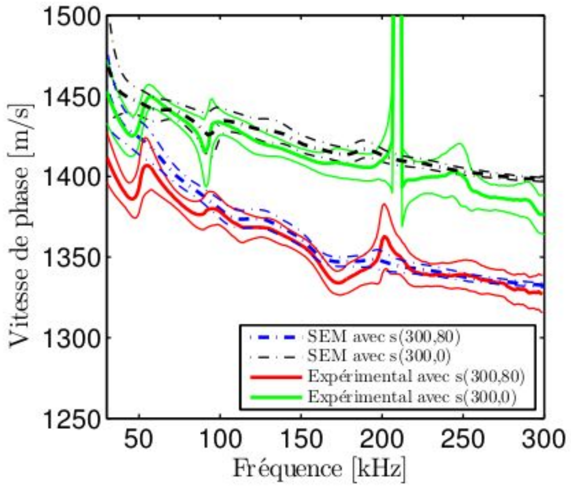
SEM2D
Y. Capdeville

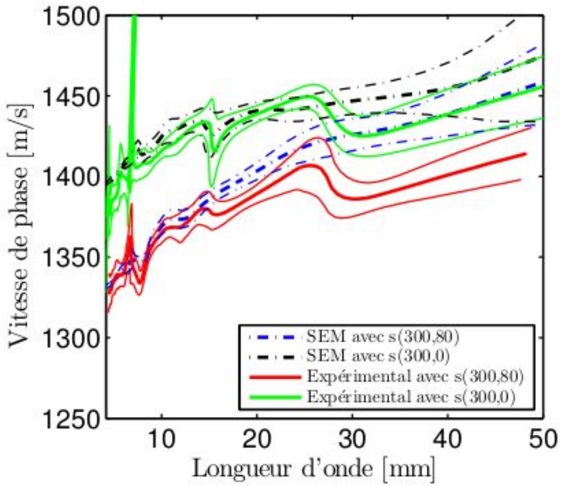
LPG

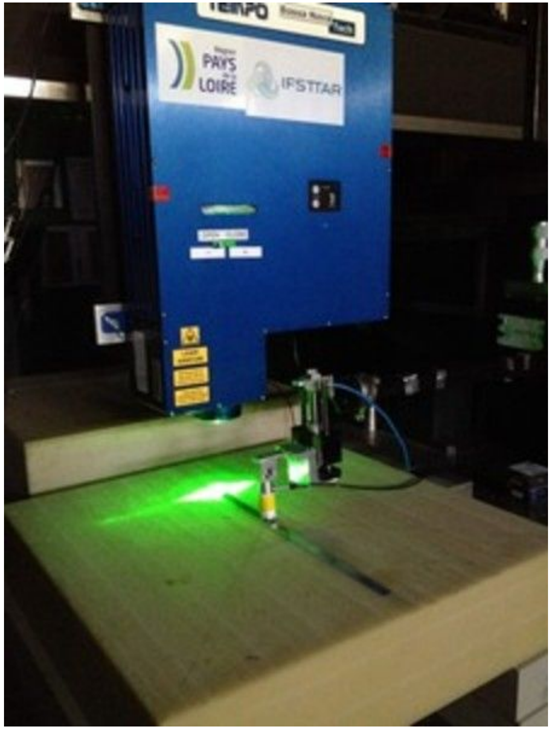
Can we used for each layer homogenized properties to compute the phase velocity dispersion curve ?

Focus on ultrasonic Surface Waves



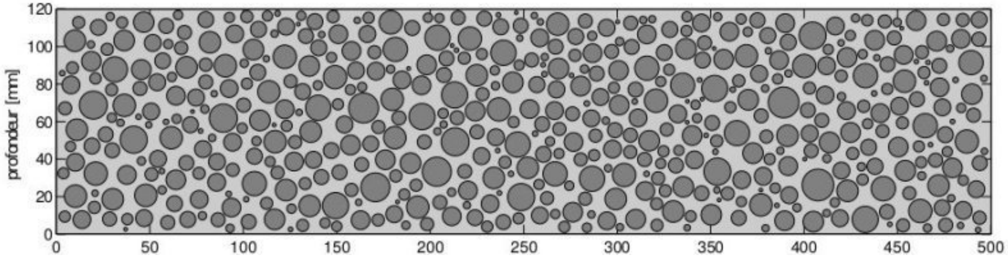


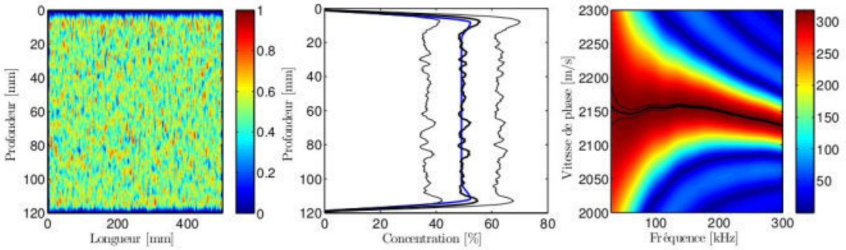




Coherent SW phase velocity dispersion curve requires more than 20 disorders (for a concentration of 12%)

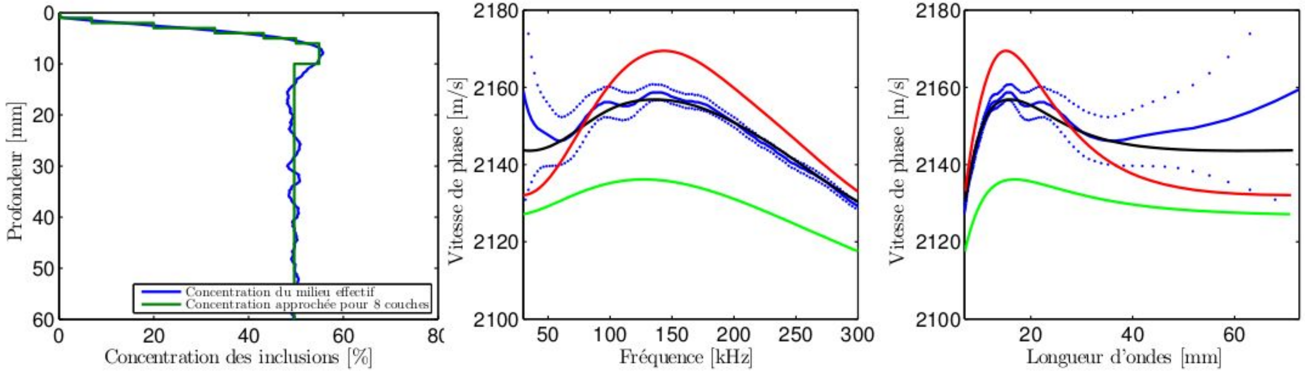
Focus on ultrasonic Surface Waves





17 disorders

8 layers

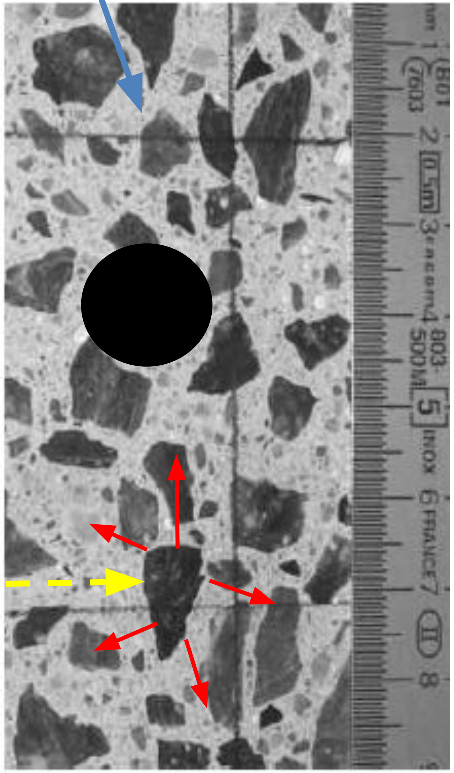


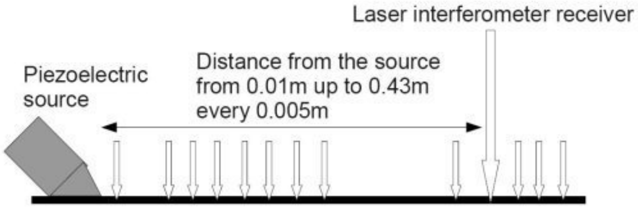
Inversion results (Geopsy, Dinver, Conoir & Norris (2010))

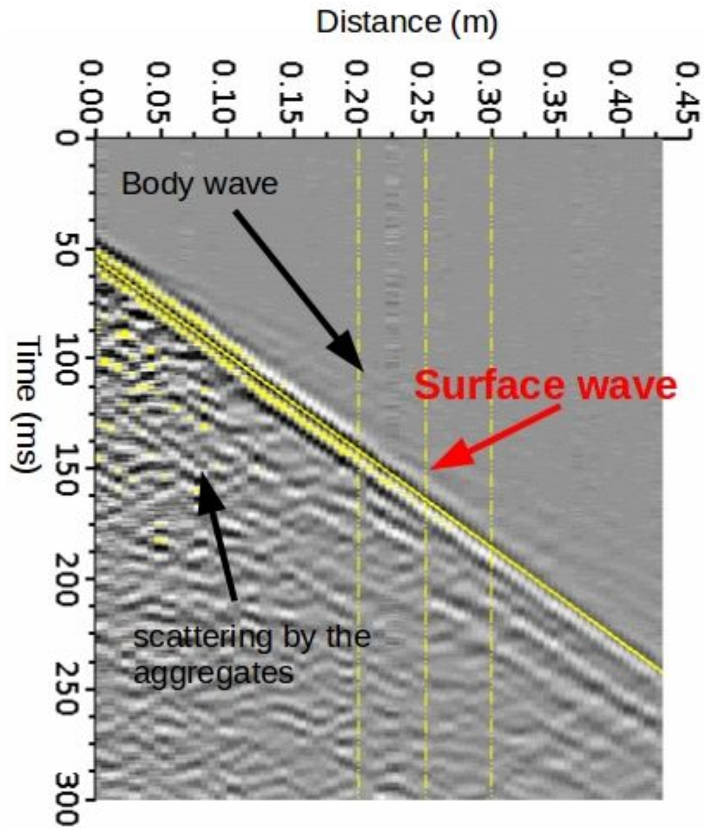
SEM2D
Conoir & Norris (2010)
ISA
Christensen & Lo (1079)

Focus on ultrasonic Surface Waves

CONTEXT: Cover concrete

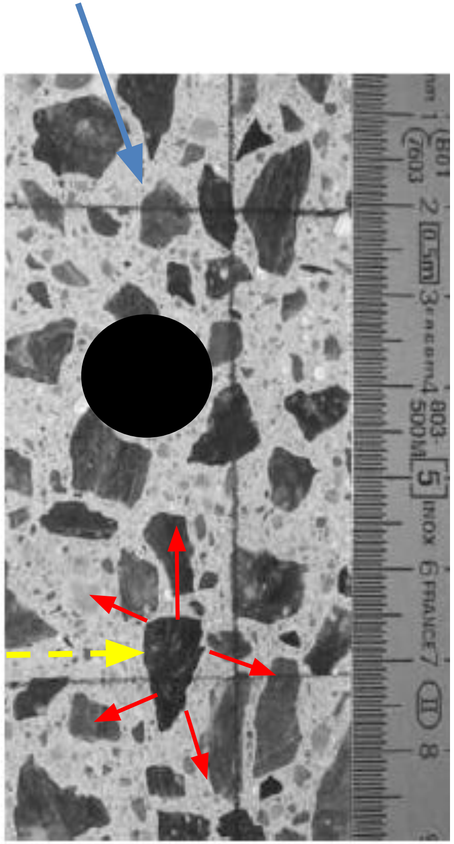


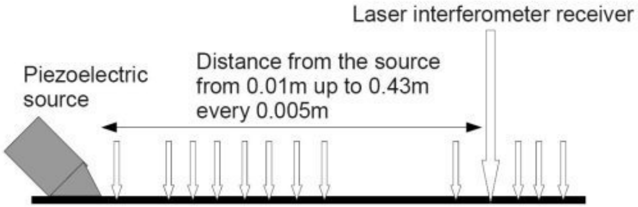


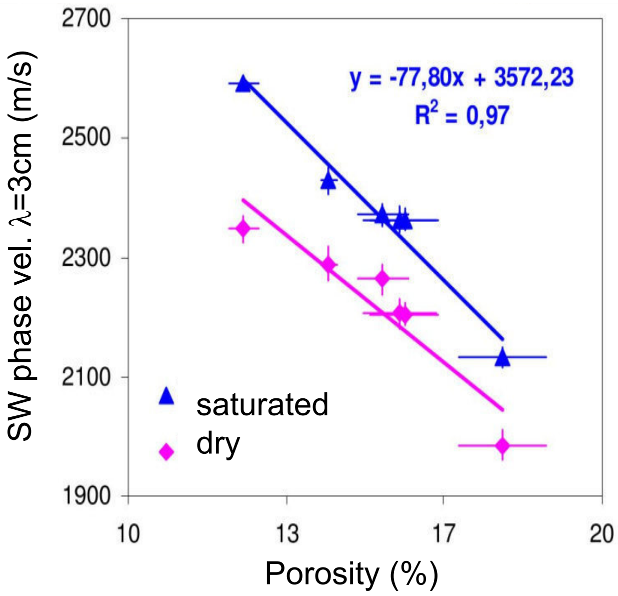


Focus on ultrasonic Surface Waves

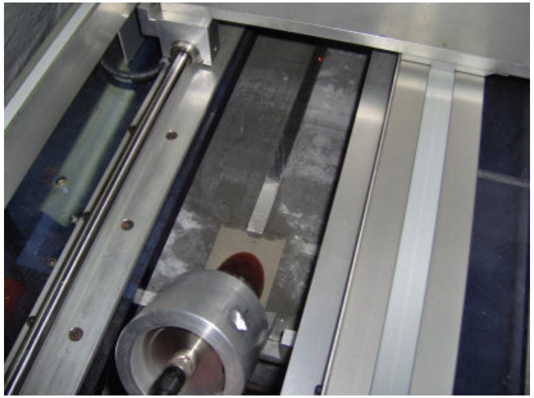
CONTEXT: Cover concrete







Focus on ultrasonic Surface Waves



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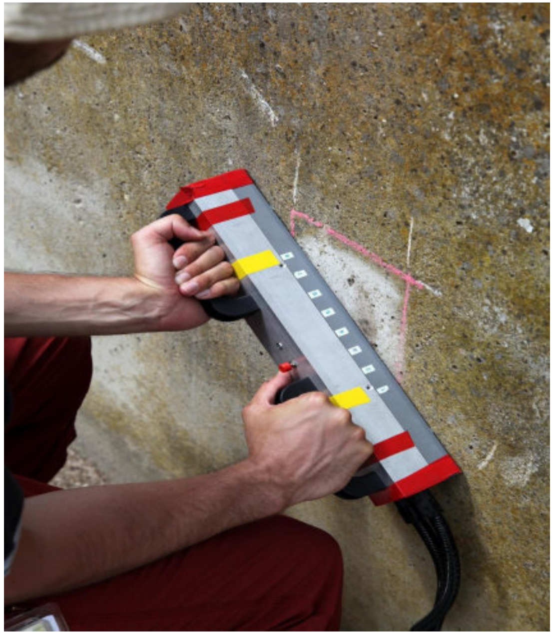
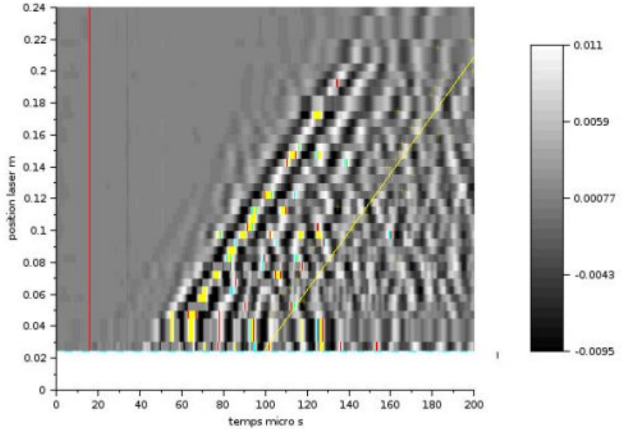
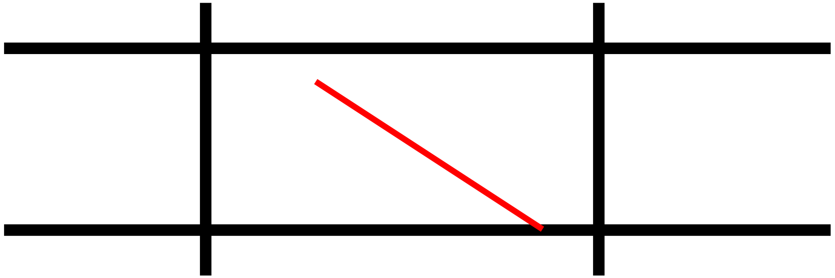




ACSYS



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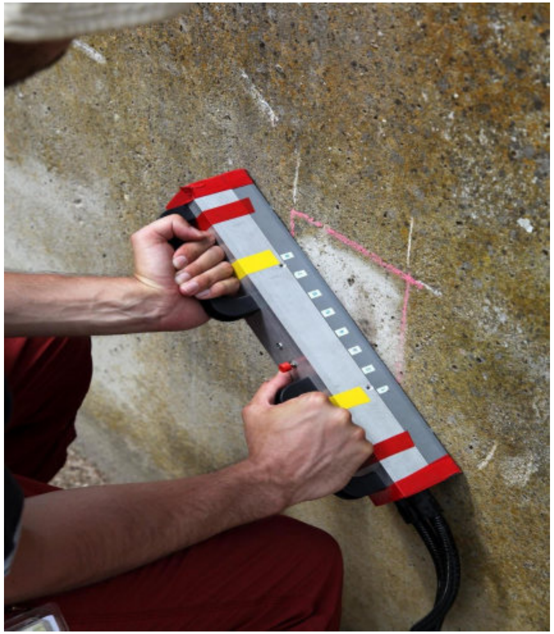
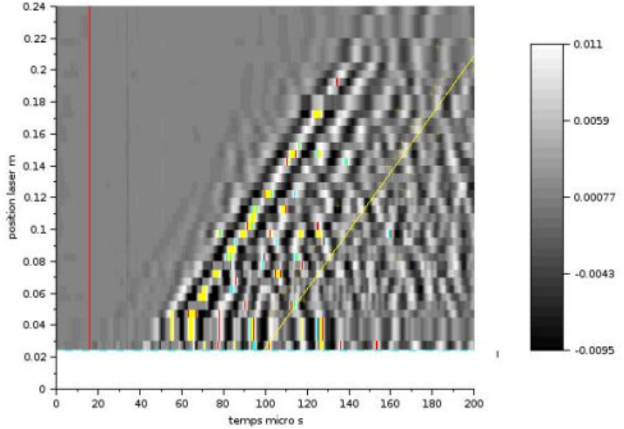
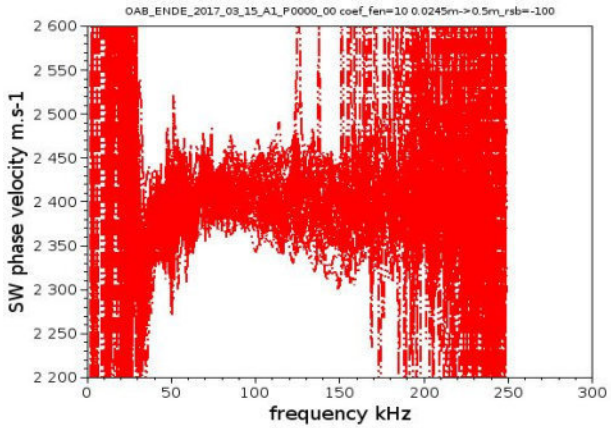
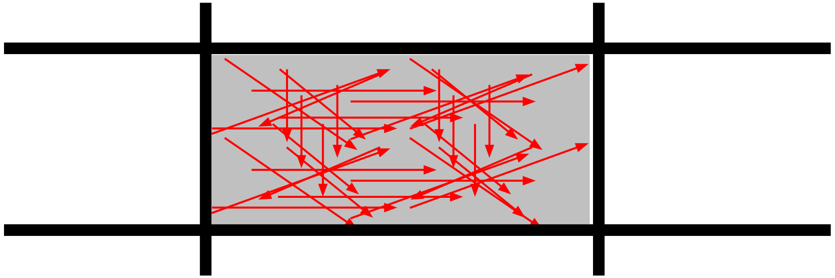






ACSYS



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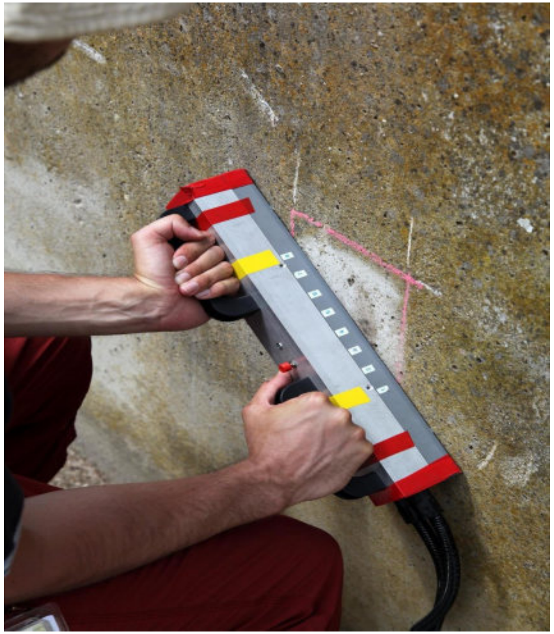

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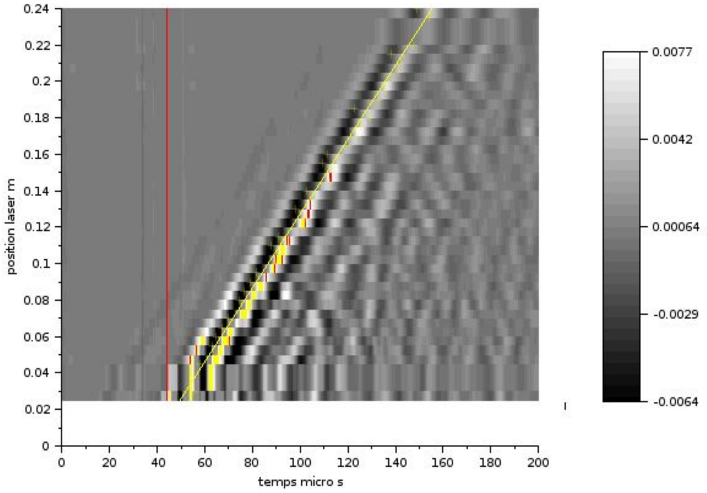
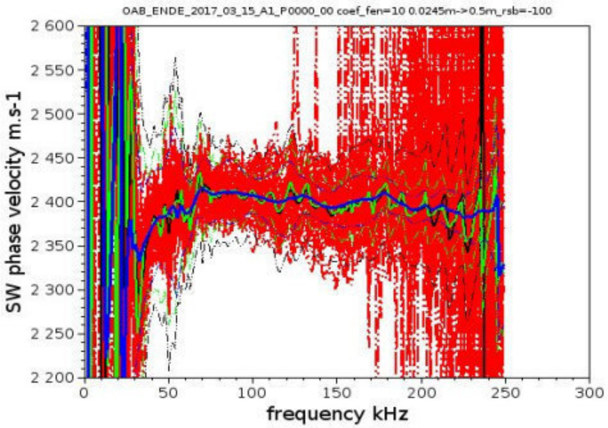
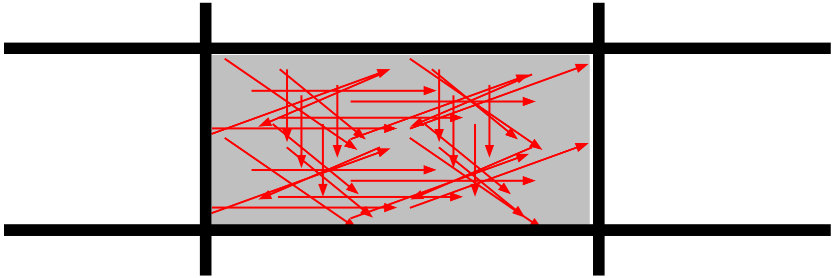


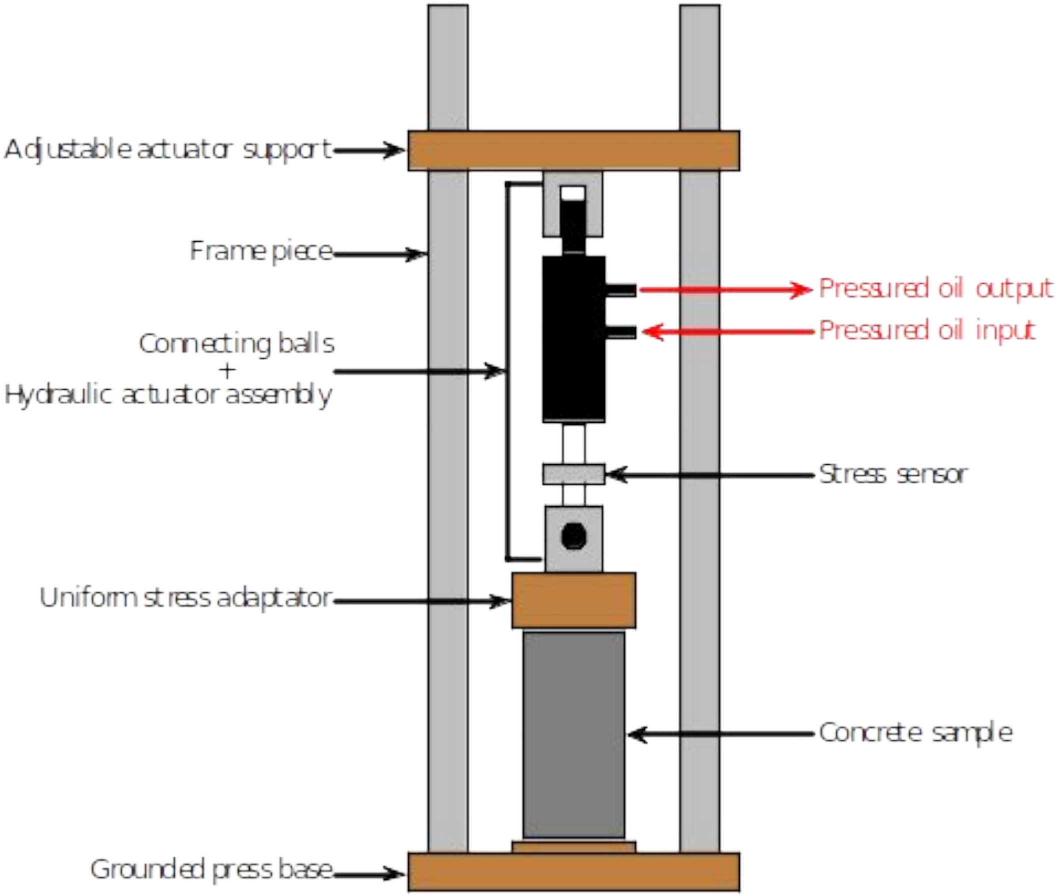


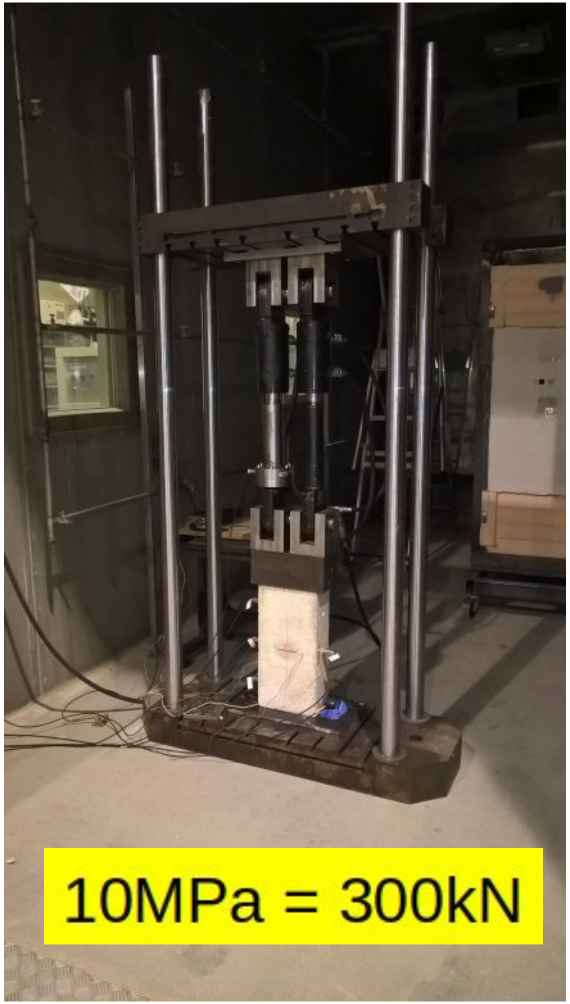
Vφ of individual seismograms
Average of individual dispersion curve Vφ
Vφ of average seismograms
Vφ of average seismograms windowed



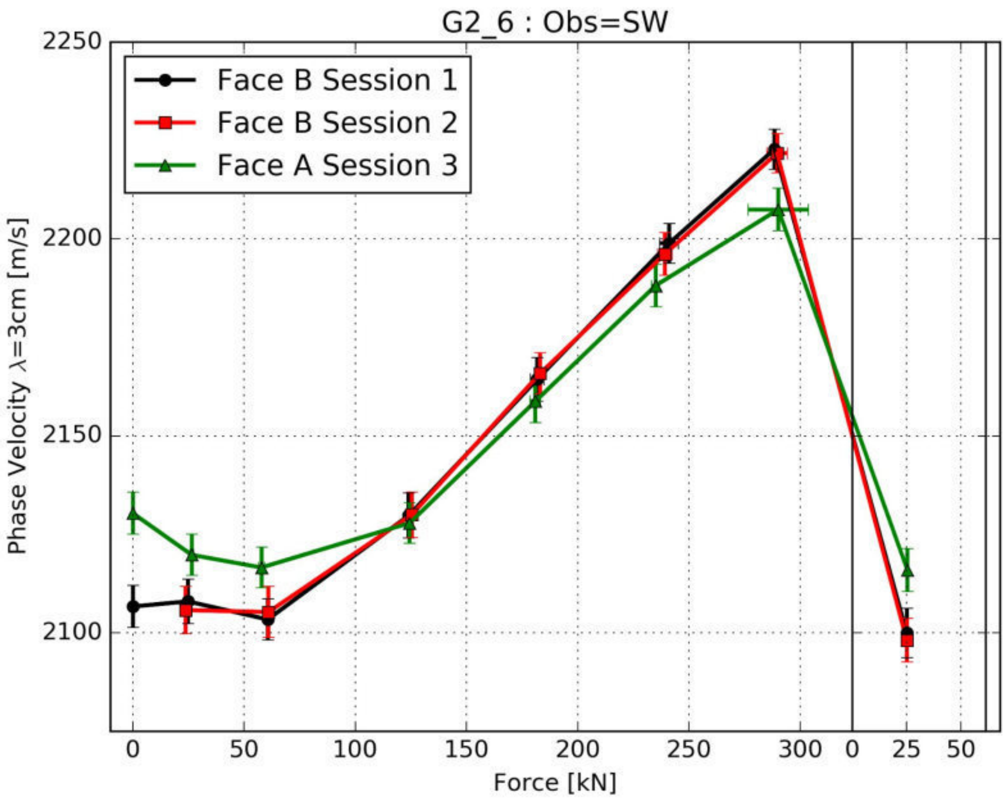
Coherent field

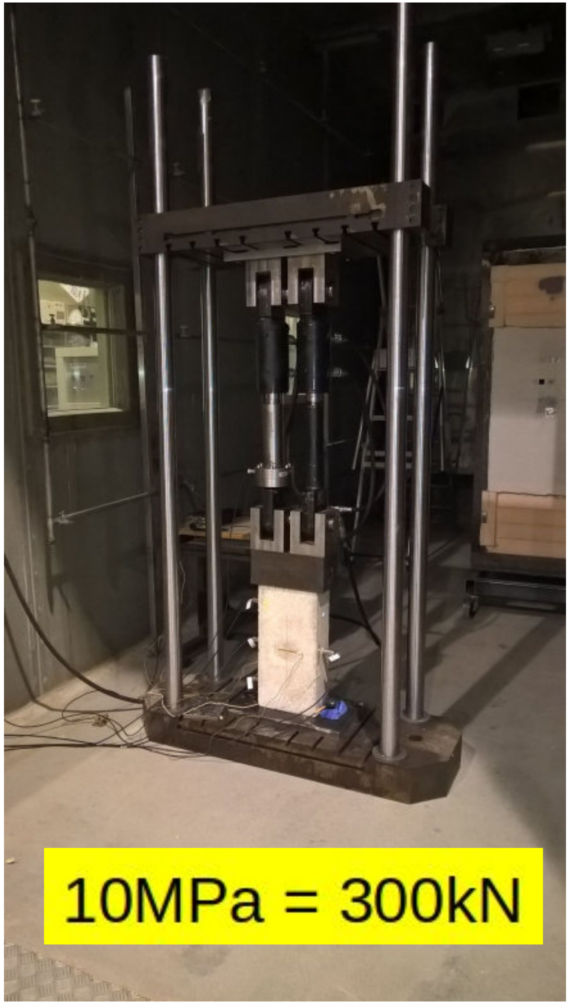
Focus on ultrasonic Surface Waves





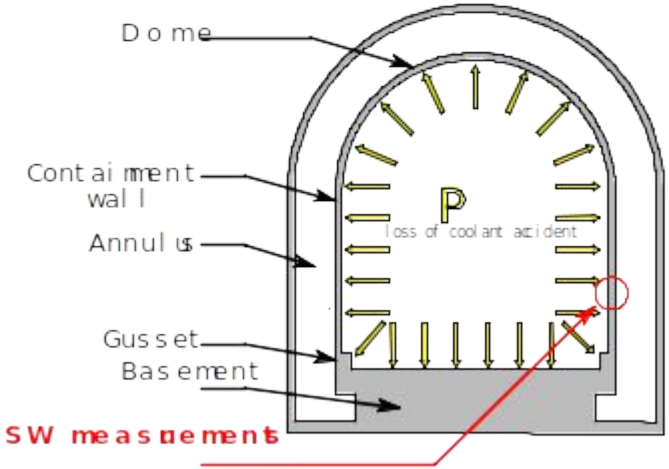
Focus on ultrasonic Surface Waves

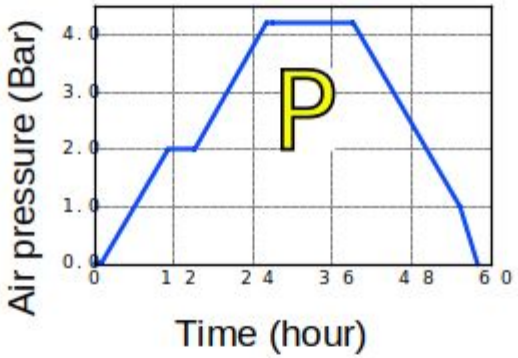




Focus on ultrasonic Surface Waves

Focus on ultrasonic Surface Waves



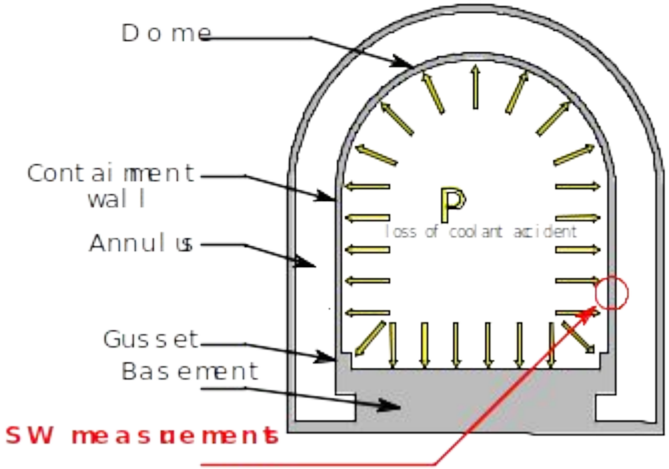


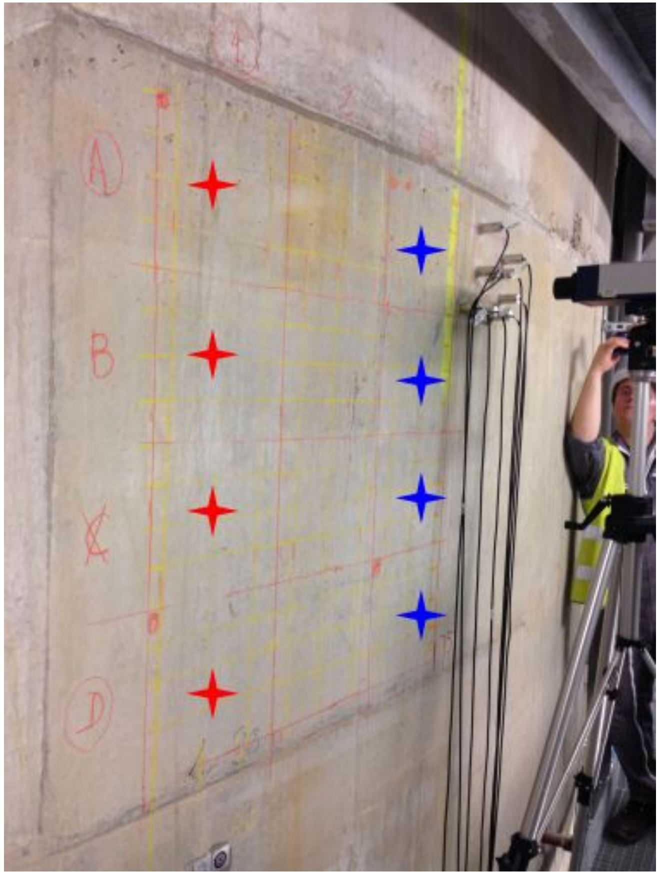
1 bar = 0.1 MPa = 14.5 psi

Nuclear containment plant

- 30 m height
- 5000 t of concrete
- 700 sensors
- 2 km of fiber optic

Focus on ultrasonic Surface Waves





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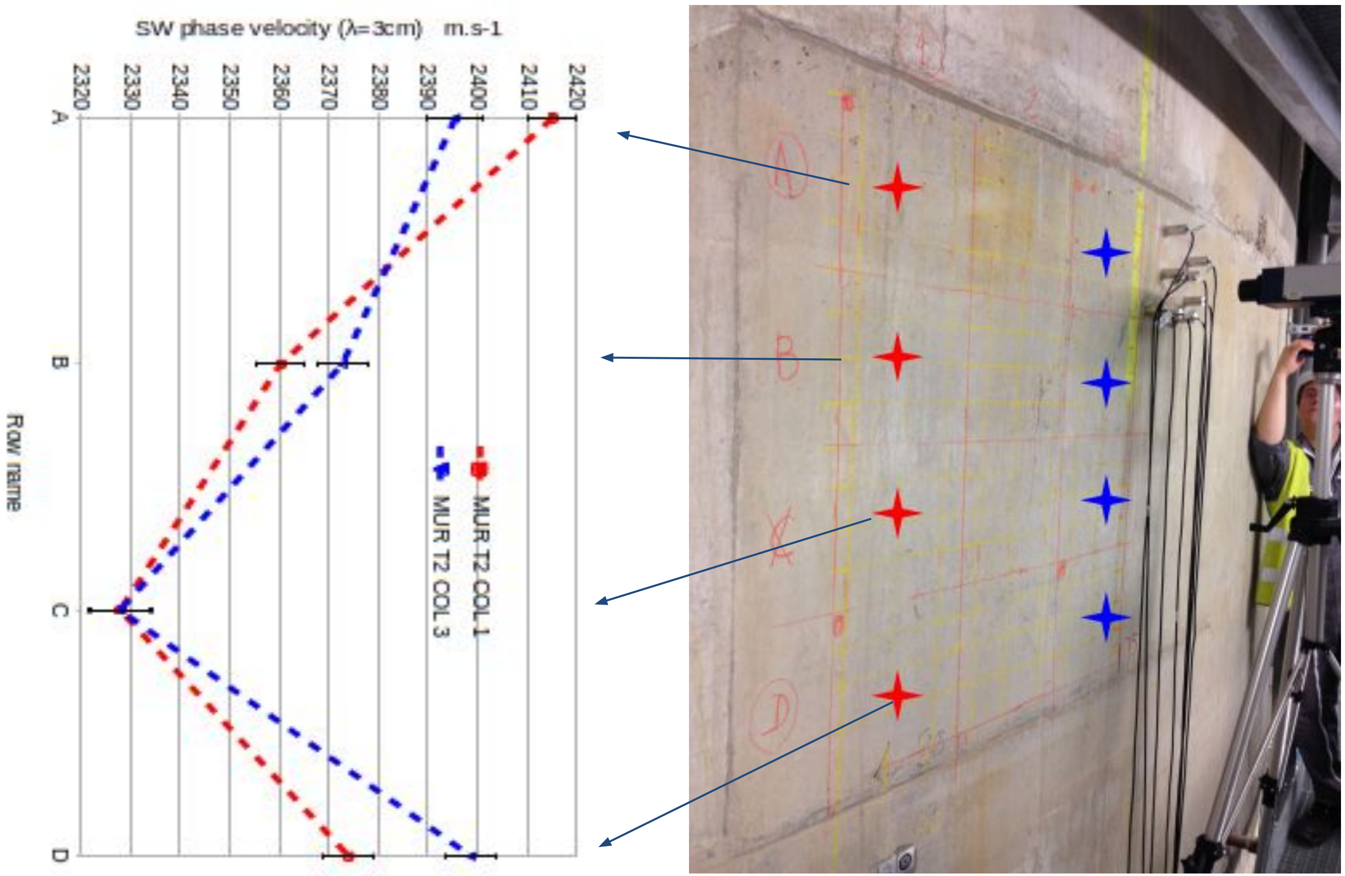
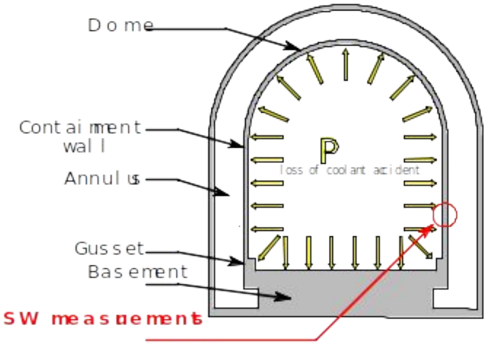
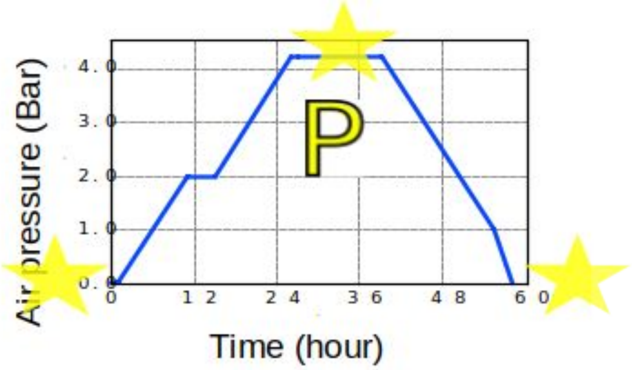
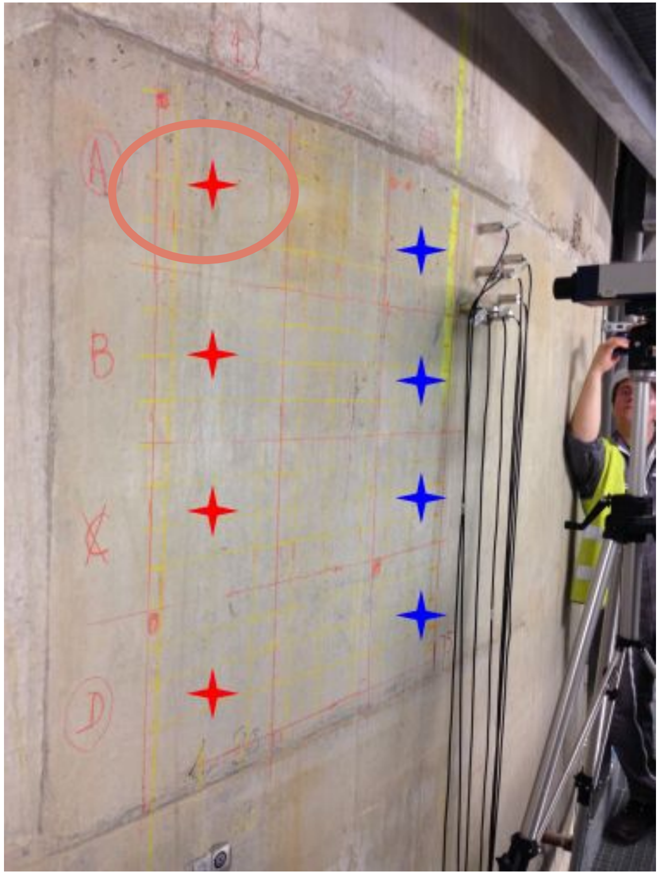
Focus on ultrasonic Surface Waves



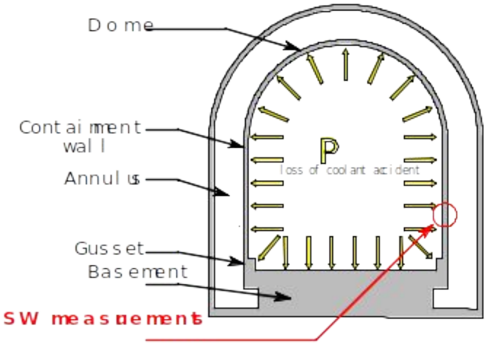
Focus on ultrasonic Surface Waves

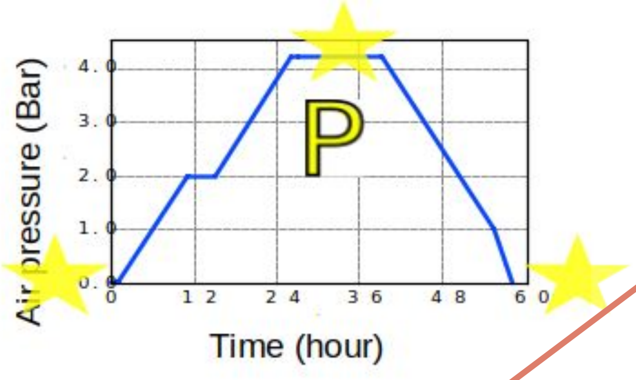


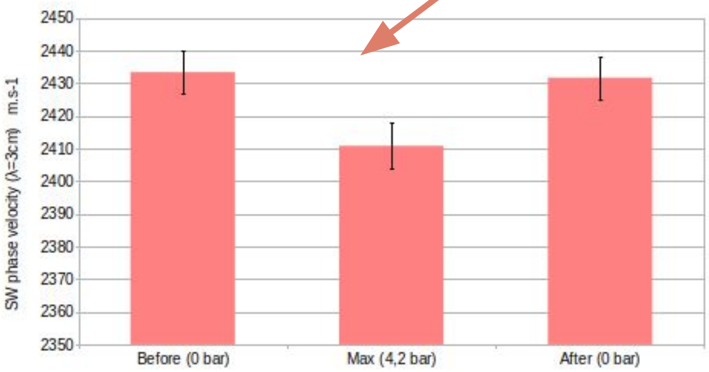


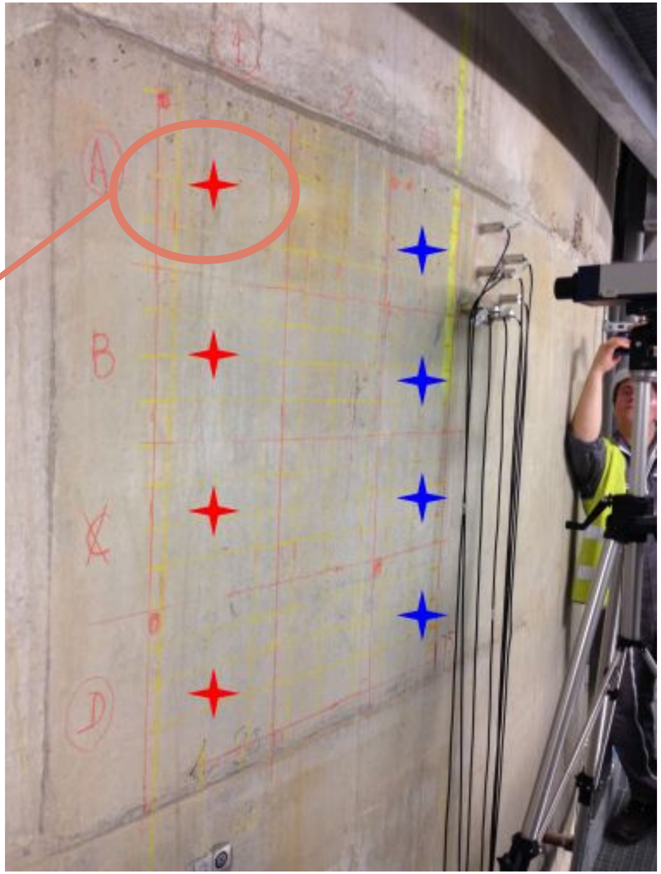


Focus on ultrasonic Surface Waves







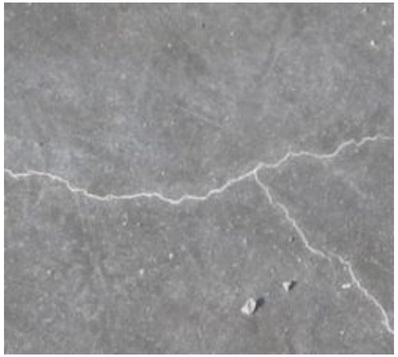


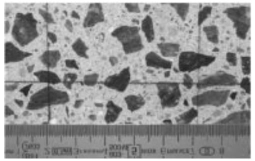
Outline

- **Recovering some concrete material properties**
  - fusion
- **Focus on Surface Waves (NDE/SHM)**
  - cover concrete
  - increasing TRL
- **Focus on Coda Waves**
  - monitoring
  - non linear
- **Fibers Optics at ultrasonics frequency**
  - project startings

Focus on CODA Wave Interferometry

CONTEXT



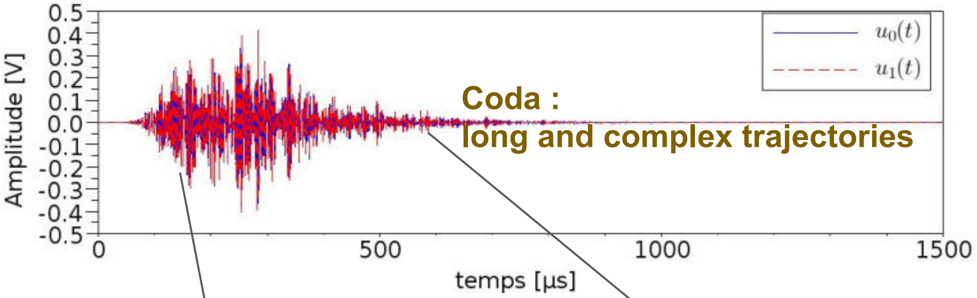


- Closed crack detection, sizing, monitoring
  - Pre-stressed concrete
  - Nuclear containment plants = ultimate barrier in the event of an accident
    - Resist internal overpressure
    - Prevent leakage

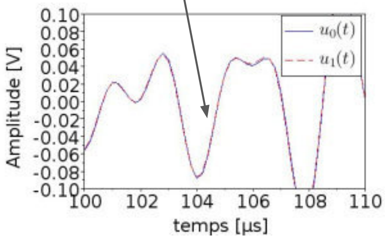
- When classical techniques fail
  - Early age detection
  - In very heterogeneous material

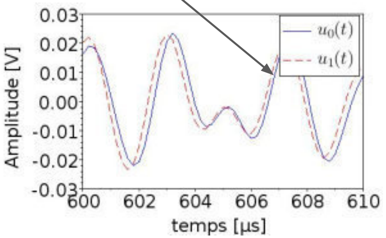
Focus on CODA Wave Interferometry

- Basic physical principle

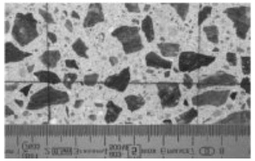


- CWI : Stretching (state 0, state 1)

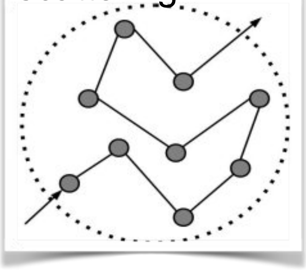




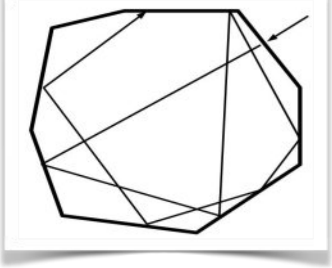
R. Snieder, Coda Wave interferometry and the equilibration of energy in elastic media. *Phys. Rev. E,* 2002.



scattering



reverberant



$$CC(\theta)=\frac{\int_{t_1}^{t_2} u_0[t(1+\theta)]\,u_1[t]\,dt}{\sqrt{\int_{t_1}^{t_2} u_0^2[t(1+\theta)]\,dt}\sqrt{\int_{t_1}^{t_2} u_1^2[t]\,dt}}$$

Extracted features:

$$\theta=\delta v/v$$

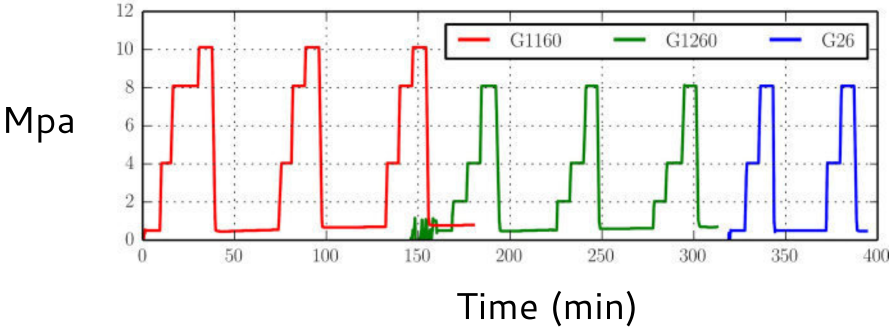
Velocity variation

$$Kd=1-CC(\theta)$$

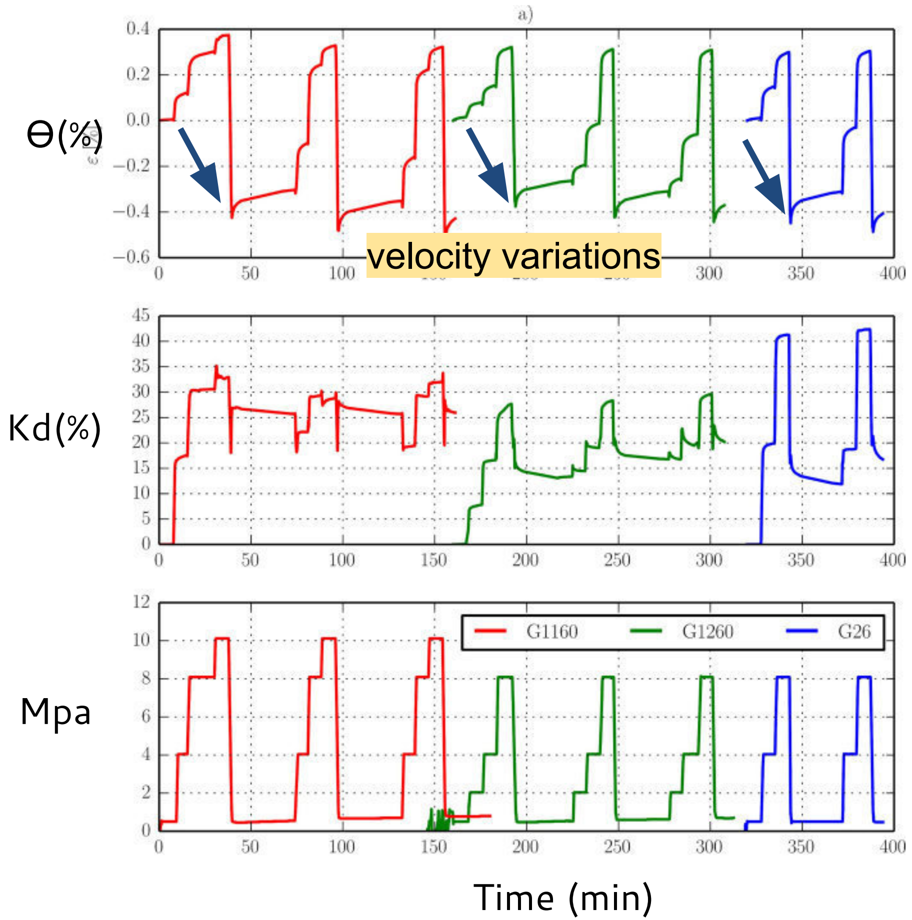
Decorrelation

Focus on CODA Wave Interferometry

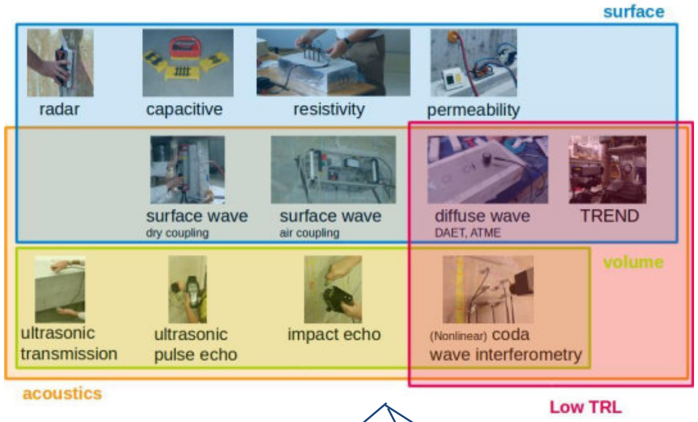
Below 30% of concrete compressive stress



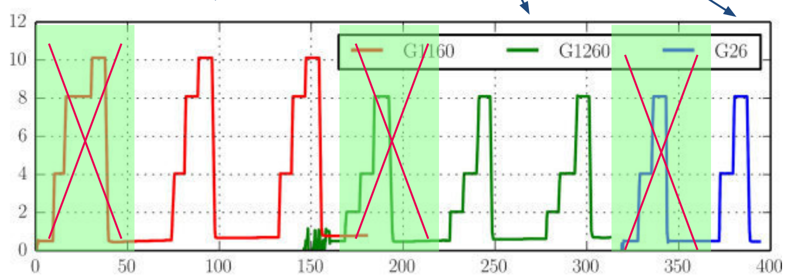
Focus on CODA Wave Interferometry



Focus on CODA Wave Interferometry



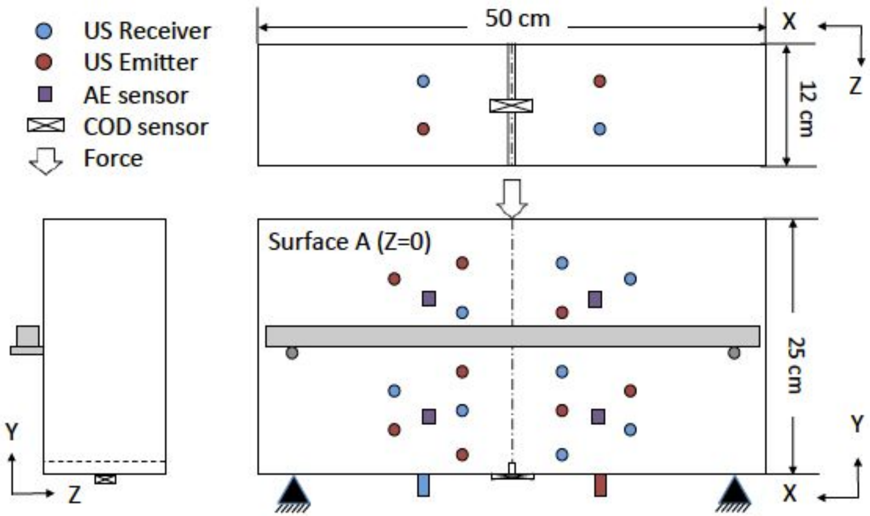
Mpa

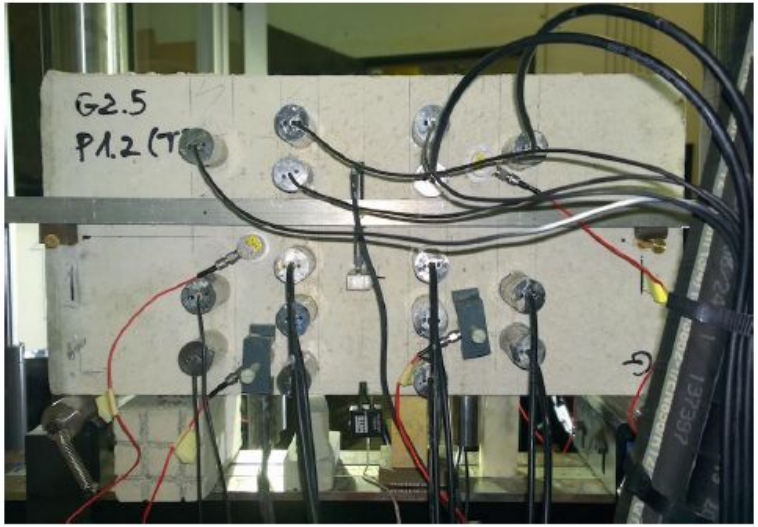


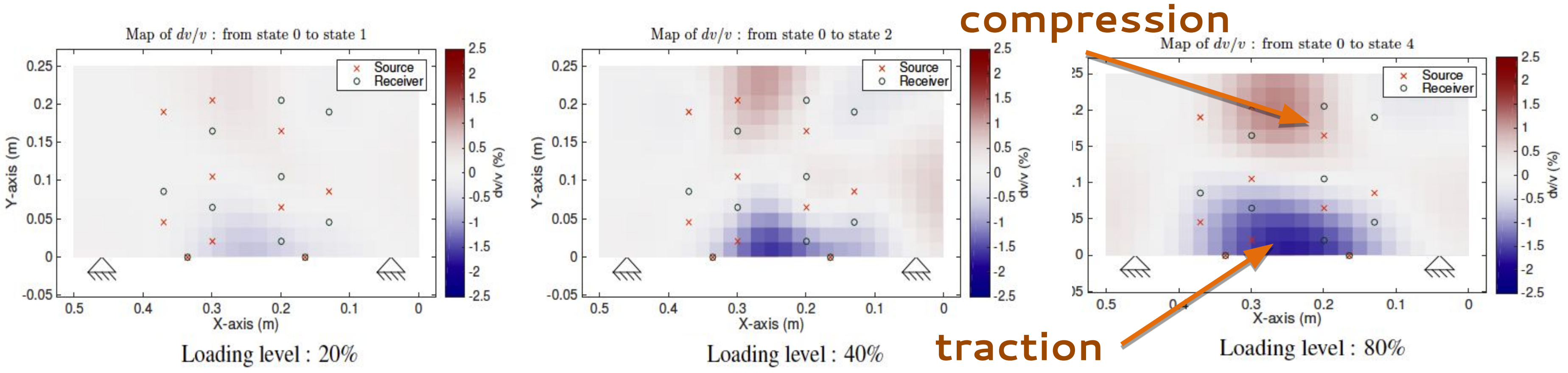
Time (min)

Focus on CODA Wave Interferometry

E. Larose
Y. Zhang



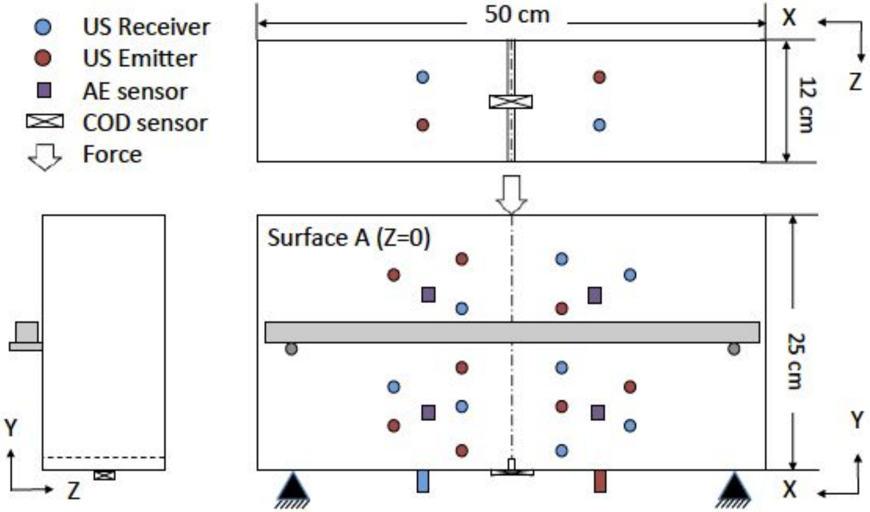


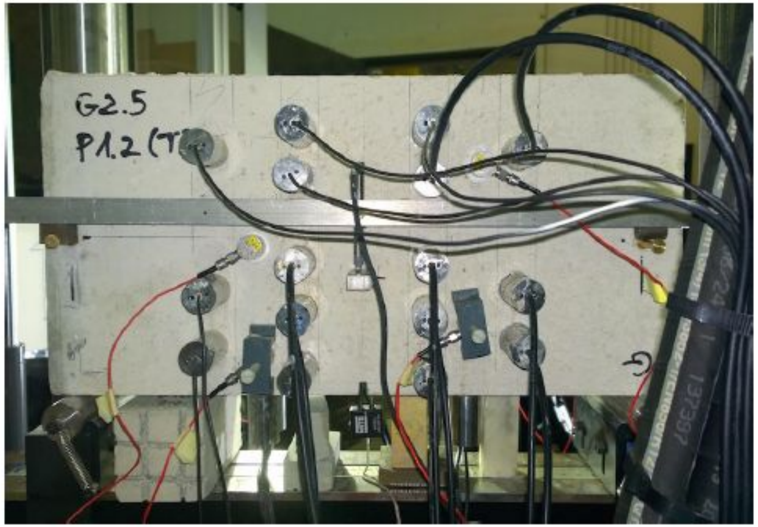


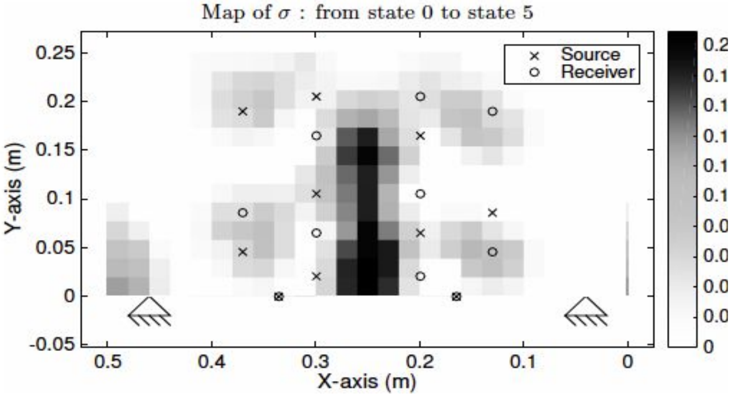
Focus on CODA Wave Interferometry

ISTerre

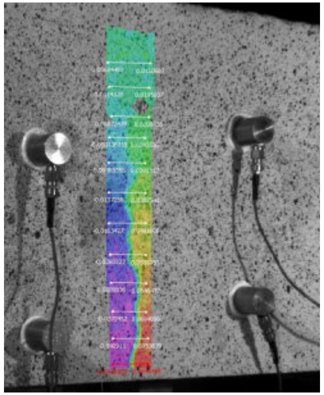
E. Larose
Y. Zhang







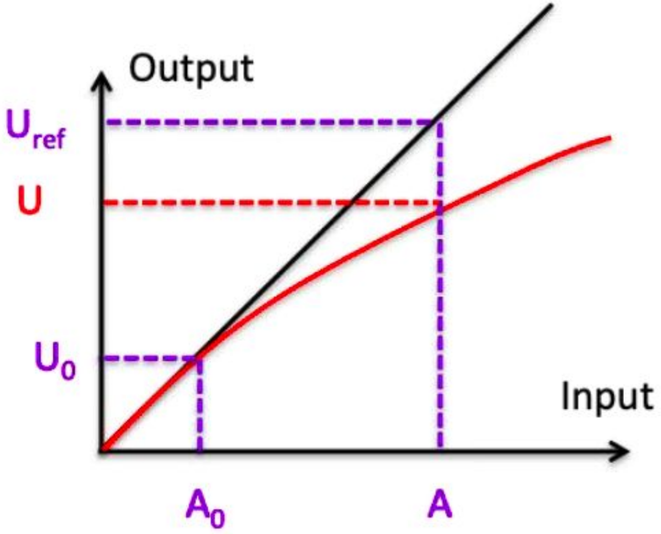
Digital Image Correlation



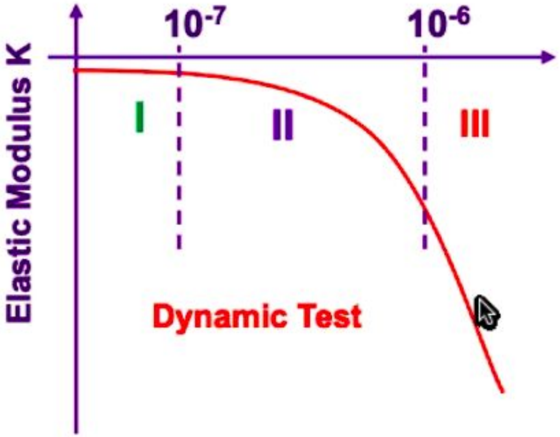
Focus on Nonlinear CODA Wave Interferometry

$$\sigma = E_0\,\epsilon\left(1+\beta\epsilon+\delta\epsilon^2+\ldots\right)+\alpha Fct\left(\epsilon, sign\left(\partial\epsilon/\partial t\right)\right)$$

Zone I Zone II Zone III



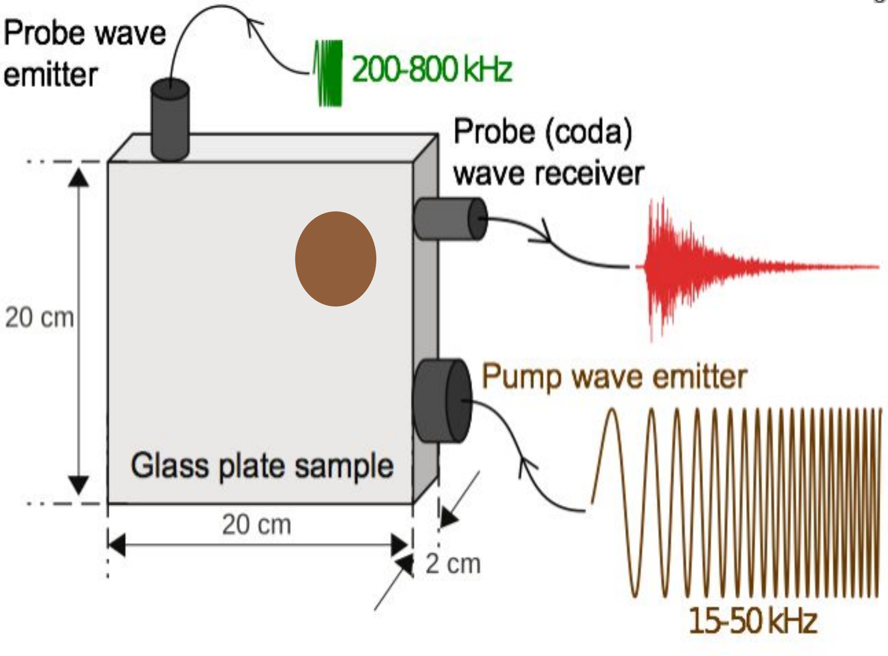
Linear Elasticity
Quadratic or Cubic elasticity (Classical nonlinearity)
Hysteretic nonlinear béhaviour

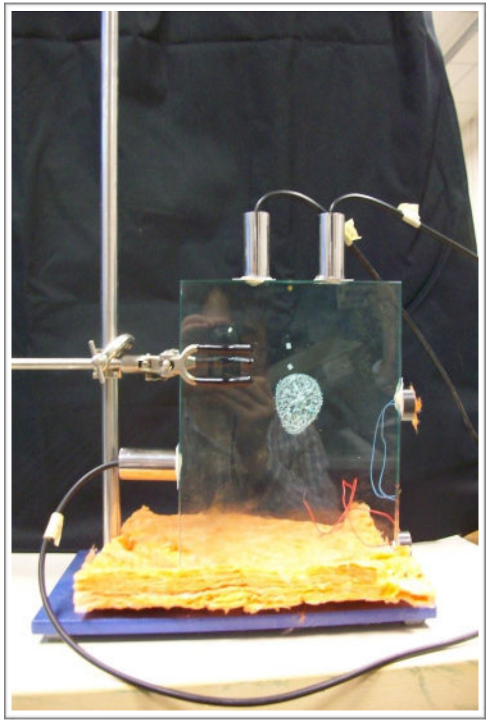


LAUM

Focus on Nonlinear CODA Wave Interferometry

$$\sigma = E_0\,\epsilon(1+\beta\epsilon+\delta\epsilon^2+\dots)+\alpha Fct(\epsilon, sign(\partial\epsilon/\partial t))$$

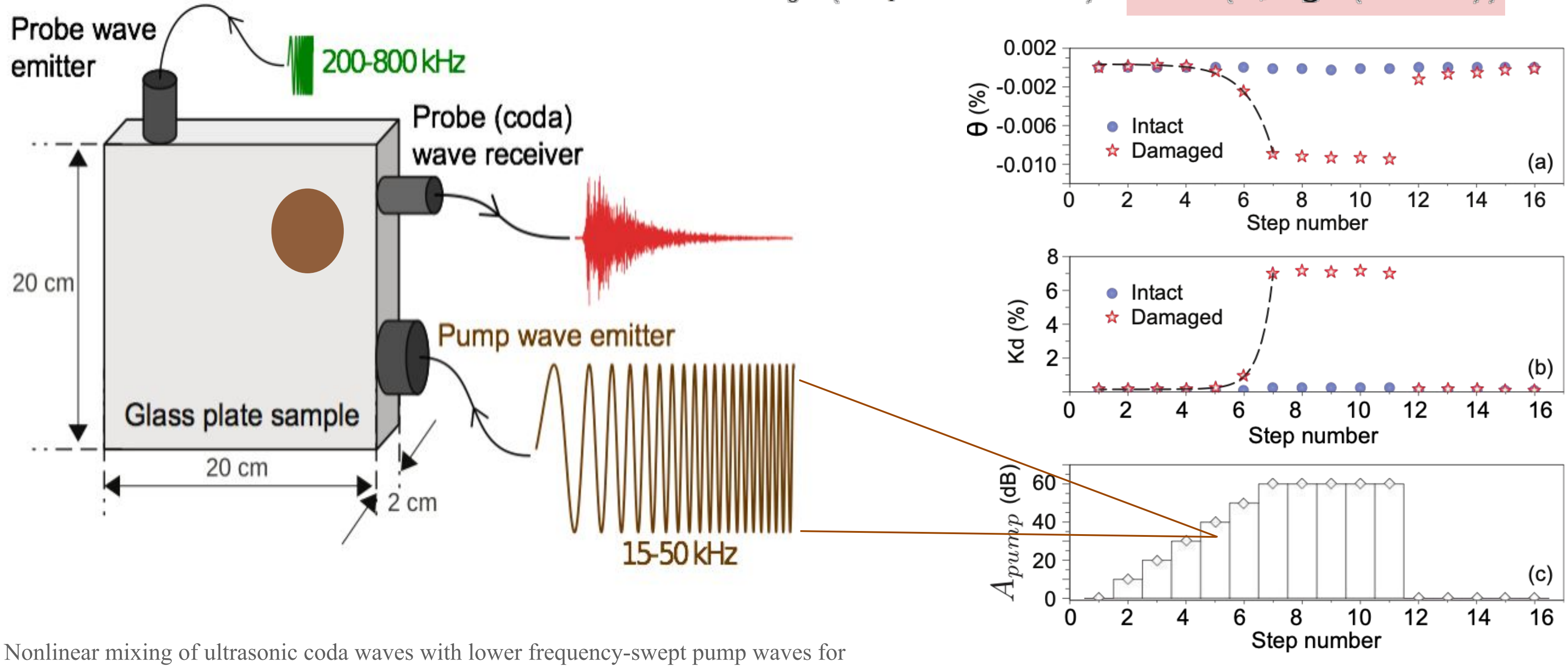




Zhang et al, Nonlinear mixing of ultrasonic coda waves with lower frequency-swept pump waves for a global detection of defects in multiple scattering media. *Journal of Applied Physics*, 2013.

Focus on Nonlinear CODA Wave Interferometry

$$\sigma = E_0\,\epsilon(1+\beta\epsilon+\delta\epsilon^2+\ldots)+\alpha Fct(\epsilon, sign(\partial\epsilon/\partial t))$$



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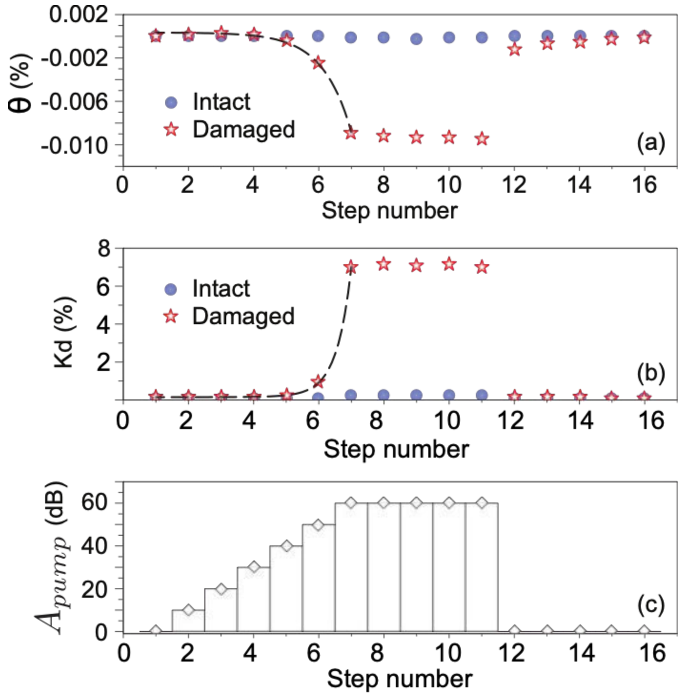
Focus on Nonlinear CODA Wave Interferometry

$$\sigma = E_0\,\epsilon(1+\beta\epsilon+\delta\epsilon^2+\ldots)+\alpha Fct(\epsilon, sign(\partial\epsilon/\partial t))$$

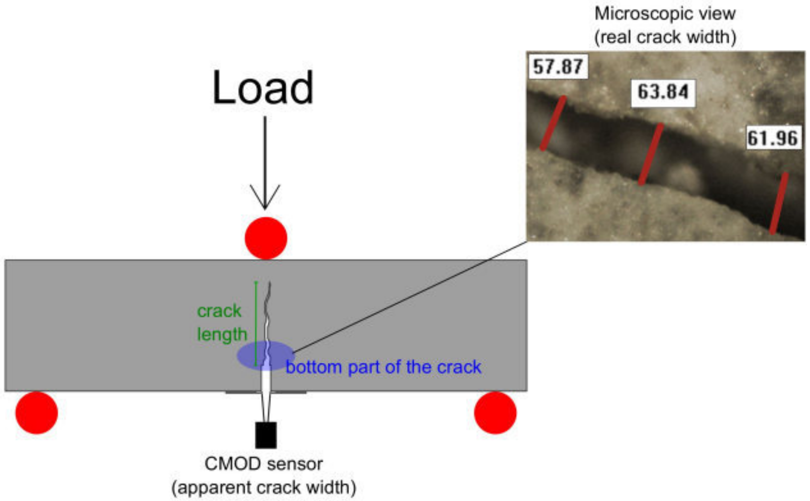
$$\theta \propto \alpha_\theta(A_{pump})$$

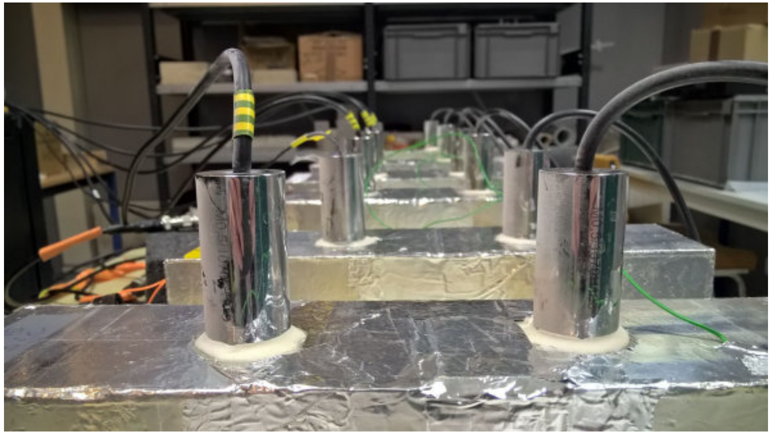
$$Kd \propto \alpha_{Kd}(A_{pump})^2$$



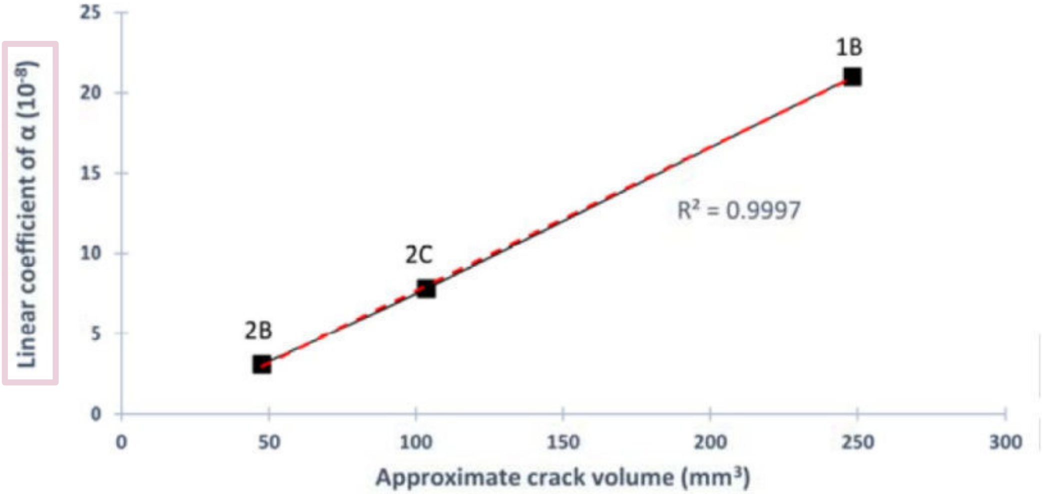
Zhang et al, Nonlinear mixing of ultrasonic coda waves with lower frequency-swept pump waves for a global detection of defects in multiple scattering media. *Journal of Applied Physics*, 2013.

Focus on Nonlinear CODA Wave Interferometry (NCWI)



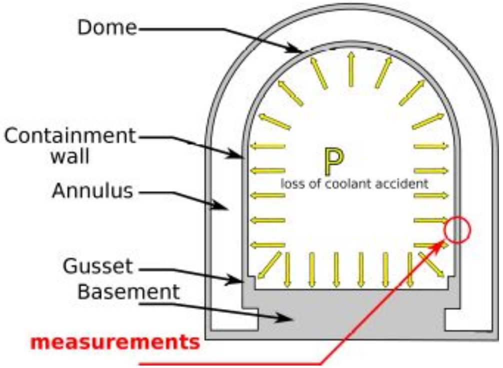


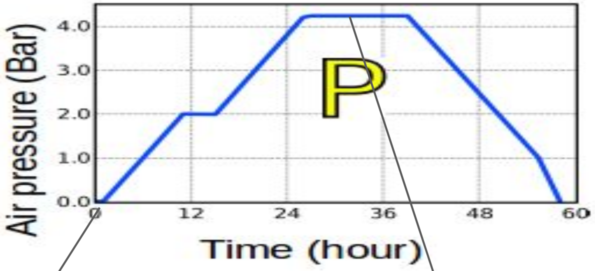
$$\theta \propto \alpha_\theta(A_{pump})$$



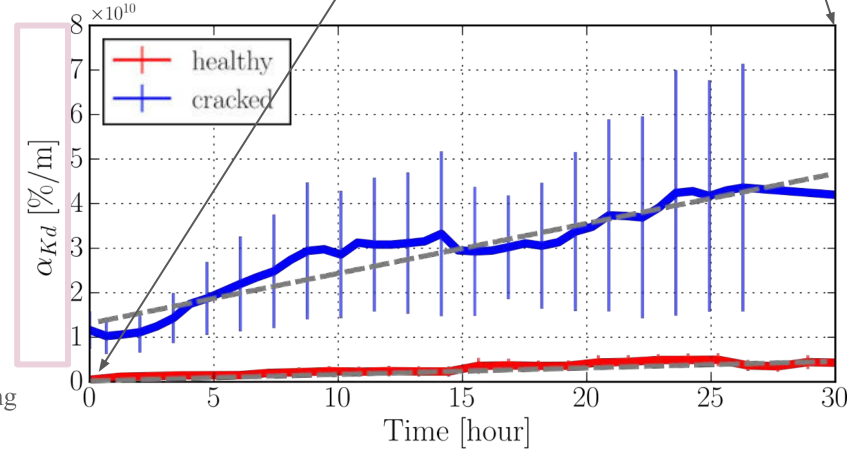
Institut de Recherche en Génie Civil et Mécanique

Focus on Nonlinear CODA Wave Interferometry (NCWI)



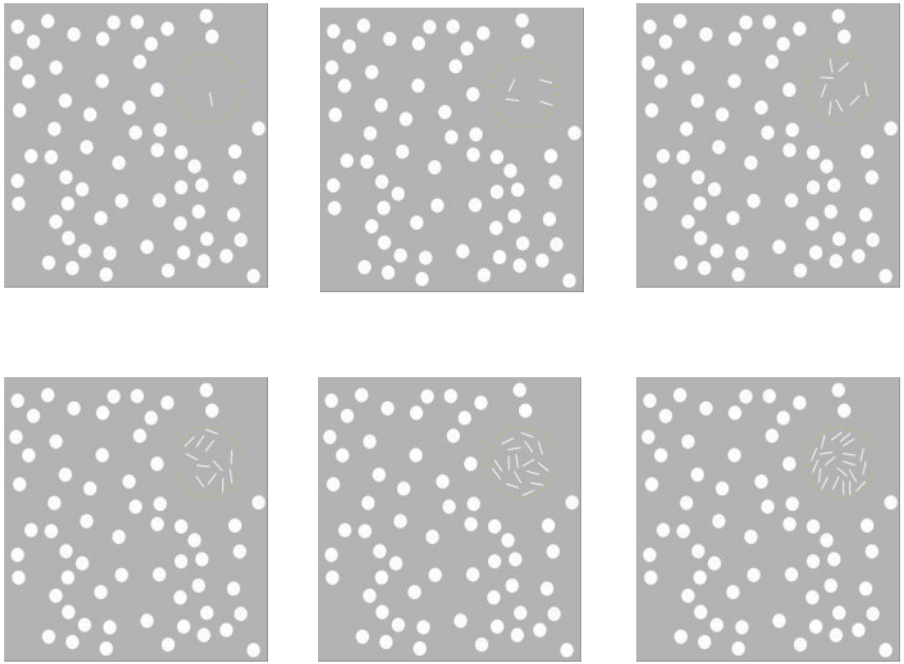


$$Kd \propto \alpha_{Kd} \left(A_{pump} \right)^2$$



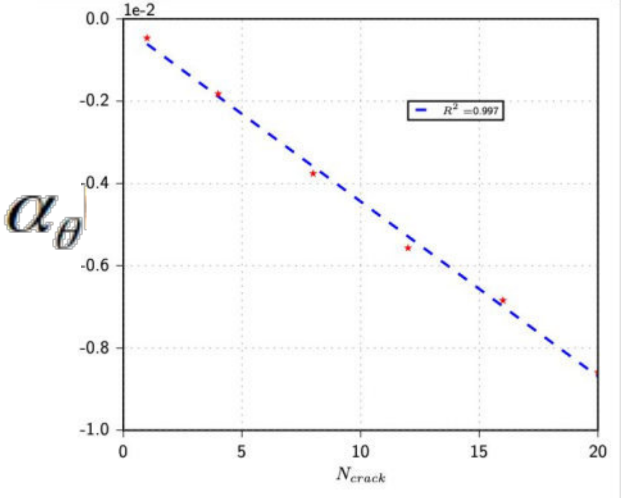
Legland J.-B. et al, Evaluation of crack status in a meter-size concrete structure using the ultrasonic nonlinear coda wave interferometry. *JASA*, 2017

Focus on Nonlinear CODA Wave Interferometry (NCWI)



G. Chen et al. Numerical modeling of ultrasonic coda wave interferometry in a multiple scattering medium with a localized nonlinear defect, *Wave Motion*, 2017

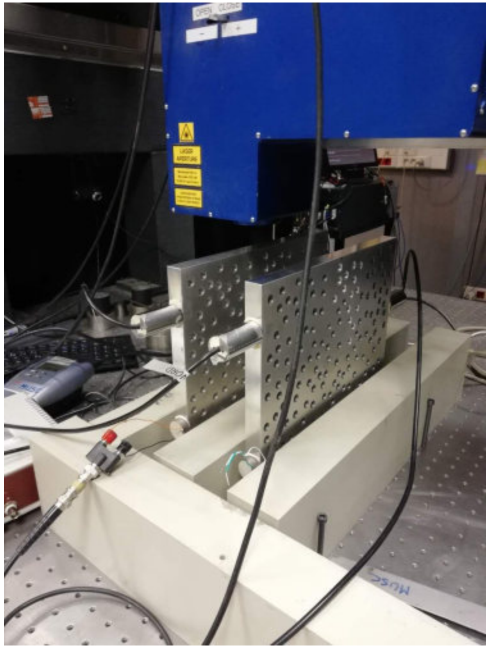
$$\theta \propto \alpha_\theta(A_{pump})$$

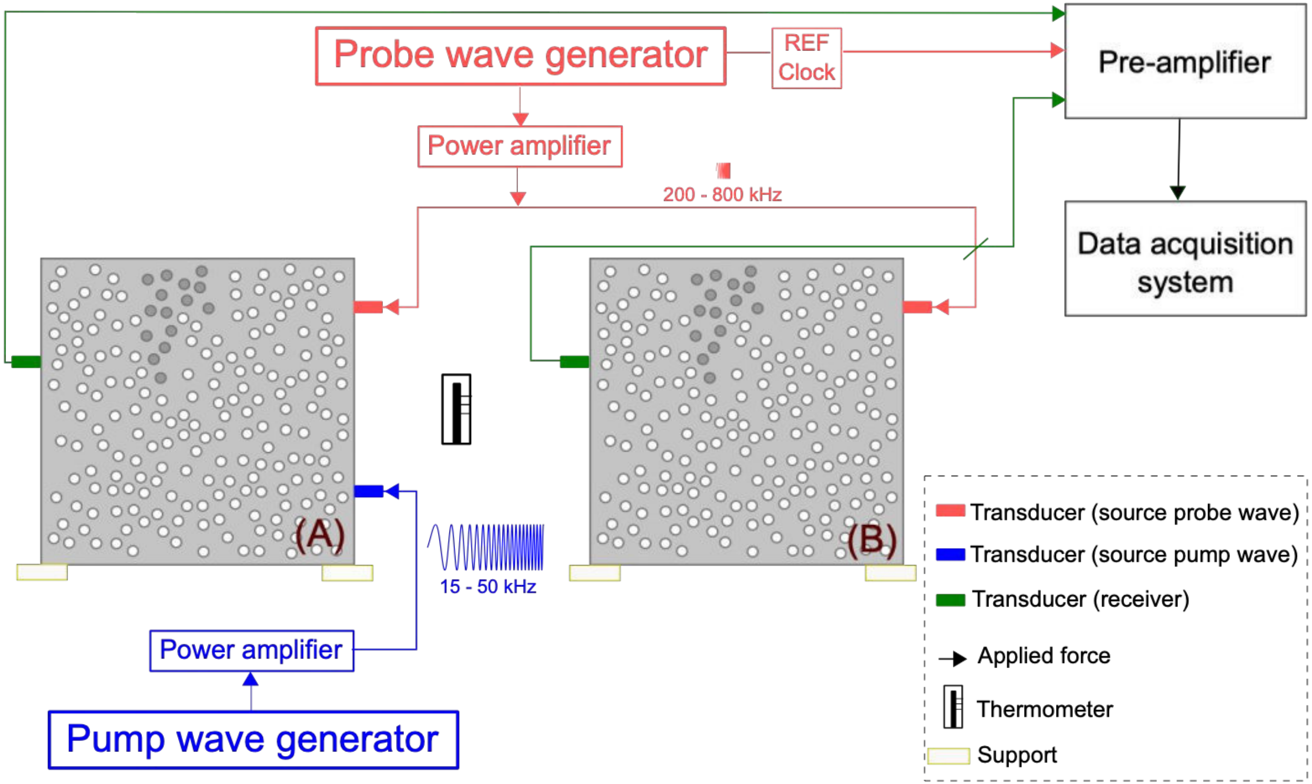


$$\theta = \alpha_\theta^{\sum L} \times \left(\sum \frac{\Delta L_{crack}}{L_{crack}}\right)$$

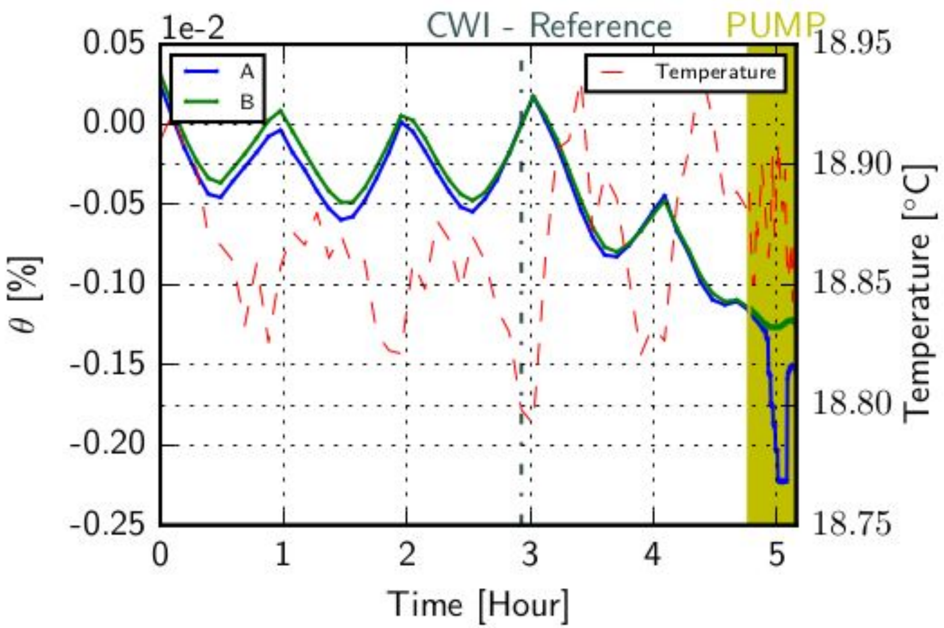
$$\mathrm{Kd} = \alpha_{\mathrm{Kd}}^{\sum L} \times \left(\sum \frac{\Delta L_{crack}}{L_{crack}}\right)^2$$

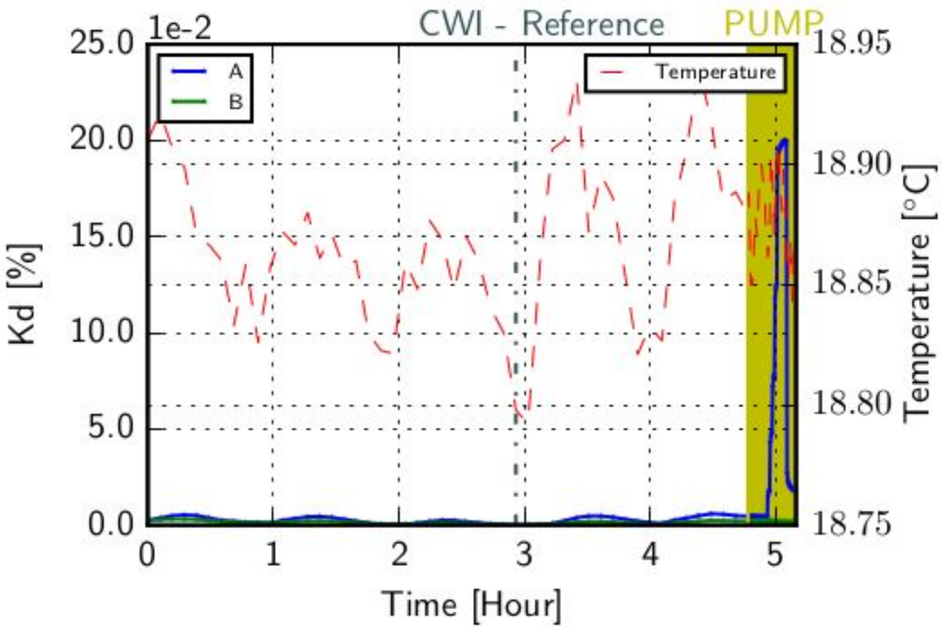
Focus on Nonlinear CODA Wave Interferometry (NCWI)

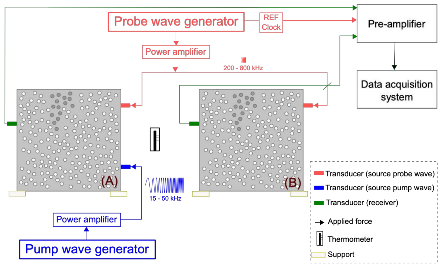




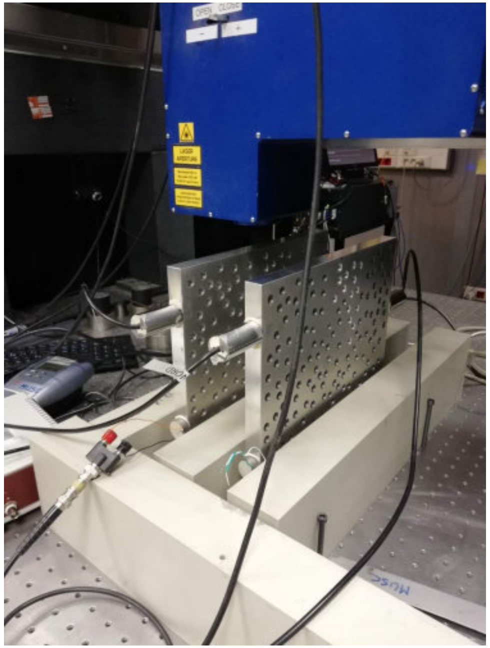
Focus on Nonlinear CODA Wave Interferometry (NCWI)



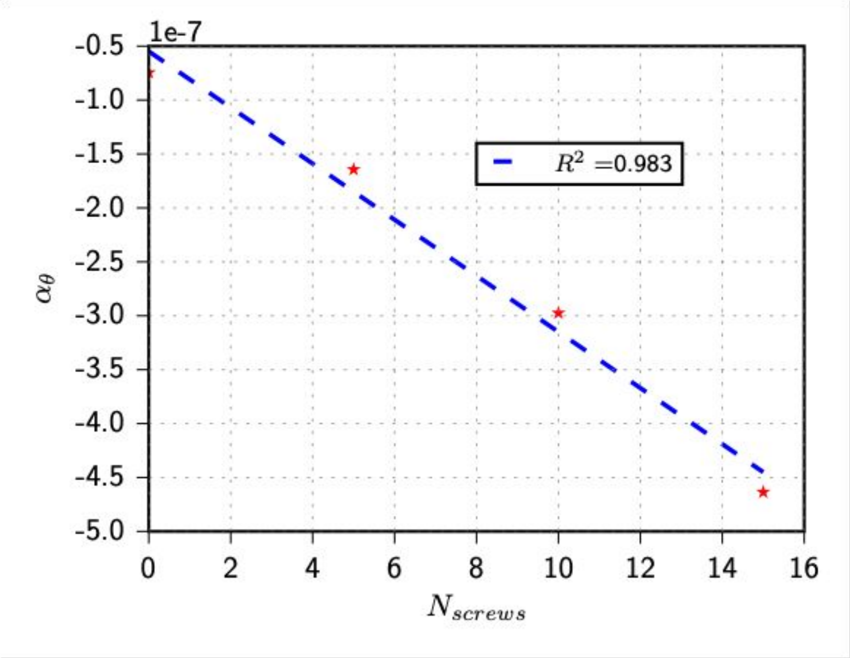




Focus on Nonlinear CODA Wave Interferometry (NCWI)



$$\theta = \alpha_\theta^{\sum L} \times (\Delta L \times N) = \alpha_\theta^{\sum L} \times (\sum \Delta L)$$

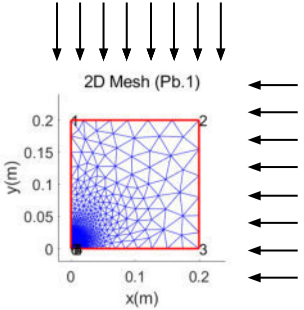


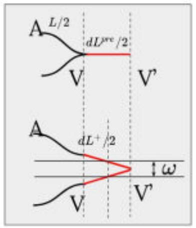
Focus on Nonlinear CODA Wave Interferometry (NCWI)

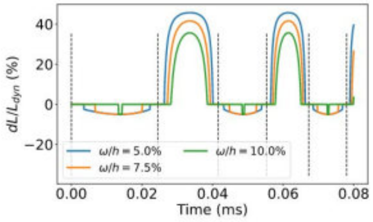
Ongoing work: imagery of closed cracks (without a reference to a "sound" material)

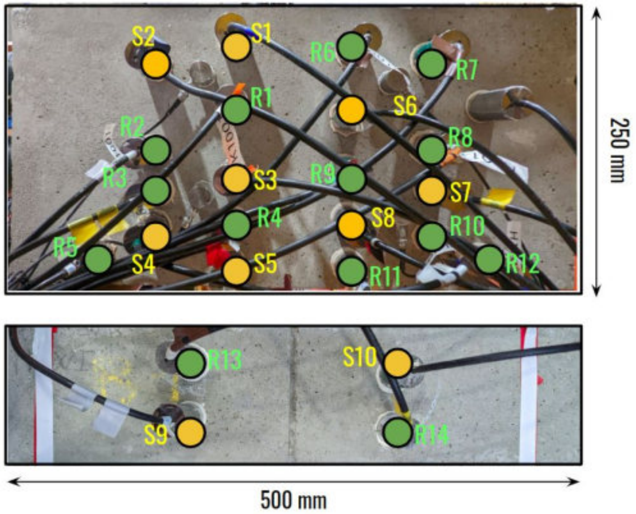
- A forward model with "few" parameters that can quantify the effect of the pump on the crack (maximum amplitude of the pump at one level, Young's Modulus, Poisson's ratio, crack length L, crack eighth, crack pre-closure length dL^{pre}, opening threshold ω)

Statique FEM

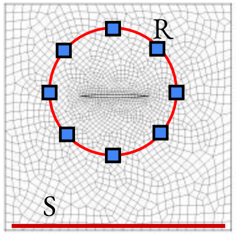


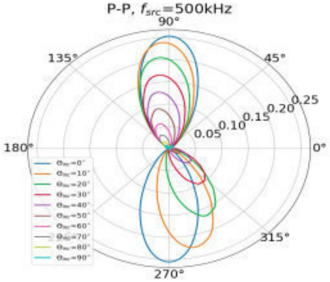






Dynamic SEM2D





average scattering cross section for a given maximum amplitude of the pump at one level

(P-P, P-S, S-S, S-P)

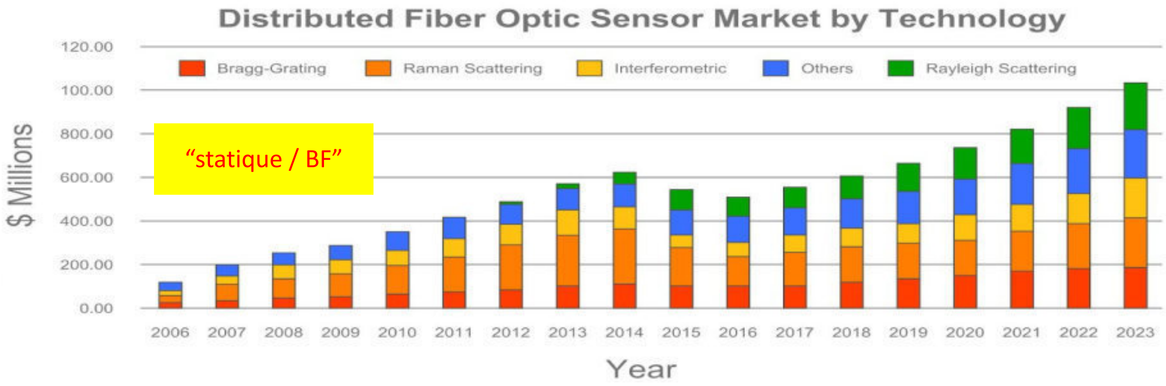
Outline

- Recovering some concrete material properties
  - fusion
- Focus on Surface Waves (NDE/SHM)
  - cover concrete
  - increasing TRL
- Focus on Coda Waves
  - monitoring
  - non linear
- Fibers Optics at ultrasonics frequency
  - project startings

Fiber Optics at ultrasonic frequency

CONTEXT

- Long term ultrasonic monitoring of concrete
  - Sensor durability in harsh environment (salty, radioactive, high temperature, ...)
  - Limited footprint of Fiber Optic
  - + Several localized sensing points along a single cable
  - Broadband transducer



Bado & Casas, A Review of Recent Distributed Optical Fiber Sensors Applications for Civil Engineering Structural Health Monitoring, 2021, Sensors, 21(5), 1818. doi
Liu *et al.*, Distributed Fiber-Optic Sensors for Vibration Detection, 2016, Sensors, 16(8). doi

Fiber Optics at ultrasonic frequency

- **Technologies** : DAS, OFDR (Rayleigh, Bragg), FBG (TDM, WDM, reflectometry,...)
- **Industrials** : optics11 (NL, pastille), ibsen photonics (Dk), redondo (USA), Ifos (USA), SmartFibers (USA), Micron-Optics (Luna, USA)... <˜20kHz
- **Academics** : Virginia Tech, CEA, Allemagne (BAM, Univ. Munich, IPHT...), UK (Univ. Southampton), Hong-Kong Polythec Univ....
- **FBG**s in development for ultrasonics on steel and composite structures

ANR-21-CE04-0007 **FO-US AIMS**
→ increase frequency (sampling at several MHz)
→ increase number of measurement points (at least 32)
→ long distances
→ reasonable cost

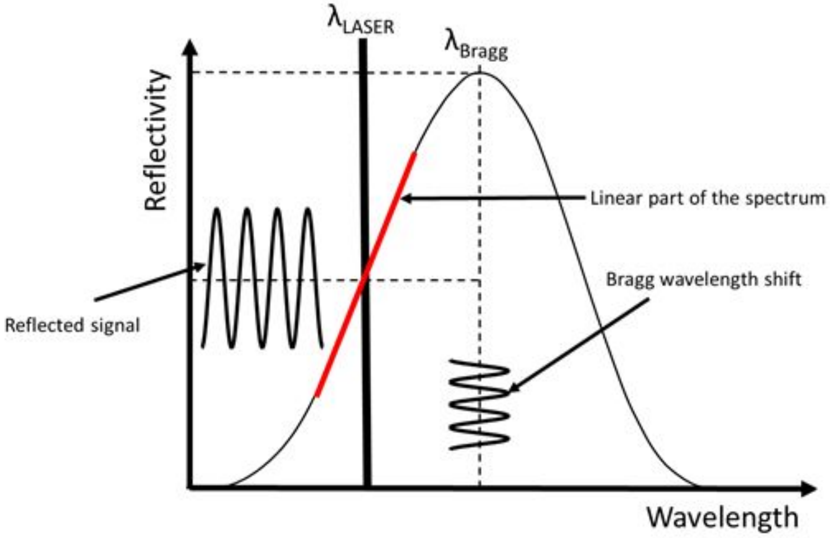
FO-US
Fibres Optiques enfouies dans des matériaux cimentaires pour l'imagerie et la surveillance UltraSonores actives et passives

Fiber Optics at ultrasonic frequency

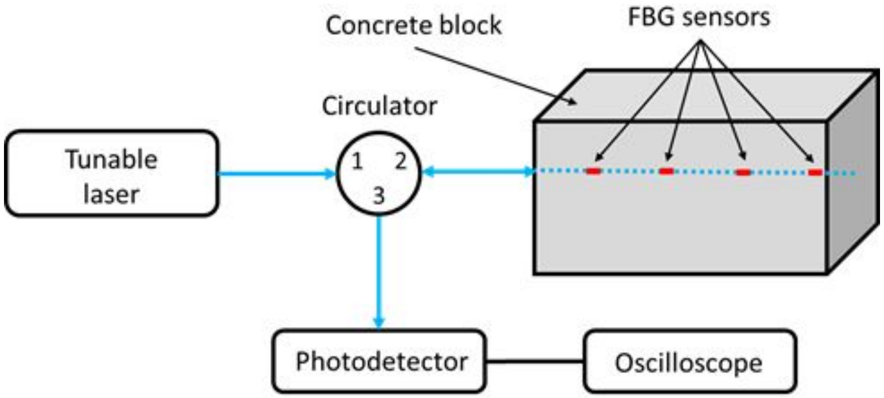
FIBER BRAGG GRATING (FBG) PRINCIPLE

- Tunable laser source
- Edge filtering method

FBG reflection spectrum



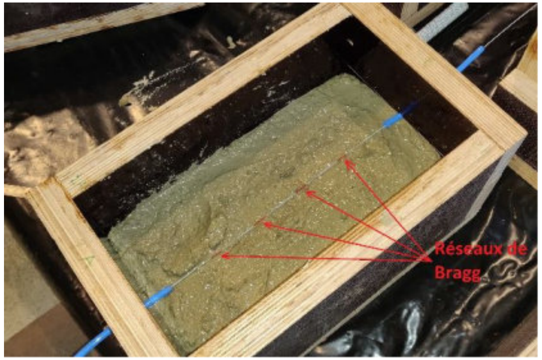
- FGB interrogator system

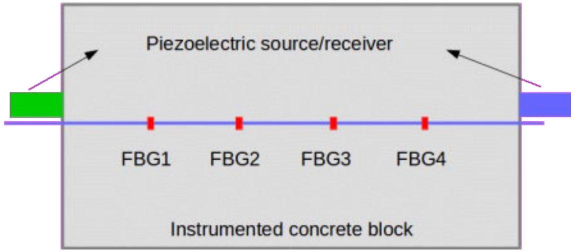


T. Druet, B. Chapuis, M. Jules, G. Laffont, E. Moulin. 2018. “Passive guided waves measurements using fiber Bragg gratings sensors”, *The Journal of the Acoustical Society of America* 144, 1198.

Fiber Optics at ultrasonic frequency

- 16 cm x 16 cm x 30 cm concrete blocks
  - Rc = 18.8 MPa ∓ 3.5 MPa

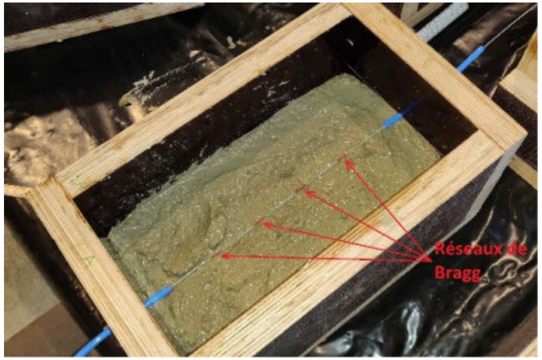


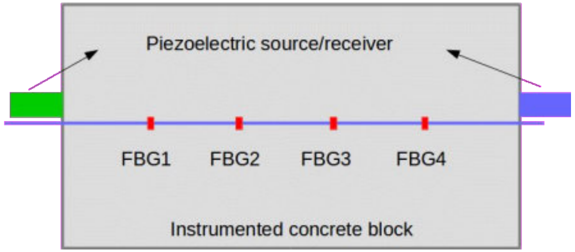


- Glued piezoelectric transducers

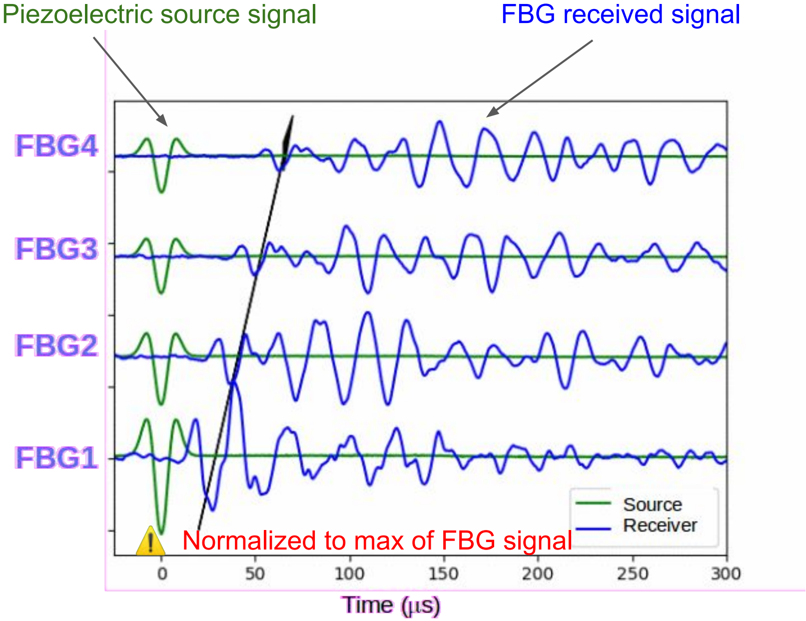
Fiber Optics at ultrasonic frequency

- 16 cm x 16 cm x 30 cm concrete blocks
  - Rc = 18.8 MPa ∓ 3.5 MPa



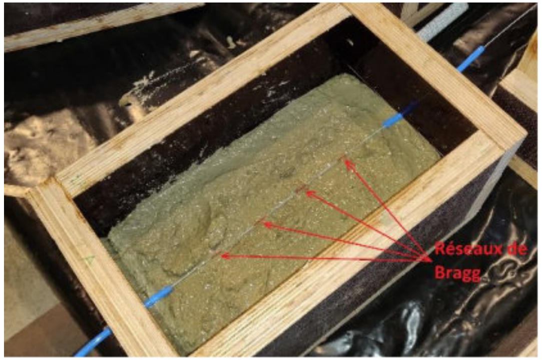


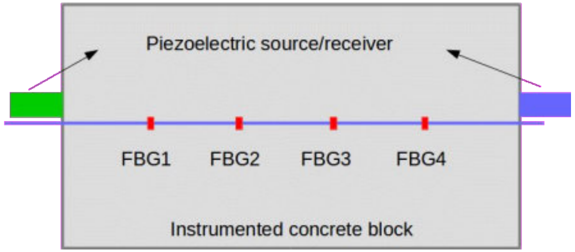
- Glued piezoelectric transducers
  - Source : 54kHz



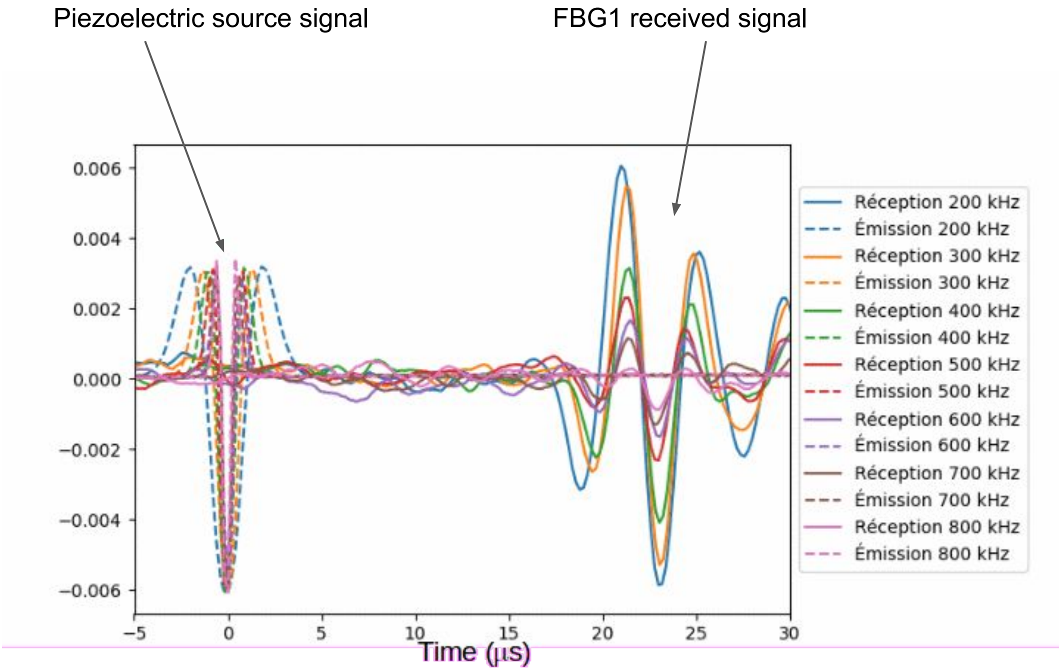
Fiber Optics at ultrasonic frequency

- 16 cm x 16 cm x 30 cm concrete blocks
  - Rc = 18.8 MPa ∓ 3.5 MPa

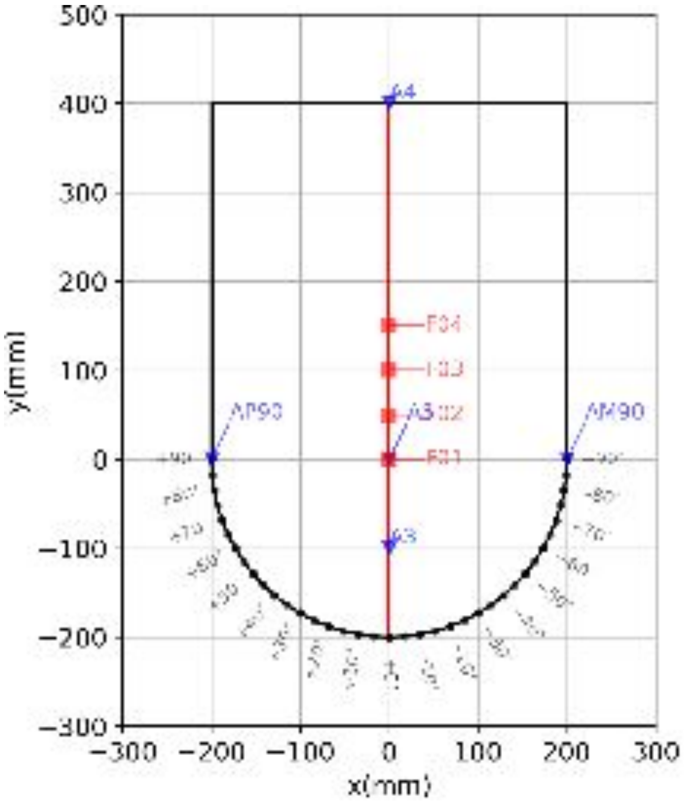


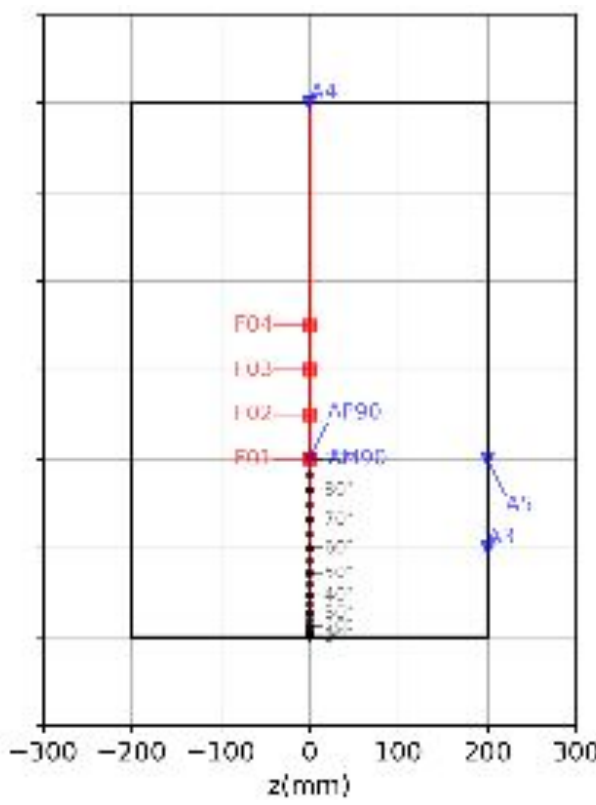


- Glued piezoelectric transducers
  - Source : 200kHz-800kHz

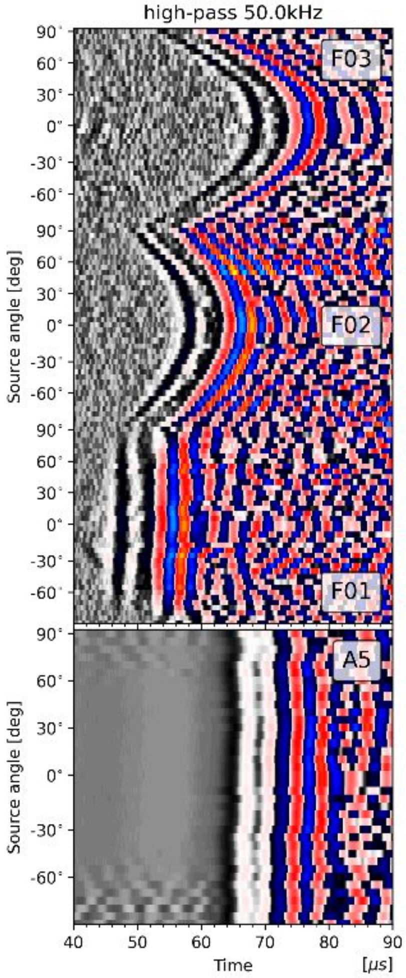


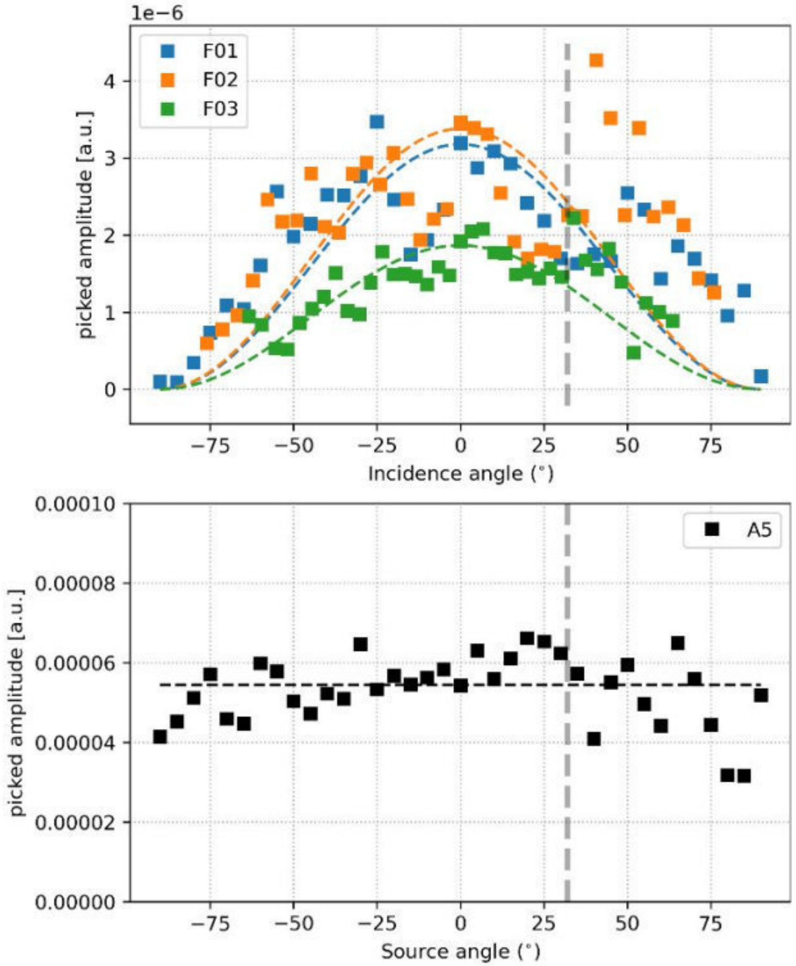
Fiber Optics at ultrasonic frequency



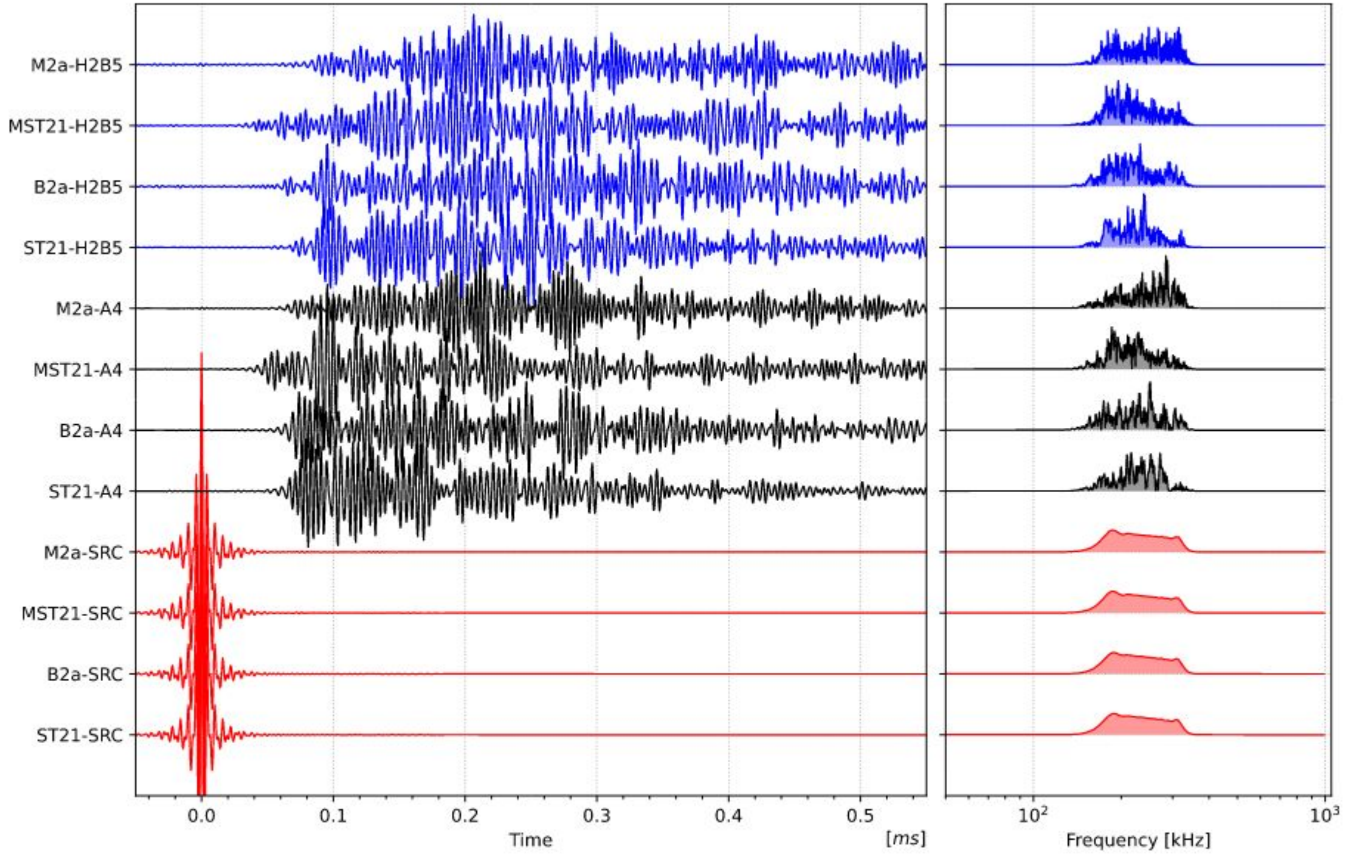


Fiber Optics at ultrasonic frequency

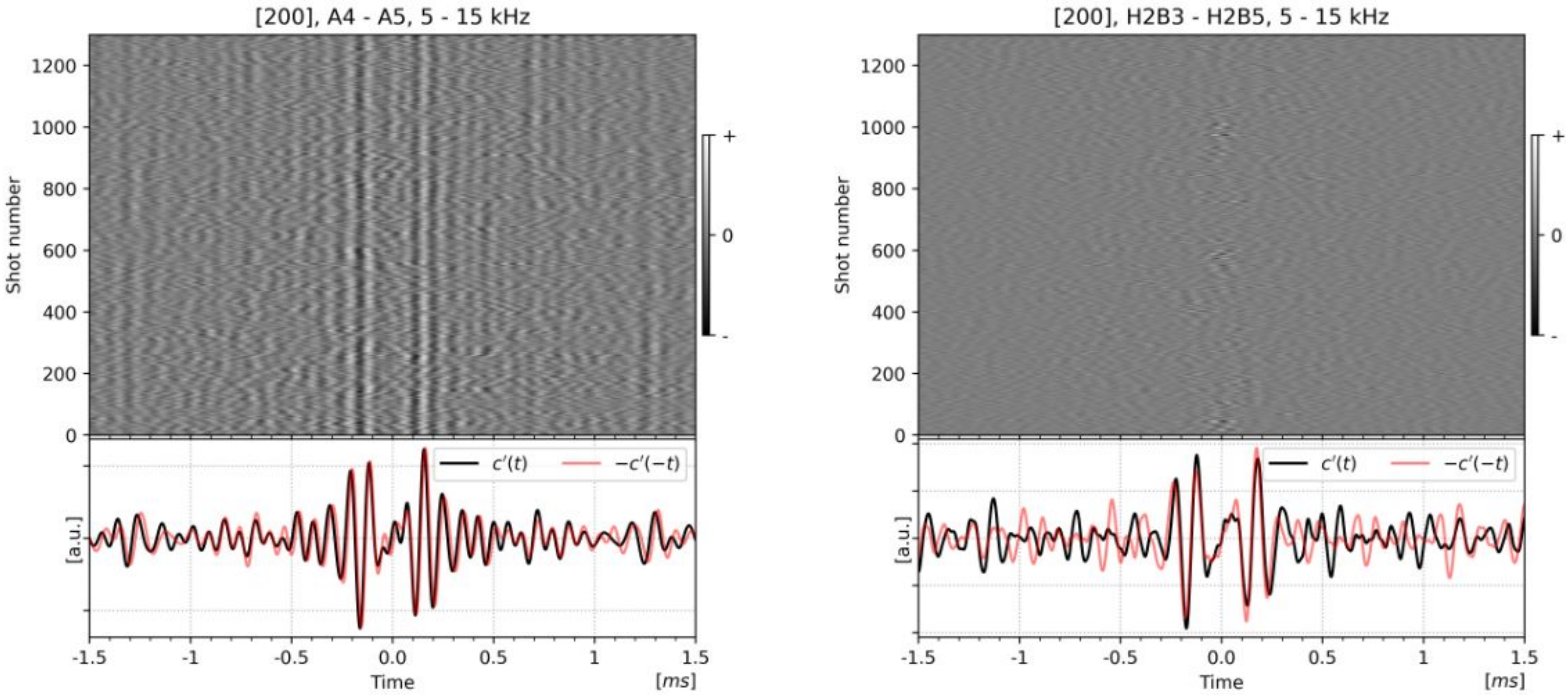




Fiber Optics at ultrasonic frequency

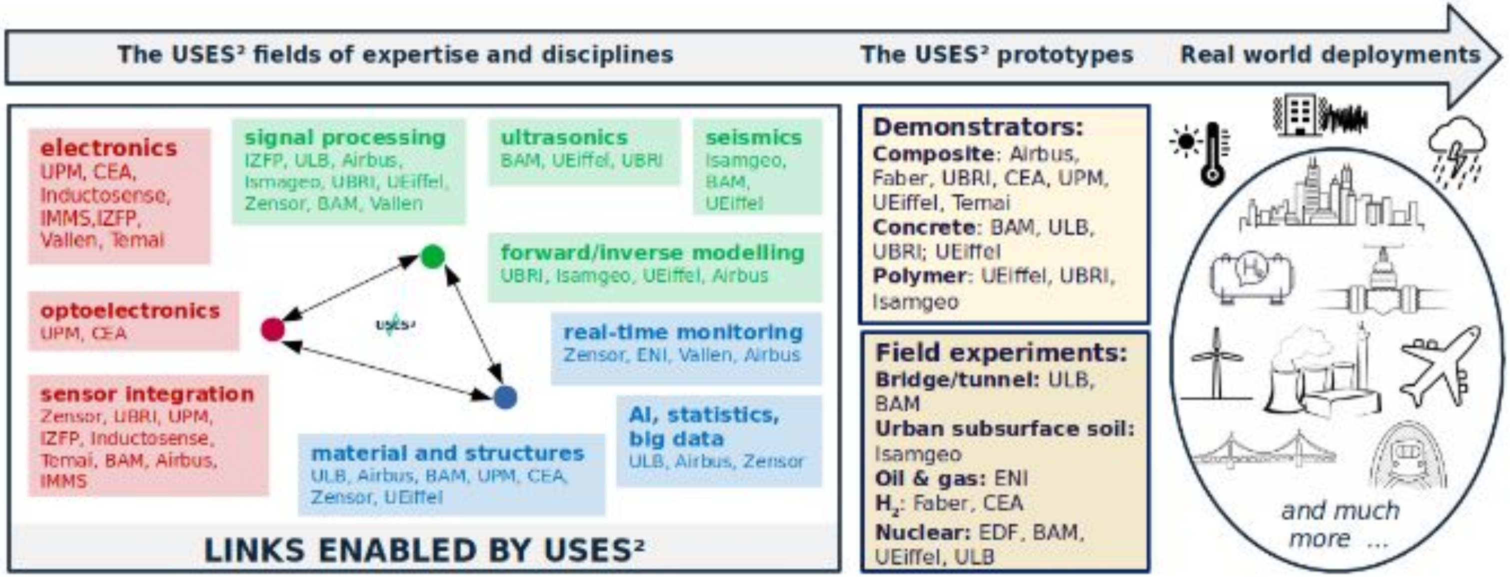


Fiber Optics at ultrasonic frequency



USES of novel **U**ltraSonic and **S**eismic **E**mbedded **S**ensors

for the non-destructive evaluation and structural health monitoring of infrastructure and human-built objects



USES²

Coda waves, Surface Waves, Fiber Optics… Some challenges and results about the monitoring of concrete structures with ultrasonic waves

Odile Abraham

Université Gustave Eiffel

LABORATOIRE GEOEND
GÉOPHYSIQUE ET ÉVALUATION NON DESTRUCTIVE