# Seismic wave propagation in heterogeneous limestone samples

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Mimic near-surface seismic field measurements at a small scale, in the laboratory, under a well-controlled environment, may lead to a better understanding of wave propagation in complex media such as in geological materials. Laboratory experiments can help in particular to constrain and refine theoretical and numerical modelling of physical phenomena occurring during seismic propagation, in order to make a better use of the complete set of measurements recorded in the field.

We have developed a laser Doppler vibrometer (laser interferometry) platform designed to measure non-contact seismic displacements (or velocities) of a surface. This technology enables to measure displacements as small as a tenth of a nanometer on a wide range of frequencies, from a few tenths to a few megahertz. Our experimental set-up is particularly suited to provide high-density spatial and temporal records of displacements on the edge of any vibrating material (aluminum, limestone, ...).

We will firstly present experiments in cuboid and cylinders of aluminum (homogeneous) in order to calibrate the seismic sources (radiation diagram, frequency content) and identify the wave arrivals (P, S, converted, surface waves). The measurements will be compared quantitatively to a direct 2D numerical elastodynamic simulation (finite elements, Interior Penalty Discontinuous Galerkin). We will then show wave measurements performed in cylindrical heterogeneous limestone cores of typical diameter size around 10 cm. Tomographic images of velocity (figure 2a) in 2D slices of the limestone cores will be derived based upon the time of first arrivals and implemented in the numerical model. By quantifying the difference between numerical and experimental results, the tomographic velocity model will be reciprocally improved and finally compared to a $X - ray$ tomographic image of that slice.

## A brief overview of the studies

*Seismic sources*

We will explore piezo-electric sources of different frequencies (100 $kHZ \sim 5\ MHz$) and test the new laser ablation source whose dominant frequency can reach 2 $MHz$ in aluminium. Avantages and drawbacks of each technology will be discussed in terms of source and wave propagation characterisation.

*Wave identification in an aluminium cube of side length 280 mm and seismic source at the center of one face*

We have identified experimentally P, S, head wave, PS, SP and surface waves measured on the cube surfaces. Meanwhile, direct numerical simulations have helped to quantitatively analyze the kinematics of wave fronts. For example, on the surface where the seismic source is excited, a P front, an S front and a PS head wave front are measured by the laser vibrometer right after the initial seismic impulse. These wavefronts can be understood by both the Huygens' Principle and the Snell-Descartes Law. In Figure 1, the seismic source excits simultaneously at time $t = 0$ a P wave and an S wave. As time evolves, waves propagate inside the volume and a P-wave propagates along the boundary as well: the latter one acts on the boundary as secondary sources which will emit both P and S waves, creating finally a new PS head wave front nicely measured in the experiments. The colours of magenta and green correspond to null amplitudes.

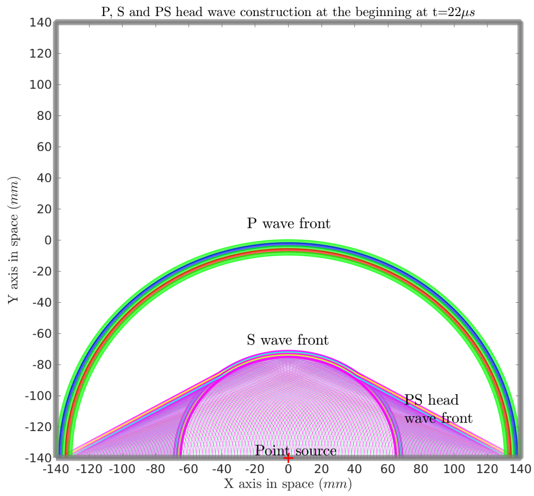
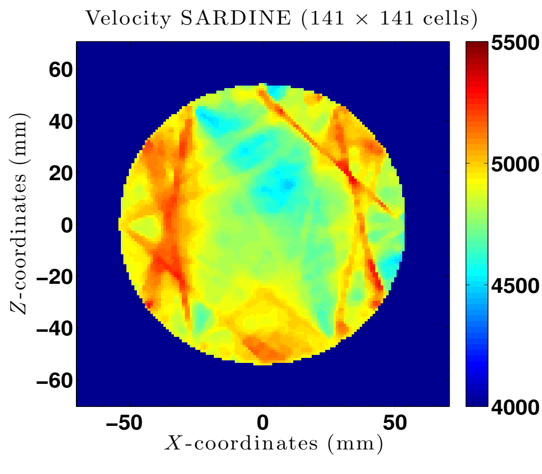


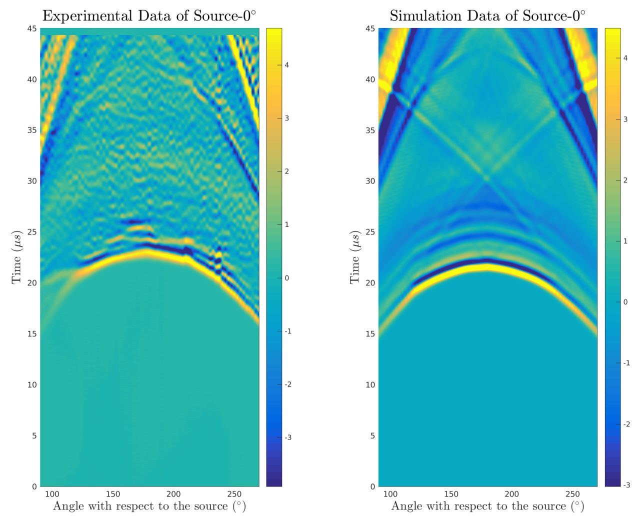

Figure 1: View from above of a 2D horizontal slice of the aluminum cube of side length 280 mm. The seismic source (red cross) emits an initial impulse at time $t = 0$. Until $t = 22$ $\mu s$, P and S wavefronts propagates within the cube as well as a head wave originating from a PS conversion as explained by Huygens' principle.

*Tomography and numerical simulation in the carbonate cylinder*

We have performed a $V_p$ tomography of a cylindrical slice of the core carbonate based upon the first P wave arrivals. Figure 2a shows the velocity model derived by using the software SARDINE. 6 sources were uniformly distributed on the surface (from 0° to 360°) while 73 uniformly distributed receivers were located along the semicircle on the other side of the corresponding source. That velocity model is then used in our direct numerical elastodynamic simulation to compute wave propagation within the cylinder slice. Figure 2b compares an experimental seismogram to a numerical one for one location of the source. In terms of first arrival times, the simulated data reproduce relatively well the measurements; the simulated first arrivals are however much smoother in terms of amplitudes than the measured ones. Some discontinuities in experimental data are not retrieved by the simulation as well thus we expect to improve the tomographic model by multiplying the number of sources and use efficiently the confrontation experiments *vs* numerics.




(a) Tomographic velocity model.




(b) Comparison between experimental and numerical seismograms, the amplitudes of displacements given in nm.

Figure 2: Tomography of the carbonate slice and direct numerical simulation.