A Monte Carlo approach applied to ultrasonic non-destructive testing

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Introduction

Non-destructive testing based on ultrasounds allows us to detect, characterize and size discrete flaws in geotechnical and architecture structures and materials. This information is needed to determine whether such flaws can be tolerated in future service. In typical ultrasonic experiments, only the first-arriving P-wave is interpreted, and the remainder of the recorded waveform is neglected. Our work aims at understanding surface waves, which are strong signals in the later wave train, with the ultimate goal of full waveform tomography. At present, even the structural estimation of layered media is still challenging because material properties of the samples can vary widely, and good initial models for inversion do not often exist.

The aim of the present study is to combine non-destructive testing with a theoretical data analysis and hence to contribute to conservation strategies of archaeological and architectural structures. We analyze ultrasonic waveforms measured at the surface of a variety of samples, and define the behaviour of surface waves in structures of increasing complexity. We invert them for the elastic properties of the sample via a global search of the parameter space which allows us to perform a complete uncertainty and resolution analysis, but the computational cost is high and increases quickly with the number of model parameters. Therefore it is practical only for defining the seismic properties of media with a limited number of degrees of freedom, such as layered structures.

Forward modelling & Dispersion analysis

Two important tools to study the surface wave propagation, and thus to characterize a layered structure, are: (1) a very accurate forward modelling to estimate the data from a known model; (2) a dispersion analysis to retrieve the frequency content of the signal distinguishing fundamental and higher modes.

The procedure applied in this work can be divided into 6 steps:

1- Define the seismic properties of a synthetic structure (Figure 1).

2- Evaluate numerically the exact Green's function for the elastodynamic equation of a spherically layered medium by expanding the displacement field into basis functions in the frequency-wavenumber (f-k) domain (Friederich & Dalkomo, 1995) (Figure 2).

3- Compute synthetic seismograms from the Green's function (Figure 3).

4- Make a dispersion analysis from the slowness-frequency (p-f) method (Forbriger, 2003) based on the slant-stack transformation of the wave-field (Figure 4).

5- Calculate the group velocity dispersion analysis using the Multiple Filter Technique (MFT) from Dziewonski (1969) (Figure 5).

6- Pick the amplitude maxima of the spectral coefficients in the f-k and p-f analysis as well as the time-frequency amplitude spectrogram to compute the corrisponding phase velocity and group velocity dispersion curves (Figure 6).

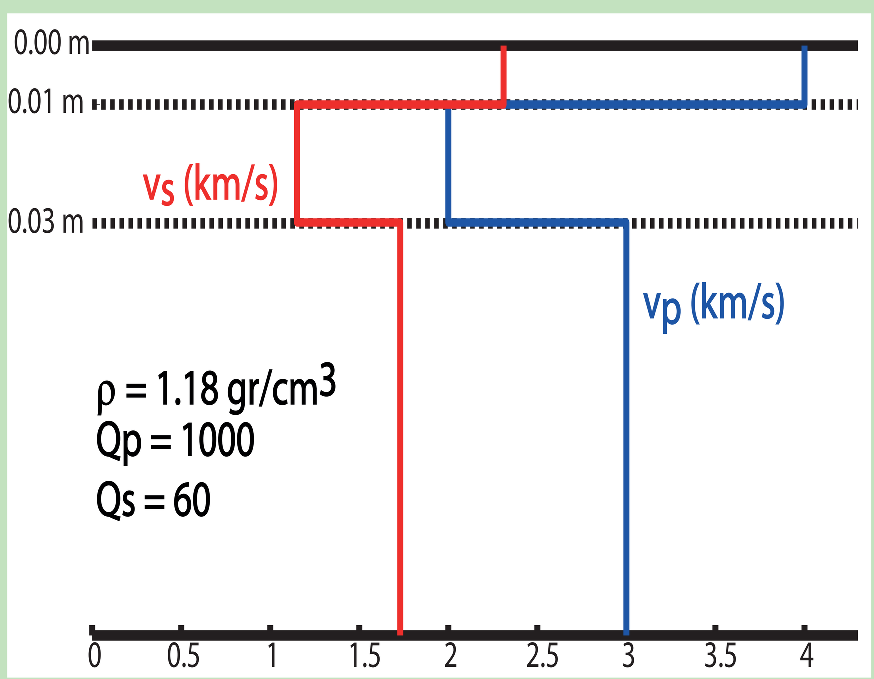

Figure 1: Compressional velocity (blue line) and shear velocity (red line) for a fast- and slow-velocity layers over a fast-velocity halfspace.

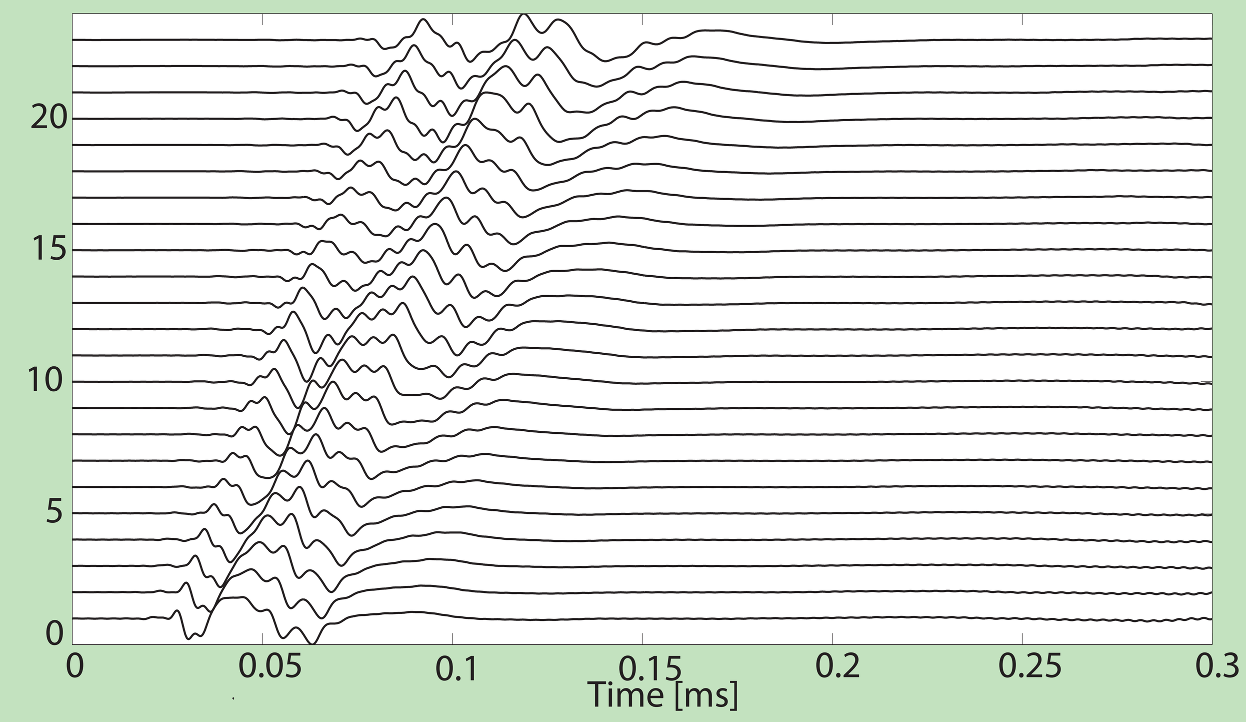

Figure 3: Vertical component displacement of synthetic seismograms calculated for the model in Figure 1 at a frequency range between 10 and 300 kHz.

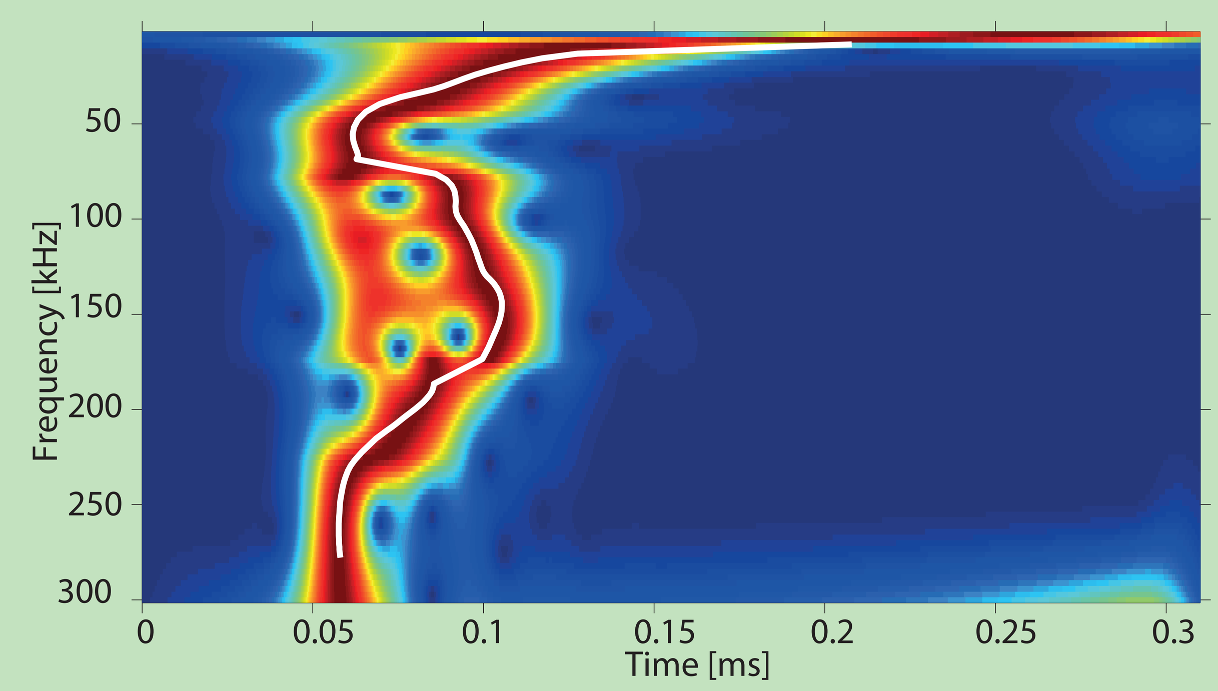

Figure 5: Time-frequency group velocity spectrum from the 13th trace in Figure 3. The white line corrisponds to the group velocity curve of the Rayleigh wave fundamental mode.

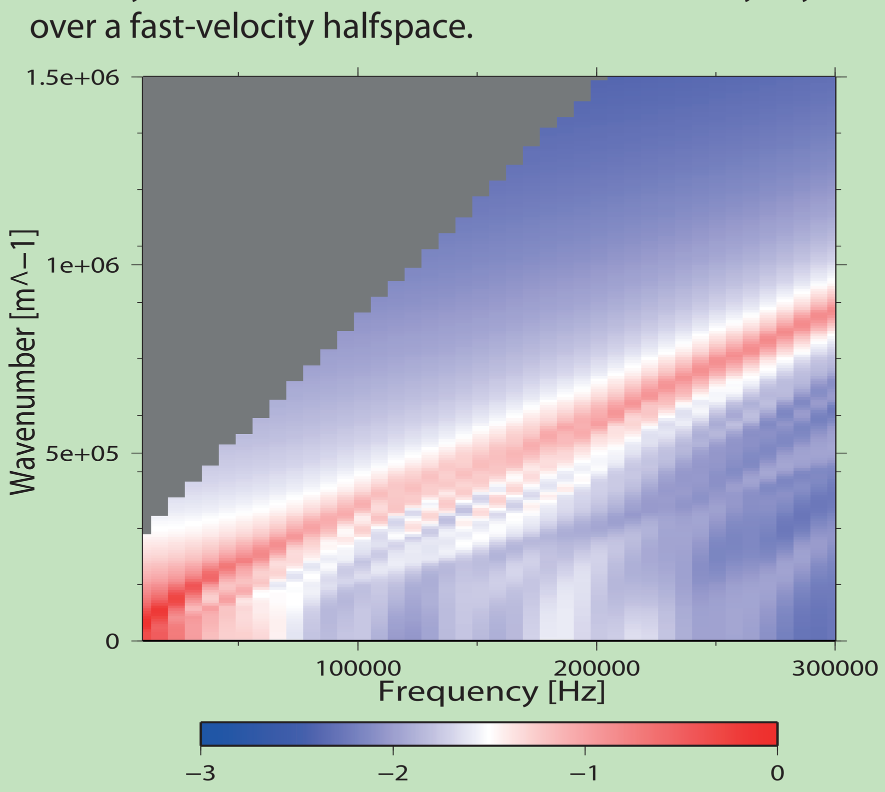

Figure 2: Spectrum of the Green's function in the wavenumber-frequency domain.

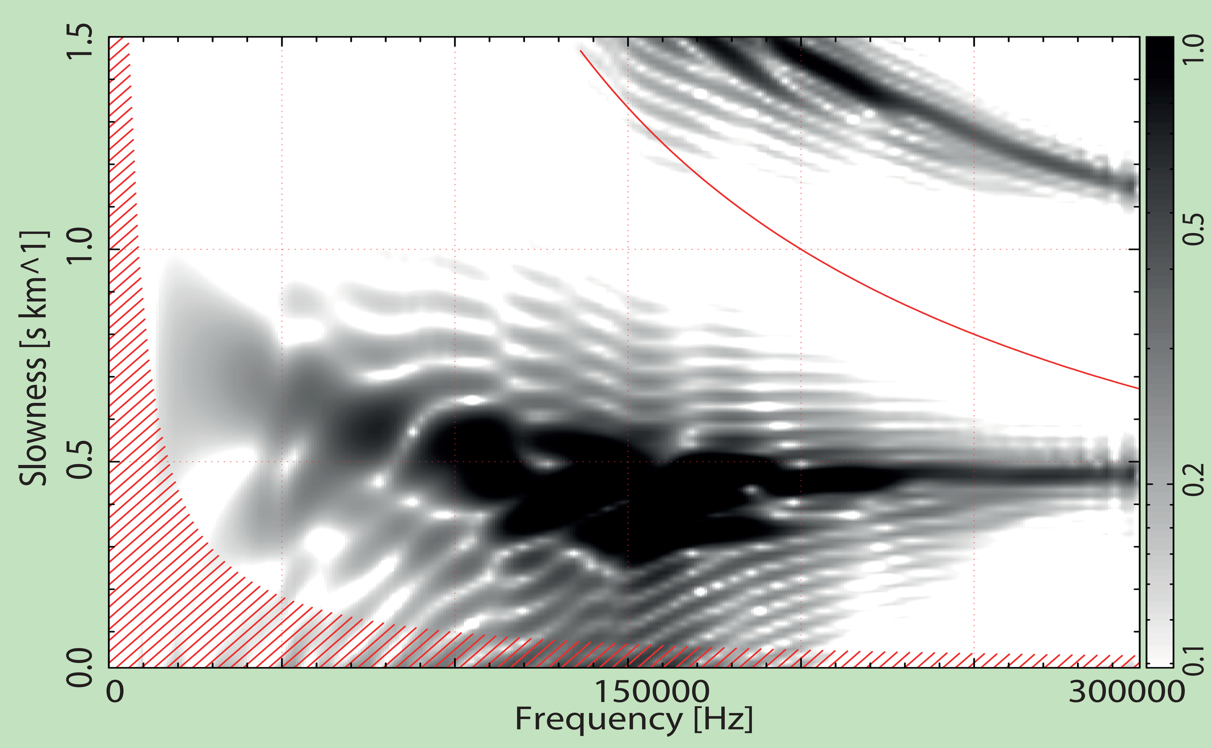

Figure 4: Spectrum of the Green's function in the slowness-frequency domain. The red hyperbola describes the aliasing limit depending on the receiver distance; while the hatched red area indicates the theoretical slowness resolution.

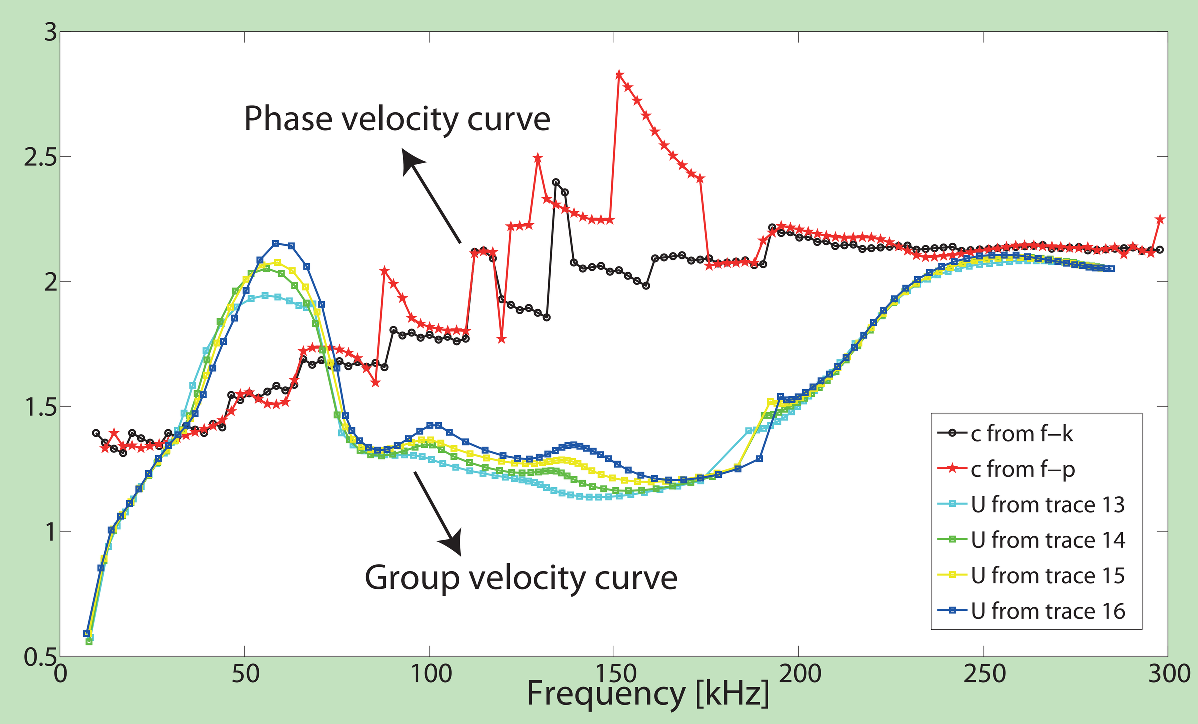

Figure 6: Phase velocity curve from the f-k analysis (black line), the p-f analysis (red line) and group velocity curve for four traces of Figure 3.

Tomographic inversion via a Monte Carlo approach

For solving the inverse problem and hence characterizing a material, we applied one of Monte Carlo methods, the Neighbourhood Algorithm. It is based on a full space search so that it samples the entire model space and attributes a misfit function to each solution compatible with the data (Sambridge 1999a). Then, all the models are turned in terms of probability density functions (pdfs) which represent all the possible information gained from the data (Sambridge 1999b). This technique gives also the possibility to invert for more than one observable and thus to infer both stiffness and dissipation characteristics of the analysed material.

In Figures 6-9 we show the results from the inversion of surface wave measurements recorded on a marble sample which was tested with a non-destructive technique at ultrasonic frequency of 10-200 kHz. We inverted for shear velocity and the quality factor Qs; the compressional velocity was coupled to the shear velocity by a scaling factor and the density was assumed known.

Figure 6: 400X205X150 mm marble sample investigated with an ultrasonic non-destructive technique.

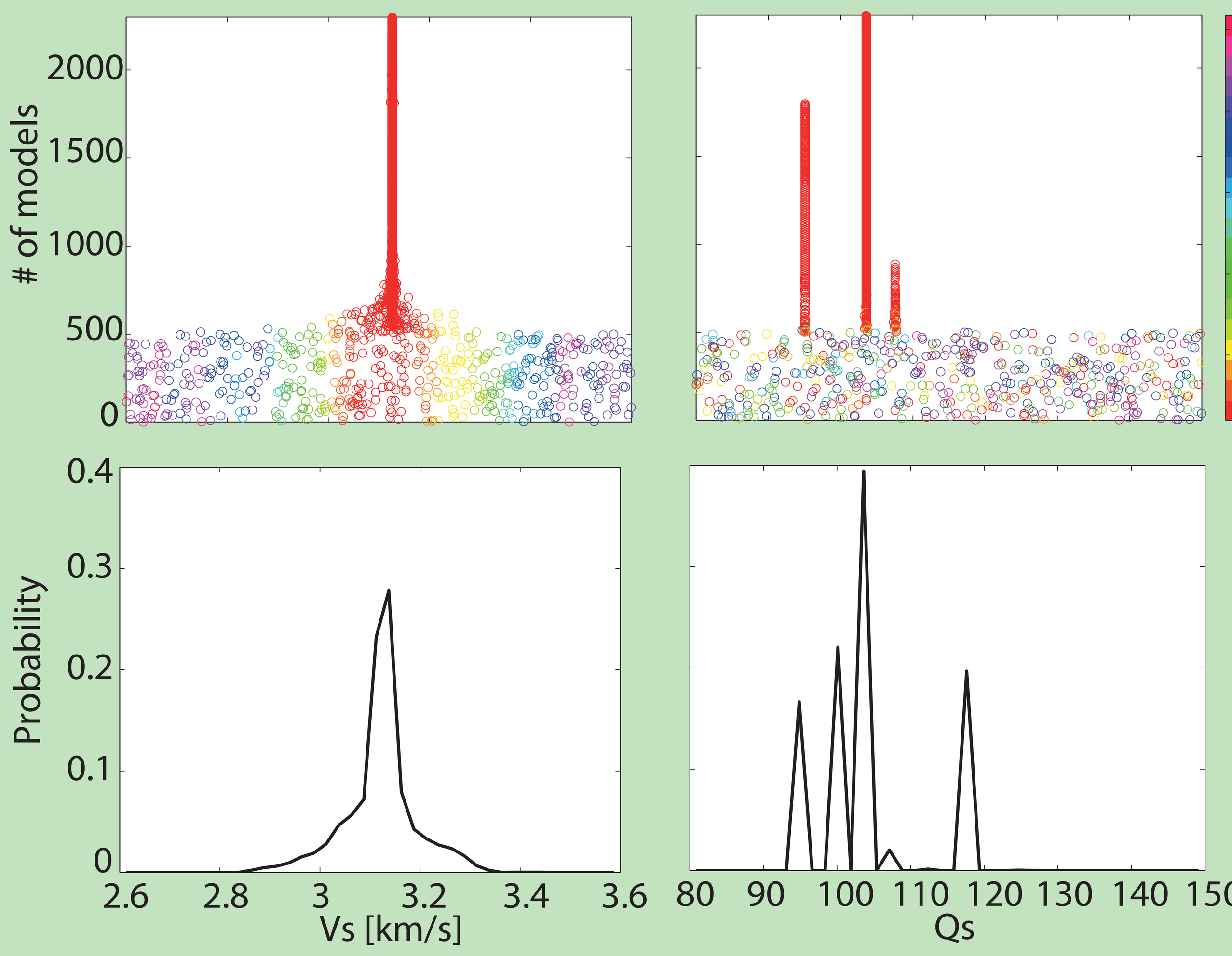

Figure 7: Sampling of 2900 models as a function of Vs, Qs and misfit in the top panel; and probability density function of Vs and Qs in the bottom panel. The boundary of Vs are fixed to (2.6; 3.6) km/s and those of Qs to (80; 150).

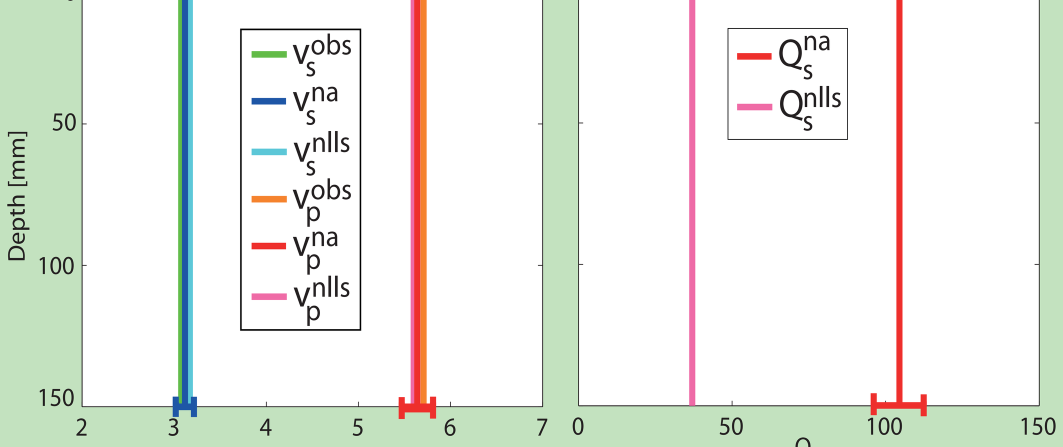

Figure 8: Vp, Vs (top panel) and Qs (bottom panel), together with their error-bars, computed from the pdfs of Figure 7 (blue and red lines, respectively). We compare our estimated model with the initial one (green and orange lines) as well as with the model computed by a non-linear least-square approach (light blue and pink lines).

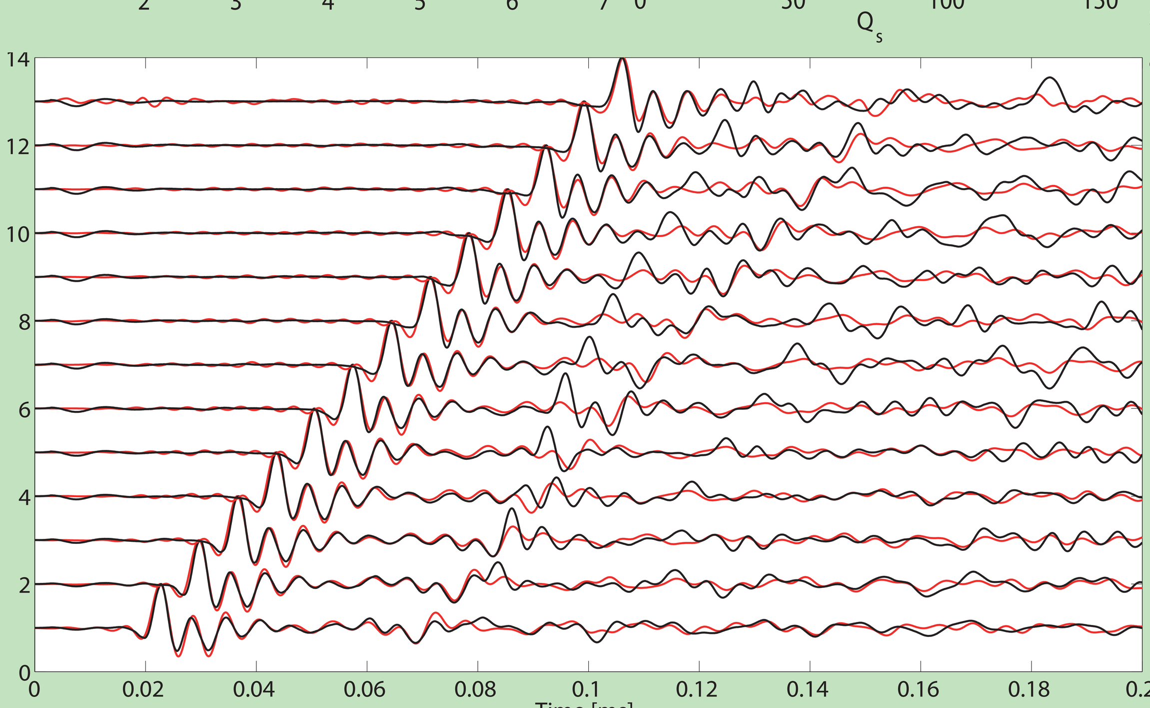

Figure 9: Comparison between seismograms computed from the model of Figure 8 (red traces) and the observed measurements (black traces).

Conclusions

This work proves the validity of a Monte Carlo approach for solving a waveform inversion and thus defining the 1-D stiffness and dissipation characteristics of synthetic structures and real samples at ultrasonic frequencies. In this context the next step is to invert also for the compressional velocity and thus to fit also the P-pick. The importance of the analysis of synthetic structures is to benchmark the propagation of ultrasonic surface waves in typical materials (e.g., marble, unweathered and weathered concrete and natural stone) tested with a non-destructive technique. For example, a fast-velocity layer over a slow-velocity halfspace describes well a pavement; while, a thin slow-velocity layer in a fast-velocity structure represents a weathered layer in an unweathered material.