Acoustics'08
Paris
June 29-July 4, 2008
www.acoustics08-paris.org

Small scale adaptation of the seismic full waveform inversion method - Application to civil engineering applications

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Full Waveform Inversion (FWI) is a very general multi-parameter quantitative imaging method originally developed to obtain high resolution images of velocities and attenuations in a natural underground medium. FWI promises relevant performances for civil engineering applications. Performances of the FWI method in seismic exploration are difficult to assess because in situ experimentations the properties of the medium are unknown. Furthermore, characteristics of the source and coupling of receivers are not controlled. In order to appraise the performances of FWI and its adaptability to subsurface applications, small scale physical models are realized and measurements are simulated in a dedicated non contact laser ultrasonic laboratory which allows to simulate seismic reflection measurement configurations. Seismograms well reproduce behaviors of real scale records in terms of waveforms but the use of a piezoelectric source with a large radiation surface area modifies the full seismograms. We applied a FWI algorithm on two synthetic data sets modelised with a punctual and a lineic source. The forward model is based on a frequency domain finite difference method. The inverse problem is solved with a gradient method scaled by the diagonal elements of the Hessian. Influence of the source on the recovered velocity medium is discussed.

Introduction

Imaging the first meters of the subsurface with seismic methods is useful for civil engineering and landscape management. Heterogeneities and strong attenuation in the near surface can make difficult the adaptation of seismic imaging methods at this exploration scale. For this reason, we have performed physical modelling at reduced scale to assess the performances of seismic methods in controlled experiments. In this paper, we will illustrate the interest of this kind of physical simulation to validate and calibrate a non conventional seismic imaging method such as Full Waveform Inversion (FWI) for near surface imaging. A non-contact ultrasonic laboratory using laser interferometry is commissioned to simulate wide angle seismic reflection measurements at centimetric scale and then reproduces propagation phenomenon in subsurface media. After a brief review of FWI principle, we shall detail the principles of the laboratory modelling. Then we shall present an example of data recorded in a model simulating the presence of an undeground cavity. The recorded data are compared to numerical simulations performed with finite difference frequency-domain code. Three points are crucial for designing realistic reduced-scale experiment: 1) definition of media with analogue materials; 2) reception simulation 3) simulation of the source. In the present study, the problem of the size of the source for seismic emission simulation will be particularly discussed and illustrated with an application of FWI.

FWI method

In most of the seismic imaging methods, only part of the information in the data is really exploited (for example, traveltimes in the case of traveltime tomography), and the full wave forms are not considered. That means that the information contained in the amplitudes is not taken into account. The specificity of FWI is to invert both phase and amplitude of all kind of waves (direct, reflected, refracted, surface waves...). This category of methods based on the inversion of the full wave field promises to be an interesting tool to recover images of complex media such as those found in the subsurface. FWI has been originally developed to obtain high resolution images of the natural underground for oil or for crustal explorations. In this study, we used the frequency-domain formulation of FWI to image near surface structures [15]. In a first stage, we shall consider only acoustic media. The FWI code that was used for this study is described in [18], [17]. The forward problem is based on a frequency-domain finite-difference method [8]. FWI is a non linear inverse problem. Resolution of such an inverse problem is conventionally performed by an iterative local minimisation of a cost function depending on the difference between observed and calculated data in the frequency domain, e.g. [14]. For applications at the subsurface scale, surface waves and diffractions by near surface heterogeneities are largely prominent. Therefore, a method taking into account the full elastic wave field will be necessary to exploit the full information in the seismograms and then enhance the quality of the imaging [6], [7]. Use of FWI for civil engineering scales requires some adaptations and performances of the FWI need to be evaluated. Physical modeling at reduced scale is a powerful tool to perform such appraisal thanks to controlled experiments.

Ultrasonic Laboratory for physical modelisation

Physical modelisation had been used for decades by geophysicists to understand different propagation phenomenon in various media [1], [4]. More recently, some authors have used physical modelisation to validate reconstruction and imaging methods [5], [9], [13]. Pratt [15] validates the seismic full waveform inversion for a crosshole configuration using a reduced scale physical model. During the last fifteen years, several research groups have studied surface waves on physical models [10] and some of them use now laser interferometry [2]. Campman et al [3] also used laser source generation. Ultrasonic modelisation of seismic measurement has been largely used for transmission configurations whereas such studies for reflection configurations remained rare. Our aim is to reproduce seismic reflection experiment configurations. The experiments were carried out in the *LCPC* (*Laboratoire Central des Ponts et Chaussées*, Nantes, France) in the MUSC (Mesures Ultrasonic Sans Contact) laboratory (fig.1 and fig.2). A Bossa Nova® laser interferometer is used as receiver and gives the amplitude of the vertical particle displacement at the surface in Angstroms.

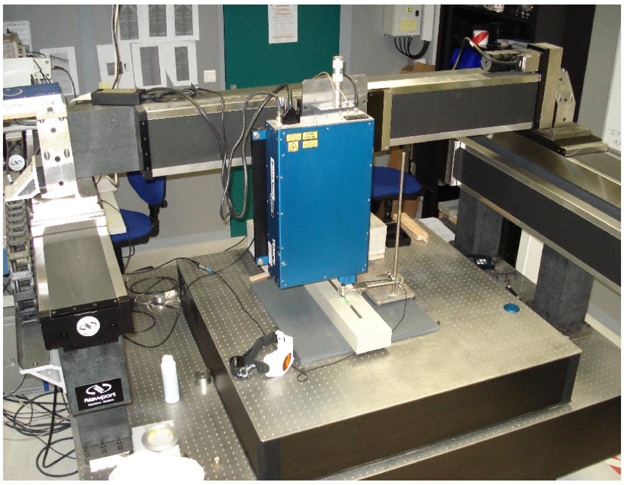

Fig.1 Laser ultrasonic seismic laboratory.

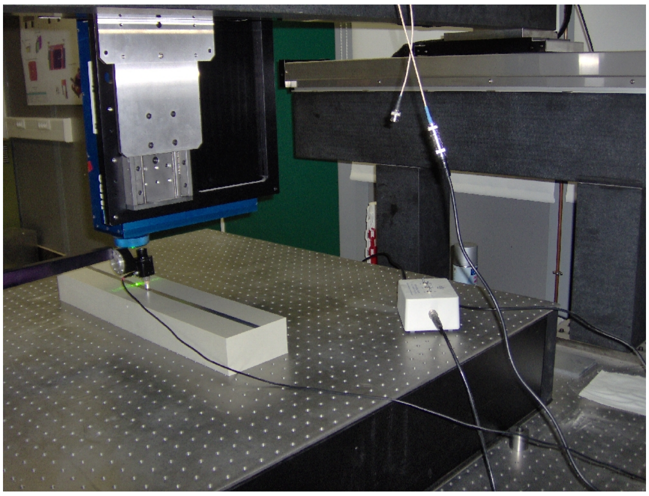

Fig.2 Acquisition of seismic data on a homogeneous polypropylen model with cylindrical void. Source is fixed on the model and interferometer scans the reflecting surface.

Signal is sampled and recorded by an acquisition card at 10MHz over 13000 points and coded on 16 bits. The full acquisition chain is able to work from 30kHz to 2MHz. Signal generation can be realized by several way, nevertheless, piezoelectric contact sources revealed the most efficient so far. The signal sent is a Ricker wavelet with a dominant frequency of 500kHz which is close to wavelets used in field seismic experiments. Both sources and receivers can be moved in two directions over the surface of the model with an accuracy of 0.01mm. Frequency repetition of the signal source is 15Hz, i.e. the ultrasonic pulse is generated every 66,6 ms and several data can be stacked for one position of source and receiver before the laser is moved. For the present study recordings were repeated at several points on the surface of the model for each source position in order to obtain seismic shot gathers.

Homogeneous model with circular cavity

Using FWI to detect underground cavities has been tested by Gélis et al. [7] and Romdhane et al. [16]. Synthetic experiments were performed to test the ability of FWI to exploit body and surface waves for imaging small-scale heterogeneities. These studies revealed some difficulties when the surface waves are involved in the inversion. Because of these difficulties and because cavity detection is an important issue, we propose to test the capacity of the MUSC laboratory to reproduce seismic data in presence of an underground cavity. In this paper, we shall limit the numerical modeling to the acoustic case. Further works will consider numerical modeling of surface in elastic media.

Description of the model

A homogeneous model in polypropylene with an empty cavity is dimensioned and realised in order to perform FWI. Longitudinal wave velocity of this material is measured at 2500m/s and Rayleigh wave velocity at 1130m/s. At 500kHz, longitudinal wavelength is 5mm. The dimension of the cavity in the model is representative of a void in civil engineering. Diameter of the cavity is one wavelength (5mm) and depth of the void roof is two wavelengths (10mm). Dimensions of the model (L=560mm, l=120mm, h=60mm) were chosen such that reflections from the edge of the model are separated at large offsets from the later-arriving diffractions from the cavity. Spacing between reception points is 1mm and recording is performed along a 180-mm long profile centred above the cavity. The source is a 18mm 500kHz circular piezoelectric contact source. For each source position and each laser position 256 emitted pulses are sent and the 256 recordings are averaged in order to improve sthe signal-to-noise ratio.

Ultrasonic seismogram

For the seismograms shown in fig.3-a, the centre of the piezoelectric source is located at a horizontal distance of 30mm from the cavity. The seismograms show in the time-offset domain arrivals of hyperbolic shape corresponding to reflected waves from the edge of the model, lineic arrivals with different slopes corresponding to direct longitudinal and Rayleigh wave propagating at the surface from source to receivers, diffractions by the cavity and multiples.

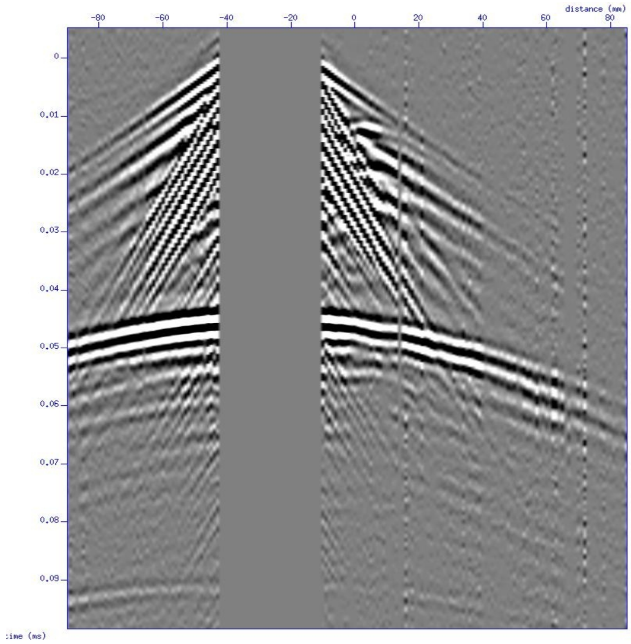

Fig.3-a Seismogram obtined on the homogeneous model with a 5 mm circular cavity at 10 mm depth.

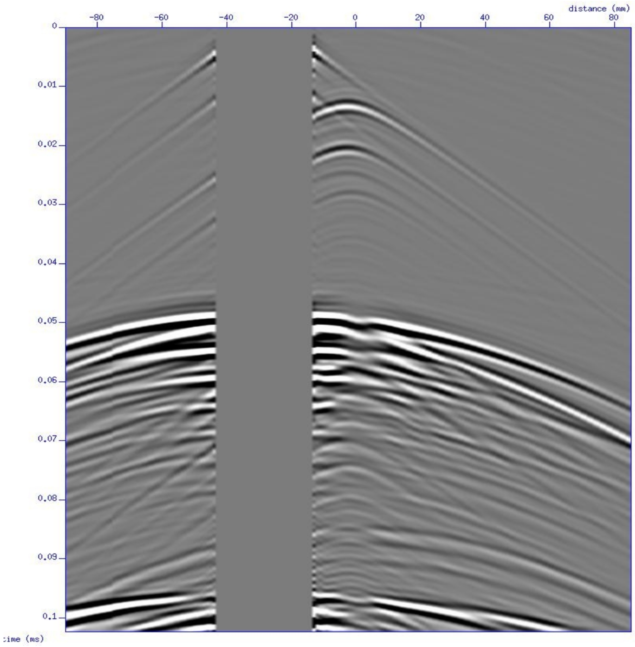

Fig.3-b numerical seismogram calculated by FDFD modelisation and simulating the experimental measurements of fig 3-a with a lineic source.

Problem of the simulation of a punctual source

The empty traces correspond to the space occupied by the source where the laser cannot access. This space is a little bit larger than the effective size of the piezoelectric transducer. In large-scale seismic exploration, sources are impact or explosion and are punctual regarding to the wavelength and the distances of propagation. Technological limitation makes the reproduction of a punctual source difficult to obtain with piezoelectric transducers. Several kinds of sources have been tested and the best compromise between frequency, dimension, directivity and energy repartition is obtained for contact circular piezoelectric source. Nevertheless, a virtual double source phenomenon is observed in the seismograms of Fig. 3-a. The source behaves like two monopolar punctual sources located at the extremities of the piezoelectric element.

A numerical modelisation using the frequency domain finite difference code (FDFD) performed for a succession of monopolar sources and a free surface reproduces the observed arrivals and the shadow caused by the cavity Fig. 3-b. Surface waves and conversion of the diffractions in surface wave are not modelised because of the acoustic approximation used in the modelling. The directivity of the piezoelectric transducer is correctly modelised and the double source effect is reproduced in term of phase but not in amplitude because the whole transducer is not modelised. Other acquisitions with different piezoelectric sources at different frequencies and with different materials confirmed this phenomenon. Moreover, directivity of the source and repartition of energy among surface or bulk waves are directly linked to the effective diameter of the source [11], [12], [19]. When wavelength becomes large compared to the size of the source, sources tend to behave like a punctual omnidirectional source. At contrary, when wavelength is small compared to radiating source, source is directive: most of the energy is then directed in front of the transducer. The consequences in seismograms are that near-offset arrivals have higher amplitudes and higher frequencies than far-offset ones, and most of the energy is contained in the reflected waves at the expense of that of the direct waves.

Today, the problem of the size of the source compared to the wavelength is a real limitation in reduced-scale seismic modelling. Different sources have been tested. Smaller size transducers are never enough powerful or are too high frequency. Using higher velocity materials (metals) in order to have larger wavelength is also precluded by the size and the weight of the corresponding models. New generation of powerful punctual piezoelectric source ACSYS® have been tested and show interesting results but are too low frequency (30-200kHz) so it is necessary to reconsider size and material chosen for the scale models. Another solution is to take into account the source characteristics in the full waveform modelling and inversion.

Data inversion with a punctual source and a lineic source

In this section, we perform a numerical experiment to illustrate the footprint of the source dimension on seismic imaging performed by full waveform inversion. The model is composed of 3 layers whose P-wave velocities are 1500, 1650 and 1800m/s from top to bottom. A circular cavity is located in the first layer. The velocity in the cavity is 350m/s. The diameter of the cavity is 5 mm. Fig. 4-a and Fig. 4-b represent the true and the initial models for FWI respectively. The finite difference grid contains 100 x 294 points. 100 receivers are positioned along the surface with a spacing of 1mm and 10 sources are positioned every 10mm.

Six frequencies (100kHz, 150kHz, 220kHz, 310kHz, 450kHz and 650kHz) were successively inverted proceeding from the low to the high frequencies and 3 iterations were performed by frequency inversion. We performed two tests using a punctual source and a 10-mm long lineic source respectively. Fig. 4-c and Fig 4-d represent the final velocity models obtained after the last inversion iteration of the highest frequency for monopolar or lineic sources respectively. Images of the cavity are in both cases recovered. Artefacts observed around the cavity and the periodic noise visible on the whole model may be due to the fact that the assumptions underlying the Born approximation are not honored in the case of such high-velocity contrasts. Indeed, the Born approximation used for the linearisation of the inverse problem allows only small diffractors in terms of size and amplitudes. Therefore, it requires imaging of small velocity contrasts only while a cavity in a solid medium represents sharp contrasts. Reconstructed velocities are sensibly closer to the true velocities when using a lineic source whereas resolution is higher when a punctual source is used. Indeed, using a large source leads to a spatial smoothing of the reconstructed image including the artefacts caused by the violation of the Born approximation.

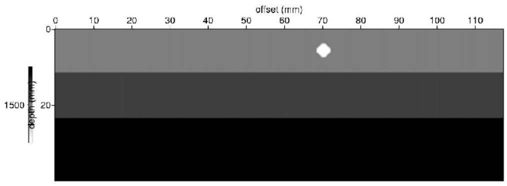

Fig.4-a True velocity model

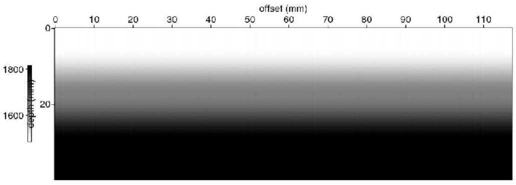

Fig.4-b initial velocity model for inverse problem

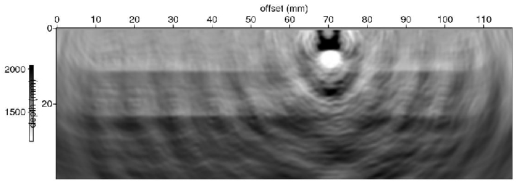

Fig. 4-c recovered velocity image with a punctual source

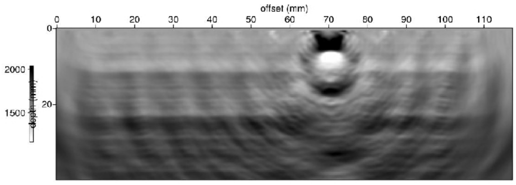

Fig.4-d recovered velocity image with a lineic source

Conclusion

An ultrasonic laboratory using laser interferometry was designed to perform seismic reflection measurements and allows us to simulate at a reduced scale P waves and surface waves arrivals for geophysical subsurface investigations. This laboratory provides experimental simulation in order to assess seismic imaging methods. In this context, the present paper shows the first step of a study to quantify the performance of Full Waveform Inversion method in the context of civil engineering topics. We illustrate this experimental capacity in the case of cavity detection by comparing experimental data with a numerical simulation obtained by FDFD under the hypothesis of acoustic propagation. Material used to simulate the surrounding medium is a bloc of polypropylene. Comparison between the recorded and computed P wave field shows a good agreement.

However, the reduced-scale source was simulated by a piezoelectric transducer which is large in regard to the wavelength propagated. Two problems remain in the data due to the source dimensions. First, a blind zone is introduced in the shot gathers at small offsets on each side of the source. Second, a double pulse is recorded as if the large source was composed of two punctual ones. This later problem can be avoided by taking into account the size of the source in the numerical simulation as we proposed. However, further investigation works are under way to use sources which can be considered as punctual with respect to the propagated wavelength.

Acknowledgments

The authors would like to acknowledge Geoscience Azur laboratory, particularly Stephane Operto for providing the forward and inverse modelisation code. We are also grateful to him for proofreading and advice. This study was partly funded by the French ANR - project ANR-05-NT05-4247.

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