THIS COMMUNICATION IS CANCELLED (PAPER IS AVAILABLE). Laboratory benchmarks vs. Synthetic modeling of seismic wave propagation in complex environments (BENCHIE Project)

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Accurate simulations of seismic wave propagation in complex geological structures with great and rapid variations of topography are of primary interest for environmental and industrial applications. Unfortunately, difficulties arise for such complex environments, due essentially to the existence of shadow zones, head waves, diffractions and edge effects. Usually, methods and codes are tested against "validated" ones, but one might wonder which method/code ultimately approaches the "real" solution. An original approach for seismics is to compare synthetic seismic data to controlled laboratory data for a well-described configuration, in order to analyze the respective limitations of each method/code. We present here some preliminary results provided by both laboratory experiments conducted in a tank and numerical simulations of wave propagation. The laboratory data have been obtained by zero-offset acquisitions at different ultrasonic frequencies on the Marseille model which is made up of anticlines, fault and truncated pyramid. The numerical results have been obtained by two methods: the Spectral-Element Method and the Tip-Wave Superposition Method.

1 Introduction

Accurate simulations of seismic wave propagation in complex geological structures with great and rapid variations of topography are of primary interest for environmental and industrial applications. Unfortunately, difficulties arise for such complex environments, due essentially to the existence of shadow zones, head waves, diffractions and edge effects. Usually, methods and codes are tested against "validated" ones, but one might wonder which method/code ultimately approaches the "real" solution. An original approach for seismics is to compare synthetic seismic data to controlled laboratory data for a well-described configuration, in order to analyze the respective limitations of each method/code. This is one of the objectives of the BENCHIE project, which brings together laboratories in France, Norway and Russia. In this presentation we will present some preliminary results provided by both laboratory experiments conducted in a tank and numerical simulations of wave propagation. The laboratory data have been obtained by zero-offset acquisitions at different ultrasonic frequencies on the Marseille model which is made up of anticlines, fault and truncated pyramid. The numerical results have been obtained by two methods: the Spectral-Element Method and the Tip-Wave Superposition Method.

2 Laboratory simulations

Several laboratory experiments were carried out at the Laboratoire de Mécanique et d'Acoustique in Marseille (France). The model used in these experiments, called "Marseille model", is partly based on the French model [1], but contains original topography like a truncated anticline and a truncated pyramid (see Figure 1). The model of size 60cm × 40cm × 7cm was made of PVC material, whose acoustic properties are similar to the properties of a real geological medium. The measured density, P-wave velocity, and S-wave velocity, are 1412 kg/m^3, 2220 m/s, and 1050 m/s, respectively. For the frequency range 500 kHz - 1 MHz, the measured P-wave and S-wave absorptions (namely, Q_P and Q_S) in PVC material are $49 \leq Q_P \leq 60$ and $27 \leq Q_S \leq 31$, respectively. The height of the anticline and of the fault of the Marseille model is equal to 40 mm, while the height of the truncated anticline (respectively, the truncated pyramid) is 15 mm (respectively, 30 mm). These values were chosen to be much greater than the wavelengths in water or PVC material. The Marseille model was immersed in water whose measured P-wave velocity was equal to about 1480 m/s. For practical reasons it lied on a thick aluminum plate. The model was illuminated by two different sources at two different far-field distances from the surface (namely, 10.5 cm and 15 cm (± 1 mm)). The sources were represented by two piezoelectric transducers excited by a pulse generator. These transducers, with central frequencies equal to 500 kHz and 1 MHz, with diameter equal to 2.54 cm and 1.27 cm, and beam angles equal to 8.3° (at -3 dB), acted also as receivers. Zero-offset seismic configurations were thus considered (see Figure 2). The area covered by the acquisition (500 mm × 300 mm) is shown in green in Figure 3. The acquisitions were performed along Y-lines with a spatial sampling $\triangle x = \triangle y$ equal to 2 mm for the frequency 500kHz and to 1mm for the frequency 1MHz. Each acquisition of the whole data for a specific distance from the surface of the Marseille model lasted 32 hours for the frequency 500 kHz and 130 hours for the frequency 1 MHz.

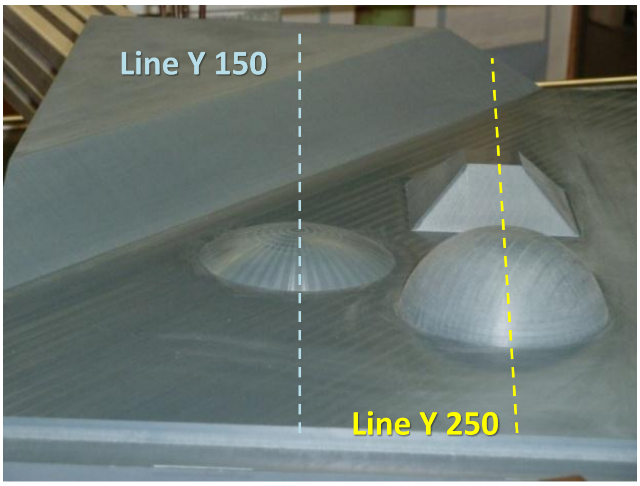

Figure 1: Marseille model with its fault, anticlines and truncated pyramid.

We present here some laboratory results. More specifically, the data acquired by both transducers along two lines (namely, Line Y 150 and Line Y 250 (Figure 3)), are shown in Figure 4 and Figure 5. These data have been obtained after application to rough data of i) a low-pass filter, in order to eliminate the harmonic resonances of the transducers, and ii) a saturation process enlighting all the signals, even the weakest ones.

By qualitatively analyzing Figure 4 and Figure 5, we can note that:

- diffractions at the edges of topographic structures can be observed for both data sets (at the frequencies 500 kHz and 1 MHz);

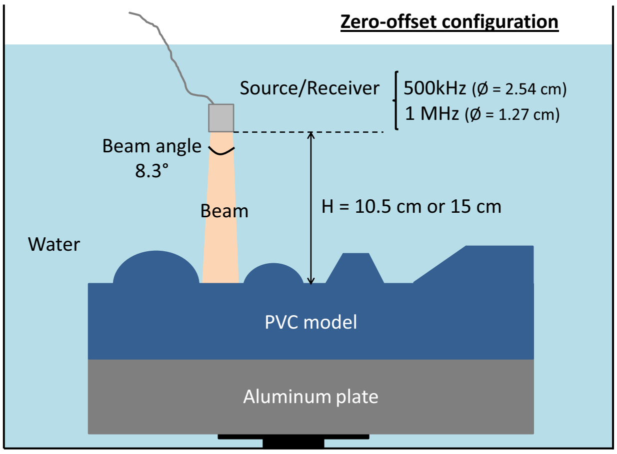

Figure 2: Acquisition design.

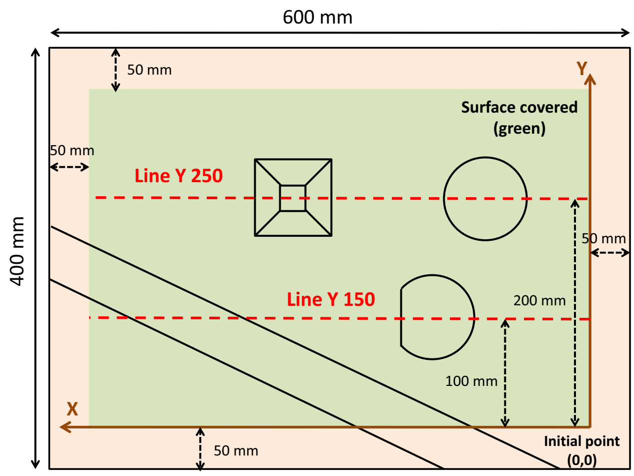

Figure 3: Surface of the Marseille model covered by the acquisition.

- the slope of the fault and the slopes of the non-truncated anticline are more visible for the frequency 1 MHz than for the frequency 500 kHz. This is probably due to the sampling of the acquisition and the bandwidth associated with each transducer. The steep slopes of the truncated pyramid are invisible;
- the signals for the frequency 1 MHz are more attenuated than the signals for the frequency 500 kHz. This is due to (weak) absorption in the PVC. Fewer multiple reflections are present on the data for 1 MHz;
- signals can be more easily separated in time for the frequency 1 MHz than for the frequency 500 kHz. Indeed, the bandwidth of the 1 MHz-source is greater than the bandwidth of the 500 kHz-source.

3 Numerical simulations

3.1 Numerical methods

Two numerical methods were tested on Marseille model and compared with data obtained in laboratory conditions : the Spectral Element Method (SEM) and the Tip-Wave Superposition Method (TWSM).

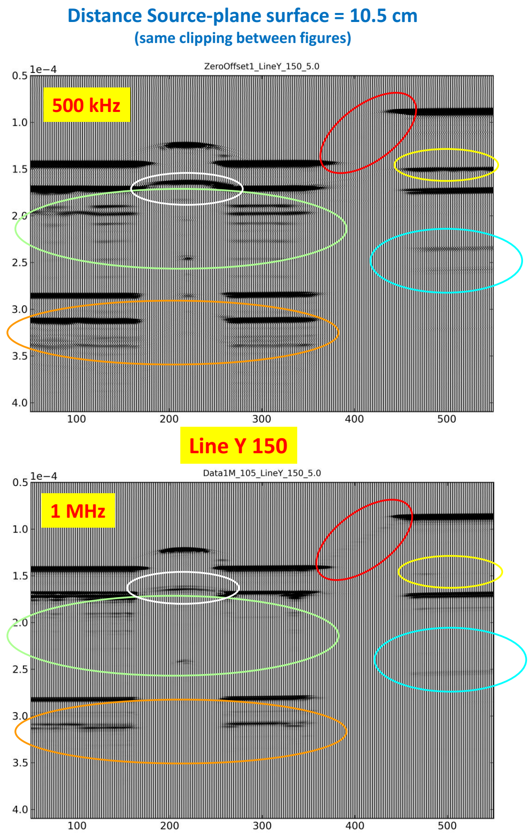

Figure 4: Comparison of data acquired along Line Y 150 for the 500 kHz-transducer (up) and the 1 MHz-transducer (bottom).

SEM is based upon a high-order piecewise polynomial approximation of the weak formulation of the wave equation. It combines the accuracy of the pseudospectral method with the flexibility of the finite-element method [2]. In this method, the wavefield is represented in terms of high-degree Lagrange interpolants, and integrals are computed based upon Gauss-Lobatto-Legendre quadrature. This combination leads to perfectly diagonal mass matrix, which in turn leads to a fully explicit time scheme that lends itself very well to numerical simulations on parallel computers. It is particularly well suited to handling complex geometries and interface conditions. As a consequence, the accurate simulation of surface wave propagation is straightforward without any additional cost [3].

In TWSM seismic wave propagation can be seen as a combination of two consequent processes: propagation inside layers with smoothly varying properties, and reflection and transmission at internal reflectors, which are represented by parameter discontinuities (Figure 6). TWSM is designed to model multiply reflected and transmitted wavefields in layered 3D media [4, 5, 6]. It can handle several reflectors of complex structure and is not limited to weak contrasts or small incidence angles. The propagation and reflection/transmission phenomena in each layer are described as action of layer tip-wave beam matrices. Their elements are approximated with the beams of the tip waves diverging from a small radiating interface element and reflecting/transmitting at each receiving interface element. The method gives the possibility to model the wavefield corresponding to specified wavecodes, as well as to collect the full seismogram within a finite time window.

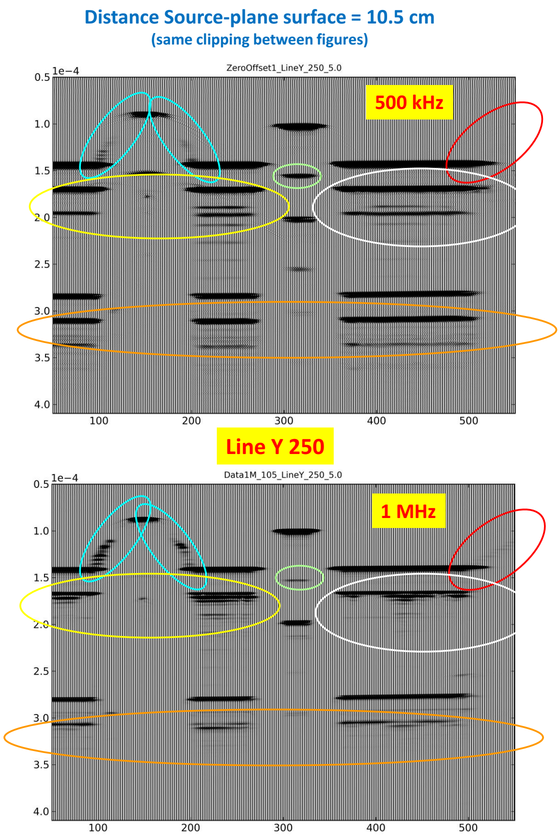

Figure 5: Comparison of data acquired along Line Y 250 for the 500 kHz-transducer (up) and the 1 MHz-transducer (bottom).

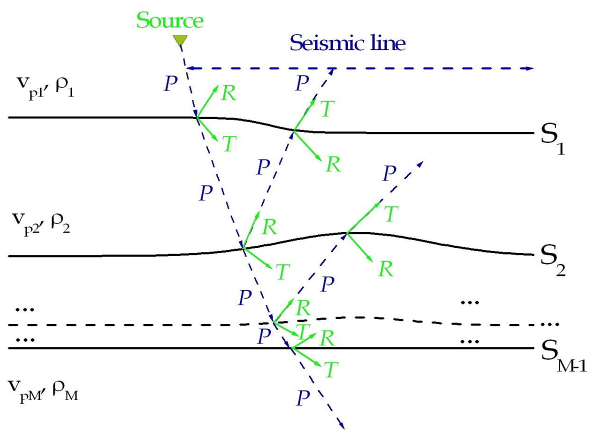

Figure 6: Schematic illustration of the TWSM concept for describing seismic wave propagation.

3.2 Comparison of numerical simulations and experimental data

Numerical simulations of wave propagation in the time domain over the Marseille model were performed using SPECFEM2D, a 2D software which implements the SEM. The model was meshed with quadrangles using the open source software Gmsh. Simulation of directional directivity of standard ultrasonic transducers was performed using a set of equidistant omnidirectional sources (like a horizontal array) whose amplitude is weighted by a Hamming window. An example of the type of radiation that can be simulated numerically is shown in Figure 7. We can see clearly in Figure 7 that the radiation of the simulated source is directed along the vertical. This radiation is obtained with 51 point sources distributed over a line length of 2.54 cm which corresponds to the diameter of the transducer used in the experiments performed for the 500 kHz frequency. Some numerical simulations of wave propagation in the vicinity of the truncated anticline of the Marseille Model are shown in Figure 7. They illustrate the different kind of effects that can be encountered with such a geometry, and more specifically the edge effects.

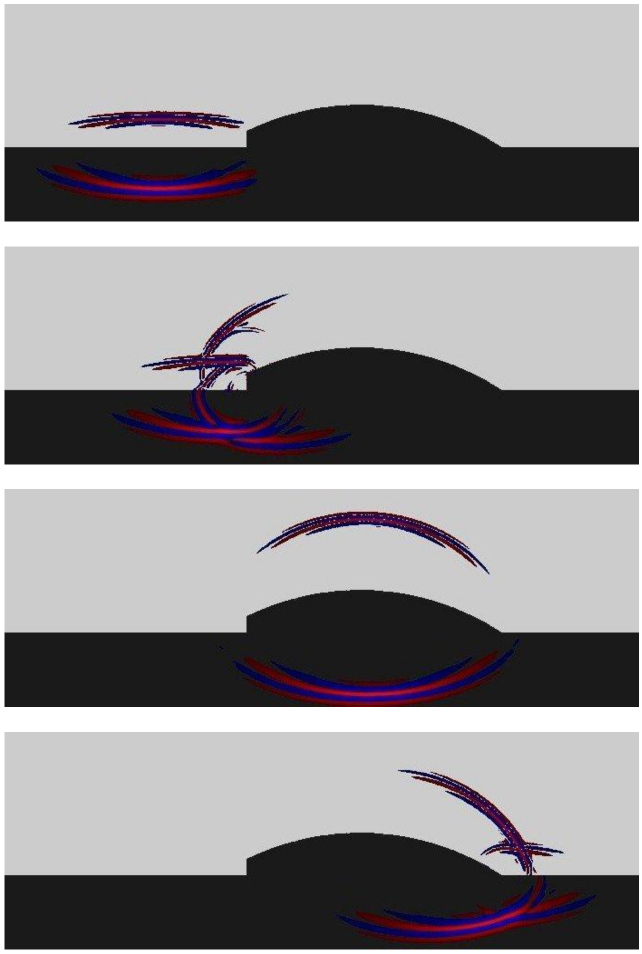

Figure 7: Simulations of wave propagation over the truncated anticline using SEM.

Package of programs based on TWSM was used for synthetic modeling of the experiments with Marseille model. We modeled the primary reflection with the single diffractions from the top of the PVC model using the 3D elastic version of TWSM. Here we present the results obtained along the Line Y150 for the transducer with the central frequency equal to 500 kHz and the distance from the surface being 10.5 cm (Figure 8). The visual comparison of the total seismogram recorded in the laboratory and the one obtained using TWSM shows that the main structures of the model appear similar on them. Therefore the more detailed comparison of two traces obtained using TWSM and recorded in the laboratory over flat part of the surface is shown in Figure 9. Quantitative comparison shows good coincidence of two traces in time window $0.14 * 10^{-3}$ s < t < $0.15 * 10^{-3}$ s and reveals minor differences in the shape and the amplitude of the signal.

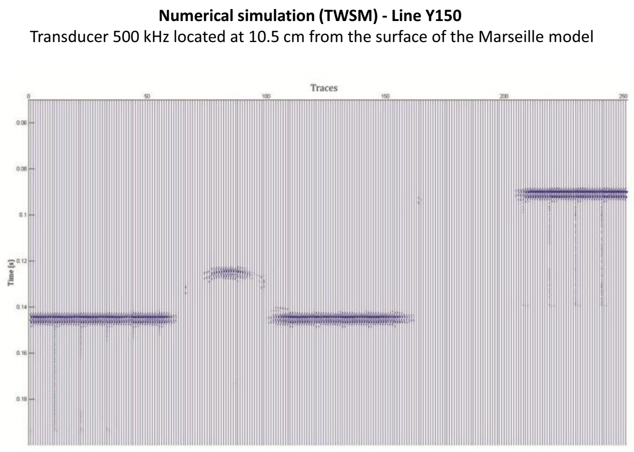

Figure 8: Synthetic seismogram of the primary reflection with the single diffractions obtained using TWSM.

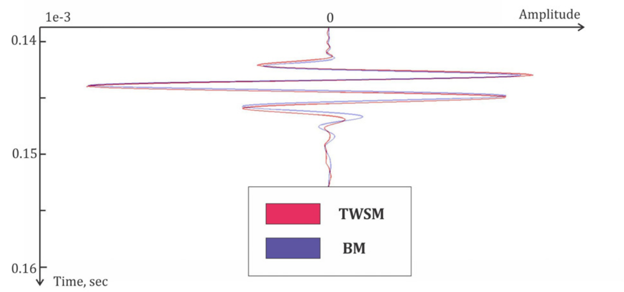

Figure 9: Comparison of two traces in time window $0.14 * 10^{-3}$ s < t < $0.15 * 10^{-3}$ s. Blue:recorded in the laboratory, red: obtained using TWSM.

4 Conclusion

The objective of the international project BENCHIE, which brings together laboratories in France, Norway and Russia, is to provide an original alternative for validation of numerical methods, widely used in seismics nowadays. This comparison should help to choose the right strategy for the further development of these methods in order to simulate higher performance (accuracy and speed) of wave propagation (forward problem) and seismic imaging (inverse problem), which is of major interest for environmental and industrial applications. First experiments were performed in zero-offset seismic configuration using a geological model with strong 3D topographies. Measurements of ultrasonic waves reflected at each point on the surface of the geological model were performed and analyzed in order to improve the understanding of the physical mechanisms involved in the interaction of the waves with irregular surface. Numerical simulations of wave propagation, based on the Spectral Element Method and the Tip-Wave Superposition Method, were carried out under the conditions of the tank experiments. Comparison of the first numerical simulations with experimental data has revealed good quantitative fit in time arrivals and instantaneous wavelet amplitudes, and admissible quantitative fit in wavelet shapes. Future work will be concerned with multi-offset seismic experiments using sources with unfocused beam.

Acknowledgements

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