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Comparing Spectral-Element Numerical Results with Laboratory Data: An Example for a Topographical Model

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Summary

Numerical simulations are widely used for forward and inversion problems in seismic exploration to investigate different wave propagation phenomena. However the numerical results are hard to be compared to real measurements as the subsurface is never exactly known. Using laboratory measurements for small-scale physical models can provide a valuable link between numerical and real seismic datasets.

In this work, we present a case study for comparing ultrasonic data for a complex model with spectral-element synthetic results. The small-scale model was immersed in a water tank. Reflection data was recorded with piezoelectric transducers using a conventional pulse-echo technique. We paid special attention to the implementation of the real source signal – and radiation pattern – in the numerical tool. It involved a laboratory calibration measurement, followed by an inversion process. The model geometry was implemented through a 3D structural mesh, which was optimized for the computational cost and accuracy.

The comparisons show a very good fit between synthetic and laboratory traces, and the small discrepancies can be assigned mostly to the noise present in the laboratory data.

Introduction

Although numerical simulations are widely used to investigate different wave propagation phenomena, synthetic results are rarely compared to physical measurements. Using a laboratory dataset measured in a well-controlled environment for a known small-scale physical model can provide a valuable basis for such comparison. Despite laboratory data is not real-life seismic data, laboratory measurements can provide a good link between purely numerical results and real measurements. By benchmarking the numerical algorithms, one can not only shed light on the accuracy and reliability of the simulations, but it can also lead to developing a robust and efficient procedure to accurately simulate realistic measurements.

Until the 1980s a huge effort was made to compare numerical results with physical measurements (e.g. Evans, 1959, French, 1974), since then most of the numerical algorithm developments lack this feedback on their reliability. Nevertheless Chen (1996) used a 2D viscoelastic finite-difference (FD) method to investigate the effect of attenuation with material samples of a simple brick shape. Later Bretaudeau (2011) used a 2D viscoelastic finite-element (FE) method for an onshore case. Favretto-Cristini et al. (2014) and Tantsereva et al. (2014) used ultrasonic measurements for a complex offshore model to compare with 2D FE and 3D discretized Kirchhoff integral simulations. Although these last two works used FEM, they were not performed in 3D with a structural mesh – respecting the geometry of the different structures – or accounting for the real source signal. In this work, we investigate the accuracy and robustness of FEM using a 3D structural mesh. Furthermore, the correct source implementation and structural meshing aspects are also presented.

Method

The Benchie model is a PVC block, containing different shapes (e.g. truncated pyramid and hemisphere), which are quite challenging for any numerical tool to correctly image. The model (Figure 1) was designed with a scaling factor of 1 : 20 000. Due to the scaling, dimensions at the seismic scale have to be divided by the scaling factor, while the seismic-scale frequencies have to be multiplied by that. Material properties, such as velocity of elastic waves and density are not scaled and PVC was chosen for the model since its properties are close to those of real geological structures. The properties measured in the laboratory are: PVC: $V_p = 2220 \pm 10$ m/s, $V_s = 1050 \pm 10$ m/s, $\rho = 1412 \pm 17$ kg/m^3, $Q_p = 55 \pm 5$, $Q_s = 29 \pm 2$; water: $V_p = 1477 \pm 16$ m/s (depending on the temperature), $\rho = 1000$ kg/m^3.

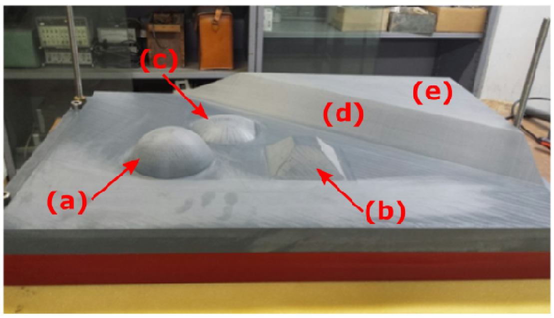

Figure 1 *Benchie model. Size: 600 x 400 x 140 mm, corresponding to 12 x 8 x 2.8 km at seismic-scale. Annotated objects: (a) dome, (b) truncated pyramid, (c) truncated dome, (d) ramp, (e) elevated plateau.*

For the laboratory measurements the model was immersed in a water tank to obtain reflection data with a conventional ultrasonic pulse-echo technique. Due to the zero-offset configuration, only one custom made transducer was used as both the source and the receiver with a central frequency of 500 kHz (corresponding to 12.5 Hz at seismic-scale). The real radiation pattern and source signal had to be implemented in the numerical simulations. It required the characterization of the transducer followed by an inversion process to get an equivalent source which later can be used in the numerical tools. The characterization was made by measuring the impulse response of the source – as pressure in water – at different angles around the source, covering 200°. After an inversion was performed for the individual source signals of each point source distributed on a disk. The goal of the inversion was to reach an overall good fit at each angle measured in the water tank for the source signal. Figure 2 shows the measured and inverted radiation patterns, showing a directivity of 35° at -3 dB. During the inversion, many parameters were investigated to optimize the fit, including the size of the disk, the number of point sources and the number of layers on which the point sources were distributed.

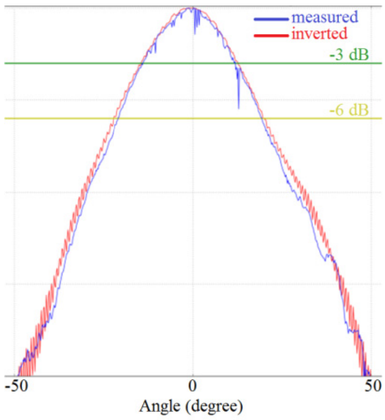

Figure 2 *The measured (blue) and inverted (red) radiation patterns of the transducer. The amplitude is maximal in front of the transducer (0°).*

For the numerical simulations Specfem3D was used, which is an open-source spectral-element numerical tool (i.e. FEM using high-order polynomial basis functions). The main advantages of using FEM include: 1) the possibility of respecting the real geometry by using a structural mesh and 2) the opportunity to use different element sizes in different regions, depending on the geometry and material properties. These two advantages together yield a high precision representation of the geometry, while using only a limited number of elements compared to regular FD schemes. Specfem uses the weak formulation of the wave-equation with a high-order piecewise polynomial approximation (Tromp et al., 2008). The computational cost is optimized by combining high-degree Lagrange interpolants to represent the wavefield and the Gauss-Lobatto-Legendre quadrature to compute the integrals (Komatitsch and Vilotte, 1998). This combination leads to a perfectly diagonal mass matrix, which uses an explicit time scheme that can be efficiently parallelized. On one hand, Specfem is highly efficient in handling complex geometries and for instance fluid-solid coupling is exactly handled by the algorithm. On the other hand the Gauss-Lobatto-Legendre quadrature requires a hexahedral mesh in 3D, which is challenging in case of structural meshes.

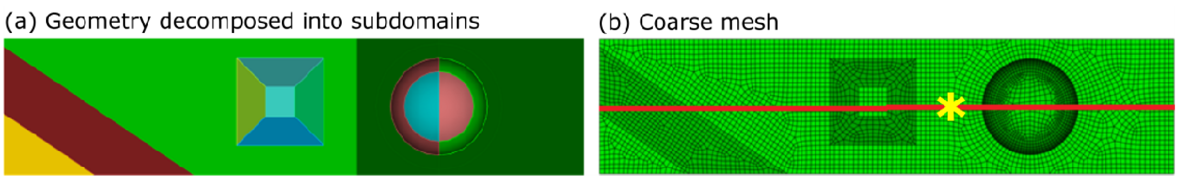

Figure 3 *The part of the model used for the numerical simulations. (a) Geometry decomposed into subdomains to optimize the mesh. (b) A coarse mesh visualized. The red line and the yellow asterisk denote the position of Figure 4, and the trace in Figure 5, respectively.*

Meshing was carried out in Cubit (Sandia National Laboratories, 2016). It was optimized for the computational cost and accuracy by considering: 1) the element size must be small enough to correctly handle even the high frequencies, 2) the size of the different elements in one material should be as equal as possible – depending on the structures – to avoid too small elements and 3) avoiding too distorted/elongated elements. Considering the velocity values and the high frequencies of the source (up to 750 kHz), one is expected to obtain an enormous number of elements. Thus only a smaller part of the total model was simulated for (Figure 3). To satisfy all the above listed requirements, a huge effort was made to decompose the different shapes/parts into subdomains (Figure 3a). After the optimization, the geometry could be represented by about 15.8 million elements.

Example

Figure 4 shows a zero-offset section from the laboratory data (along the red line denoted in Figure 3b) with interpretation. It is important to highlight here that due to the broad radiation pattern, the laboratory section contains some reflections from the truncated dome (annotated by (c) in Figure 1), which was not included in the numerical simulations.

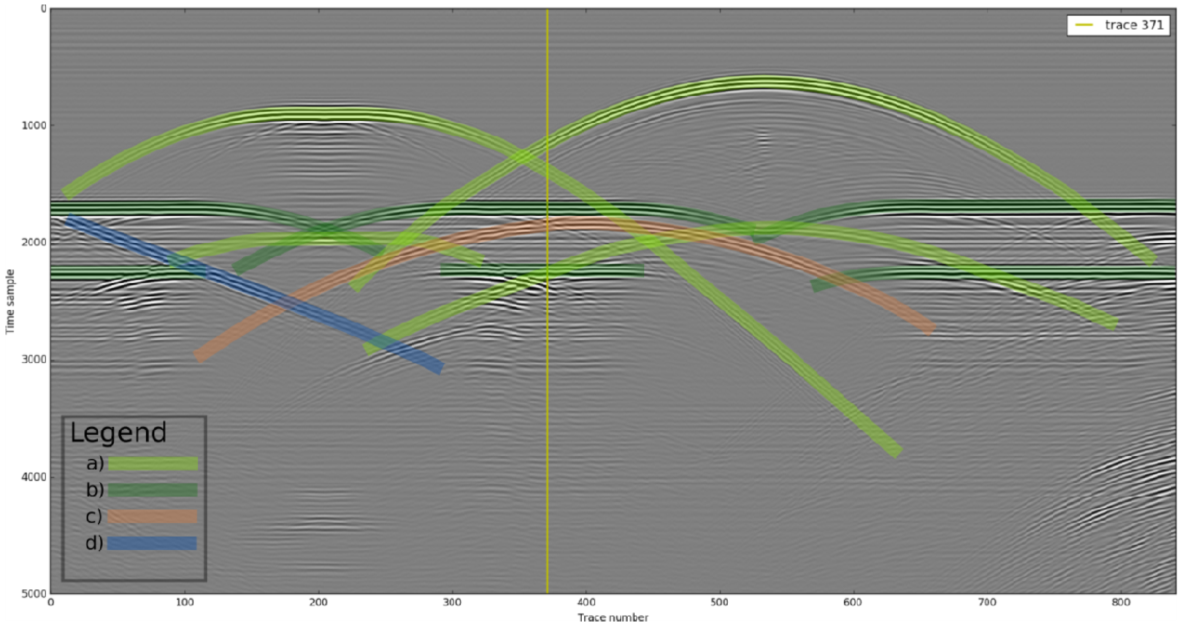

Figure 4 *Zero-offset cross-section from the laboratory data with interpretation along the red line in Figure 3b. The vertical yellow line corresponds to the yellow asterisk in Figure 3b. Interpreted events: (a) reflection from the top & bottom of the PVC (related to the plateau), (b) reflection from the top & bottom of the PVC (related to the pyramid & dome), (c) reflection from the truncated dome, (d) reflection from the ramp.*

Figure 5 shows an example for the comparison of a laboratory trace with the corresponding synthetic trace, obtained with FEM. The trace is located between the dome and the truncated pyramid, annotated by (a) and (b) in Figure 1, respectively. Furthermore, the trace is denoted by the yellow asterisk in Figure 3b) and the vertical yellow line in Figure 4. Using the annotations in Figure 5, the following interpretation can be given: (a) reflection from the side of the dome, (b) reflection from the side of the pyramid, (c) reflection from the top of the pyramid, (d) diffraction from the edge of the pyramid & diffraction from the edge of the dome, (e) reflection from the bottom of the PVC model below the pyramid, (f) reflection from the bottom of the PVC below the dome & diffraction from the edge of the pyramid.

Comparison between the laboratory (blue) and the synthetic (red) traces shows a very good fit in terms of arrival time and amplitude. However there are some small discrepancies, e.g. in the transition between event (e) and (f). Another small phase-mismatch can be found in case of event (d), or between event (a) and (b). There are two possible reasons for these misfits: 1) the laboratory data is contaminated with noise and 2) the inversion process for the source may not be perfect, also partly due to the noise recorded during the laboratory characterization of the source transducer.

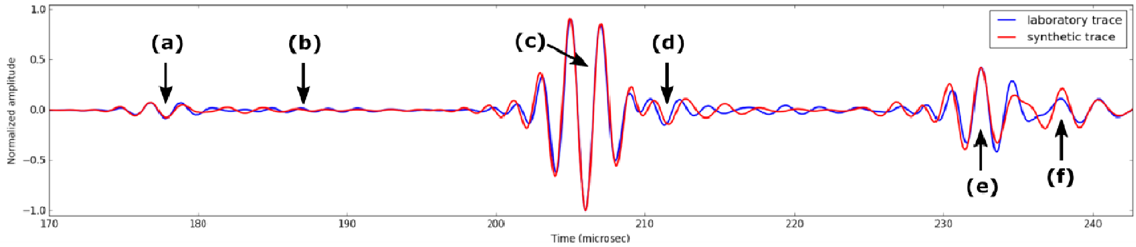

Figure 5 *Comparison of laboratory trace with synthetic result for trace 371. Annotated events are discussed in the text.*

Discussion and conclusions

We have reproduced real laboratory measurements with high precision, using FEM with a structural mesh. Comparison of laboratory data and synthetic results shows a good fit. To reach this good fit one has to account for 3D effects and viscoelasticity, as well as accurately implementing the characteristics of the real transducers used for the laboratory measurements. Furthermore, using a structural mesh, one has to optimize for the number of elements to reduce the computational cost as much as possible. We have showcased some small discrepancies between the real and synthetic data, which can for instance be related to noise in the laboratory data or not accurate radiation pattern implementation of the transducer. Checking the effect of all these issues and improving them will be part of our future work, as well as optimizing further the meshing process and comparing the results with other numerical methods (e.g. FDM). Last but not least, doing a quantitative misfit analysis for phase and envelop misfits and comparing laboratory and synthetic results for multi-offset configuration will also be performed in the future.

Acknowledgements

This project has received funding from the European Union's Horizon 2020 research and innovation program under the Marie Skłodowska-Curie grant agreement No 641943. We also thank CNRS for financial support through PICS BENCHIE project.

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