Acoustic response of thin cylindrical structures piercing horizontally stratified media

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Summary

We analyze response of vertical cylindrical structures embedded in horizontally stratified media. Both the cylinders and the host media are liquid. Diameter of the cylinders is less than or approximately equal to the dominating wavelength of the signal, which represents investigation of some boreholes and natural pipes using conventional seismic exploration. We model the data with the spectral element algorithm and benchmark the method against a precise semi-analytical solution. The results show that the spectral element algorithm is a reliable method for modelling such a structure and that even thin cylinders can produce strong scattered waves visible on the recording.

Main objectives

1. To show applicability of the spectral element method for modelling acoustic wavefields in stratified media pierced by thin cylinders.

2. To demonstrate detectability of the waves scattered on thin cylinders.

New aspects

Both source and receiver are placed outside a cylinder to record its response. A precise semi-analytical method is used for benchmarking.

Introduction

Different cylindrical structures are present in the subsurface. Natural blowout pipes were observed in various conventional seismic datasets (Cartwright et al., 2007; Moss and Cartwright, 2010; Løseth et al., 2011). Their lateral dimensions are usually less than or of order of the dominant seismic wavelengths. Surprisingly, there are evidences that man-made boreholes could have been detected in a seismic survey (Landrø, 2011). This fact, combined with the apparent possibility to locate small objects using surface seismics shown by Raknes and Arntsen (2014), has led to the recent emergence of a technique called Surface Seismic Monitoring while Drilling (SSWD, Evensen et al., 2014; Moser et al., 2016), which aims to trace trajectories of boreholes using surface seismics. In this paper, we discuss methods useful in modelling of cylindrical structures, show some simple synthetic data and discuss detectability of the cylinders using conventional seismic experiments.

Modelling techniques

The history of analysis of wavefield interaction with cylinders started with a work by Lord Rayleigh, who gave an analytical solution for plane acoustic waves scattered on small compared to the wavelength circular obstacles (Strutt, John William, 1896). Numerous papers have been published since then to describe acoustic and elastic wave propagation in the presence of cylindrical structures (Faran, 1951; Mow and Pao, 1971). Most of the publications considering cylindrical structures in stratified media are in the domain of borehole seismic exploration (Peng et al., 1996; Falk et al., 1996). But traditionally in geophysics, either the source, or the receiver, or both of them are placed inside the borehole. In other words, the cylindrical structures are used as a tool for exploring the surrounding media. But the tool itself has not been properly investigated from the outside. Larger structures, like blowout pipes, have not gained much attention in terms of modelling, too.

The only article covering exclusively a method for modelling the wave scattering by cylinders in stratified media was published by Rice and Willen (1987). They derived an analytical solution in terms of wave-number integrals, so it is precise and relatively easy to implement. The price paid for the solution is restriction to acoustic media and the impossibility to describe a finite cylinder with arbitrary filling. Two possible simple filling options are: hollow (zero pressure on the wall) and infinitely rigid (zero displacement on the wall). Although the method does not allow for a general case, it can be used for benchmarking other modeling techniques.

The most popular numerical techniques nowadays are Finite Difference (FD) and Spectral Element (SE) methods. Using the former in its standard form does not seem reasonable for the problem at hand. In order to describe a small heterogeneity, one should have a very dense grid, which leads to high memory requirements and enormous computation times due to the stability criterion. The first problem can be tackled using grid refinement as proposed by Falk et al. (1996), Pitarka (1999), but in order to significantly increase the computation speed, one should perform tedious parallelization of the algorithm. Even if it is done, the FD method is well-known for giving not very precise results due to the boundary smearing.

Although it has similar computation speed limitations, the SE method does not possess that crucial memory requirements since it is possible to have elements of different size within one model, and it allows for precise not smeared boundaries. Besides, there is an effective parallel open source realization of the algorithm readily available called SPECFEM (Komatitsch and Tromp, 1999). We used this method for modelling in the work.

Synthetic wavefields

The left panel of Figure 1 depicts geometry of the model considered in the paper. Two liquid half-spaces are separated by a horizontal boundary at 1000 m depth. The upper layer has c_1=3000 m/s, ρ_1=2000 g/cm^3, the lower one has c_2=3500 m/s, ρ_2=2300 g/cm^3, where c and ρ are the acoustic velocity and density, respectively. The source is placed at 600 m from the cylinder axis and at 100 m depth. The field is recorded at two receiver lines lying at the source-cylinder axis plane: line x is horizontal at zero depth, line z is parallel to the cylinder offset by 10 m from its axis. The source pulse is a Ricker wavelet with dominant frequency 20 Hz.

We computed a seismogram using the semi-analytical algorithm for an infinite empty cylinder with radius 2.5 m (Fig. 1, right). The seismogram is clipped for better visibility. In addition to the expected direct and reflected waves (orange and green), one can see waves diffracted on the cylinder (magenta) and on the cylinder-boundary intersection (cyan). Notice the difference between the latter event and the theoretical moveout both at small and large offsets. The line is computed for a point diffractor placed at the intersection of the cylinder axis and horizontal boundary. Apparently, the cusp and the smaller arrival times are the effect of finite width of the cylinder, although the cylinder is 30 times thinner than the dominating wavelength.

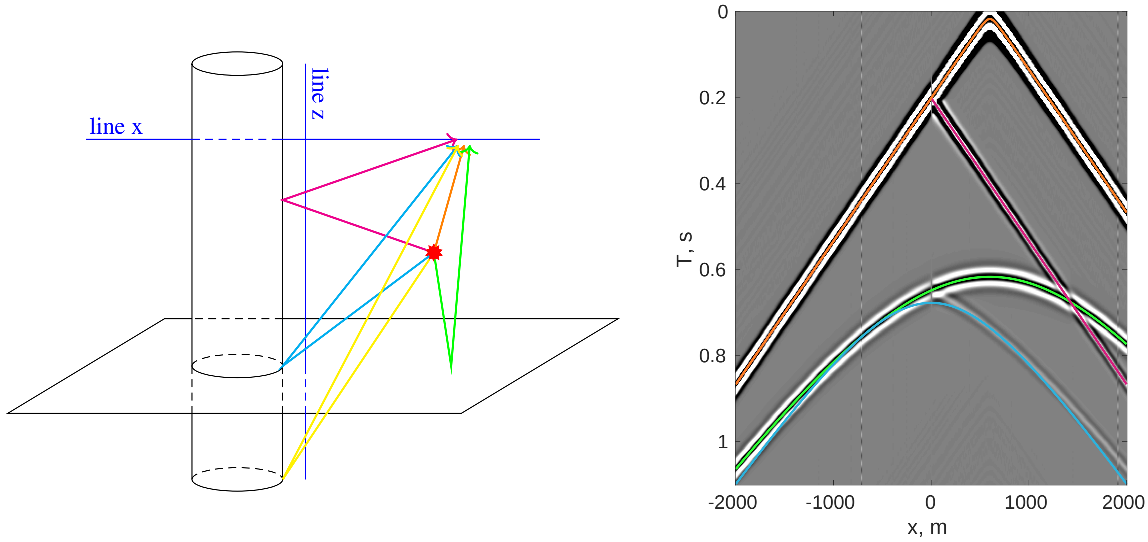

Figure 1 *Left: Modeled geometry, where a cylinder intersects a horizontal boundary, dark-blue – receiver lines, arrows – possible raypaths. Right: line x seismogram computed with the semi-analytical code for an empty infinite cylinder with radius 2.5 m.*

Another dataset for the same model was computed with the spectral element method. Figure 2 shows the comparison of the solution (red) with the semi-analytical data (blue). There is almost no visible difference. Same precision level was achieved for a thinner cylinder (radius 0.25 m) meaning that the SE algorithm is capable to handle objects of small dimensions.

Of course, in reality, there are no infinite cylindrical structures. Especially if we deal with boreholes, the cylinder bottom is always within the depth range of recorded waves. And the cylinders are never empty or infinitely rigid, but the filling always has finite densities and velocities. Now, we consider a slightly more complex model, where the cylinder is truncated at depth 1250 m. The cylinder is filled with water with c_w=1500 m/s, ρ_w=1000 g/cm^3. The cylinder radius and the host medium parameters are the same.

Figure 3 depicts a seismogram from line z recorded in the model. Colours of the events correspond to those from the previous pictures. Note that the unmarked event is the reflection from the model bottom. Since the recording line is very close to the cylinder, the diffracted events we observed in previous data interfere with the direct and reflected waves and hence are not visible in the figure. However, one can see an event with negative apparent velocity coming from below the reflector (yellow in Fig. 3). The moveout was computed for the refracted wave diffraction on a point at the cylinder bottom axis. Dispersive behaviour of the event suggests that not only the refracted wave diffracts on the cylinder end, but also the waves propagating inside the cylinder. It is remarkable that when the cylinder is hollow, this event is not so strong due to the absence of tube-waves diffraction. Moser et al. (2016) described appearance of the diffraction on the borehole head, but in their case the event did not have the dispersive character since their modelling techniques did not support proper handling of tube-waves.

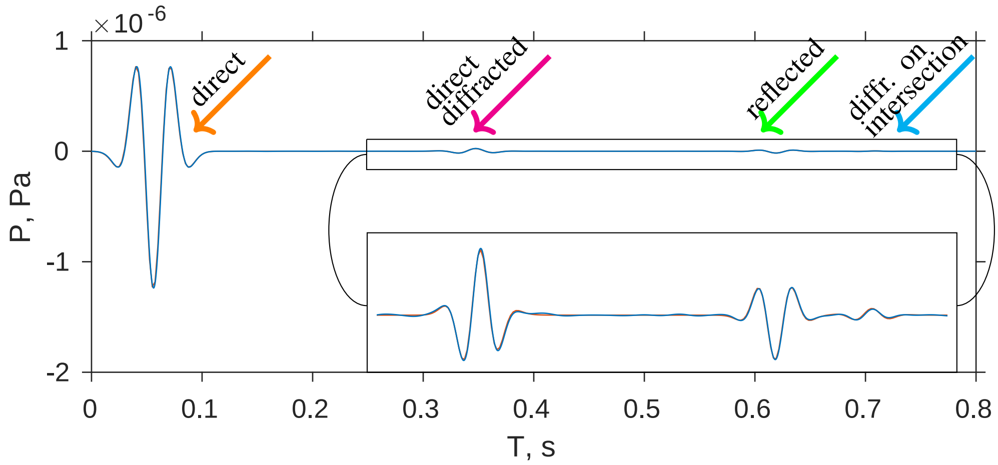

Figure 2 *Comparison of semi-analytic (blue) and SE (red) solutions for an empty cylinder with radius 2.5 m, trace at x=440 m, line x. There is almost no difference between the overlapped traces.*

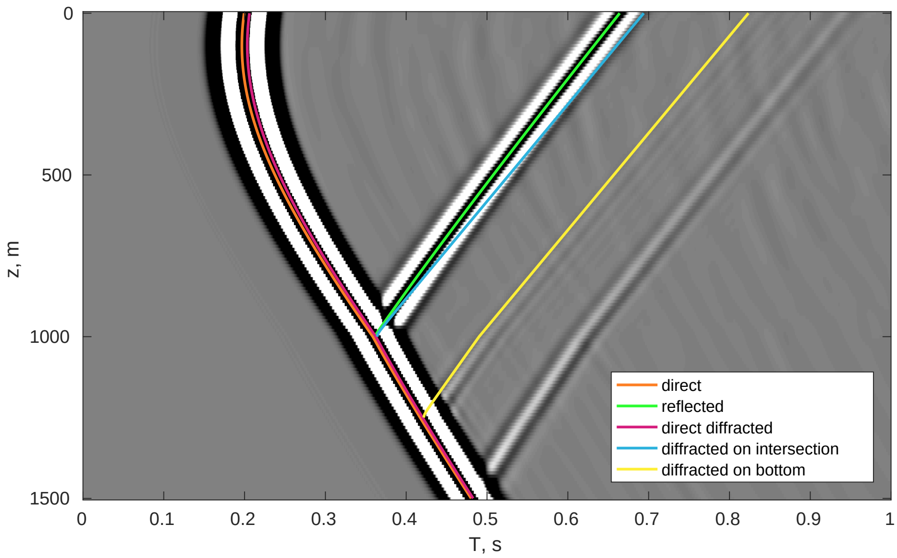

Figure 3 *Line z seismogram computed with the spectral element code for a truncated water-filled cylinder with radius 2.5 m.*

Conclusions

Modelling of wavefield propagation in media with structures of dimensions less or equal the dominant wavelengths (such as boreholes or natural blowout pipes) is not a trivial problem. Analytical solutions are not sufficient to describe realistic situations, and the most popular numerical methods (finite difference and spectral element) get stuck in the computation requirements. Between them, the spectral element method is less demanding and seems to be more accurate. We computed a simple model with a hollow infinite cylinder using the method and benchmarked it against a semi-analitical solution. The spectral element method proved to produce reliable results. We used the method to simulate a slightly more complicated situation where the cylinder is truncated and water filled. The results shown that even if the cylinder diameter is 30 times less the dominant wavelength, the recording comprises distinguishable cylinder contribution, which can be used for its imaging. Among the events are: diffraction from the cylinder, diffraction from the cylinder-strata boundaries intersections, diffraction from the cylinder bottom. Their behaviour is different to that of point diffractions, and strengths depend on the impedance contrast between the cylinder and the host medium strata.

More research is necessary to describe these dependences and to consider the problem when the host medium is elastic. Although the spectral element method provides reliable results, this analysis demands massive computations, and the spectral element method will become highly inefficient. An alternative modelling technique is needed. The boundary element method (Gaul et al., 2003) seems to be a perfect candidate. Instead of splitting the entire volume into elements, the method uses only parts of the boundaries, which leads to easier memory requirements. The method does not carry the load of the stability criterion, meaning that its computation speed does not decrease with decreasing structure size. Vice versa, the method should be the faster, the smaller the object, since the less elements will be needed to describe the boundary. In case of a cylinder in a horizontally stratified medium, the method can be adapted using the symmetries and analytical expressions for the Green's functions, making the method very attractive for the problem.

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