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NUMERICAL MODELING OF LOW FREQUENCY SOUND PROPAGATION IN THREE DIMENSIONAL SHALLOW MARINE ENVIRONMENT WITH SOLID SEABED

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ABSTRACT

The study of low-frequency (below 100 Hz) sound propagation characteristics in the shallow sea has recently gained importance in light of concerns about the potential impact of anthropogenic noise on marine ecosystems. Since the canonical models of sound propagation consisting of horizontally layered waveguides with a fluid seabed are found to be unsuitable to be applied to several realistic cases of the shallow marine environment, as these models neglect possible effects of the irregular topography of the seabed and the conversion between compressional and shear waves in the solid seabed, we have to resort to numerical modeling of the coupled acoustic-elastic wave field in a heterogeneous three-dimensional domain. In the present work, we use SPECFEM3D, an open-source software widely used in seismology and based on the spectral element method, to perform a series of numerical experiments aimed at investigating the possible effects of different shapes and depths of the solid seabed on the acoustic wave field generated in water by a monopole source. We have found that a solid and non-horizontal seabed can alter the typical leakage effect of sound energy to the seabed and significantly reduce transmission loss.

Keywords:

1. INTRODUCTION

The underwater ambient noise in the low frequency band (below 100 Hz) is dominated by anthropogenic acoustic sources [1]. These sources consist primarily of commercial shipping and secondarily of marine seismic exploration activities. Given the small attenuation in this frequency band, these sources contribute to the noise pollution also at long-range, but we can expect particularly strong effects at close range in shallow waters (i.e. seabed depth not greater than 10 wavelengths). It has been found that seismic surveys in shallow waters can raise the noise within 1 km of the activity by 30-45 dB above the natural ambient level [2].

Modeling underwater sound propagation is a fundamental aspect of studies on the potential impact of anthropogenic sound sources in the marine environment [3]. There are a number of sound propagation models in the literature, the choice of which depends on the acoustic problem to be solved. In shallow water problems, the propagation of sound from the source to the receiver does not follow only a direct path, but interacts with the sea surface, the seabed and the substrates, creating reverberation effects. Physical properties of the sea bottom and range dependent water depth could produce important 3-D effects [4] and are therefore fundamental parameters to be considered in the modeling. Given the computing power available today, a modeling tool based on the numerical solution of the 3-D wave equation in the time domain is a good choice to solve shallow water problems for finite-frequency signals. Among the numerical methods that can be used to solve the equation, the spectral element method (SEM) seems particularly suitable as it combines the geometrical flexibility of finite elements methods with the accuracy of the spectral methods [5]. In the present work, we use the SEM implemented in the open-source software package SPECFEM3D Cartesian [6] to perform a series of numerical tests that demonstrate the importance of taking into account the elastic stiffness of the seabed when modelling the acoustic pressure generated by a monopole

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source close to the water surface in a shallow water body with inclined bathymetry. The SPECFEM3D software allows simulations of coupled acoustic and elastic wave propagation [7] in 3-D spatial domains characterized by irregular geometry and with frequency independent intrinsic attenuation [8]. Spurious reflections from the spatial domain external borders are avoided thanks to perfectly matching layers [9].

The tests we present consist of comparing the solution for the case where the seabed is realistically modeled as a viscoelastic medium (and therefore allows for shear strain) with the solution for the case where the seabed is approximated by a fluid medium for simplicity.

2. SIMULATION SETUP

We consider a simplified shallow water scenario with a visco-elastic seabed sloping in the x direction and a water layer thickness of 150 m to 50 m (Fig.1). The slope has a length of 500 metres and its profile has a convex-concave shape described by the cosine function. We investigated the acoustic wavefield generated by a 10 m deep monopole imitating an air gun positioned at three different positions: one directly above the center of the slope and the other two above the deep and shallow parts of the seabed, each 500 m from the central source in opposite directions (points S_1, S_2 and S_3 in Fig.1). Even though the spatial domain in y-direction is invariant, we pose the problem as a 3-D problem to adequately account for the attenuation due to the spreading of the waves generated by point sources. The propagation of elasto-acoustic waves

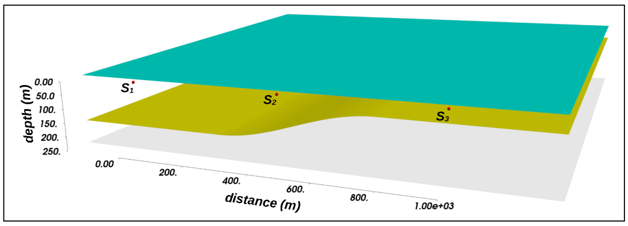

Figure 1. Schematic representation of the geometry of the modelled scenarios. The flat top surface represents the sea surface and the curved surface is the sea floor. S_1, S_2, and S_3 are three positions of the monopole sources.

in attenuating media is governed by the following physical quantities: the mass density ρ, the compressional and shear wave velocities c_P and c_S as well as the bulk and shear elastic quality factors Q_κ and Q_μ. In Tab.1 we give the values of these parameters that we took into account in the simulations.

Table 1. Values of elasto-acoustic parameters in the medium

	ρ (kg/m^3)	c_P (m/s)	c_S (m/s)	Q_κ	Q_μ
water	1000.	1500.	-	∞	-
seabed	2000.	1800.	500.0	150	50

In the simulations we adopt the second time derivative of a 50 Hz Gaussian pulse as the far field source signature (Fig. 2).

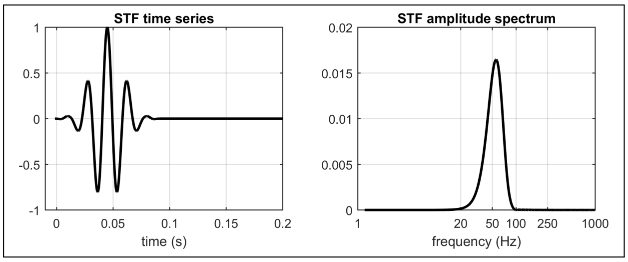

Figure 2. The normalized far field source signature.

To obtain accurate solutions with SPECFEM, we need to discretize the spatial domain into a set of non-overlapping hexahedral elements whose size is not larger than the local minimum wavelength [10]. We placed the scenario depicted in Fig. 1 in a box 1500 metres long, 320 metres wide and 250 metres thick and we partitioned it in a mesh of almost one million hexahedral elements with size in the order of 5 m, which allows an accurate solution in a frequency range up to 100.0 Hz if we consider the lowest wave speed in Tab. 1.

We simulate each scenario twice, once assuming that the seabed is a elastic medium (with the shear wave velocity defined in Tab.1), and once assuming that it is a fluid medium.

3. RESULTS

We analyze the numerical simulations in terms of propagation losses (PL) of peak pressure and sound exposure, which are defined in analogy to the classical sound propagation loss as

$$N_{PL,x} = L_{S,x} - L_x, \tag{1}$$

where x stands for either pk or E and we consider the following definitions

$$L_{pk} = 20\log_{10}\frac{\max(|p(t)|)}{p_0} \tag{2}$$

$$L_E = 10\log_{10}\frac{\int_0^T p^2(t)dt}{p_0^2 t_0} \tag{3}$$

with p_0=1 µPa and t_0=1 s [11]. To illustrate the results of the tests, we consider the differences between the PL estimated with the *solid* seabed (i.e. with conversion to shear waves taken into account) and with the *fluid* seabed (i.e. with conversion to shear waves neglected).

$$\Delta N_{PL} = N_{PL}(\text{solid}) - N_{PL}(\text{fluid}). \tag{4}$$

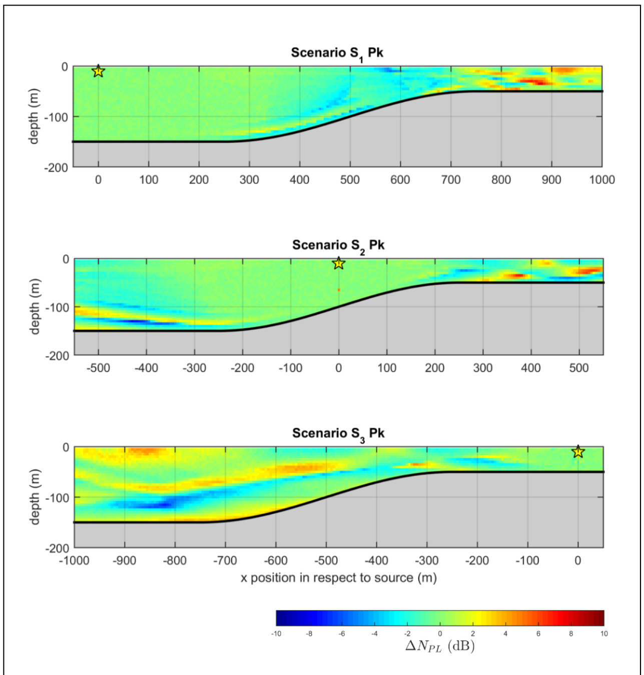

Figure 3. Distribution of the difference in propagation loss for the peak pressure between the solid and fluid seabed for three positions of the source marked by the yellow star

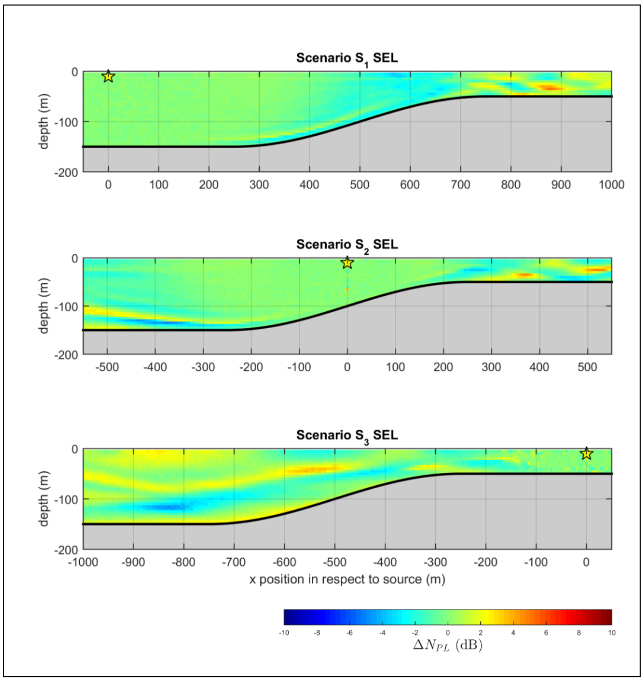

Figure 4. Distribution of the difference in propagation loss for the sound exposure level between the solid and fluid seabed for three positions of the source marked by the yellow star)

In Figs. 3 and 4 we plot the difference defined in Eqn. (4) for the peak pressure level an sound exposure lever respectively, for the three cases of the source location over the vertical profile in the x-direction. We see that the variation in PL is only small in the immediate vicinity of the source. At distances more than ten wavelengths, the PL can vary by up to 10 dB if we fully consider the solid nature of the seabed, compared to the simulation that considers the seabed as a fluid.

4. CONCLUSION

We have used an open-source high-performance software based on the spectral element method in a numerical experiment to investigate the possible effects of neglecting the solid nature of the seafloor when solving shallow water acoustic problems with variable bathymetry. We have considered scenarios where the source is close to the sea surface, which is typical of anthropogenic sources of acoustic pollution (e.g. acoustic sources used in marine seismic surveys). The results of the numerical experiments were interpreted in terms of propagation loss in a distance range of up to 1 km over a vertical plane. Differences of up to 10 dB were found between the simulations with and without consideration of the seabed as a solid body, indicating that the stiffness of the seabed should not be neglected in the physics-based numerical modelling of acoustic noise in shallow water scenarios. We plan to extend the presented numerical experiments to more realistic cases of bathymetry, a larger distance range and to cases with seabed with different values of shear wave velocity.

5. ACKNOWLEDGMENT

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