Modeling explosion generated Scholte waves in sandy sediments with power law dependent shear wave speed

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Abstract: Experimental measurements of Scholte waves from underwater explosions collected off the coast of Virginia Beach, VA in shallow water are presented. It is shown here that the dispersion of these explosion-generated Scholte waves traveling in the sandy seabed can be modeled using a power-law dependent shear wave speed profile and an empirical source model that determines the pressure time-series at 1 m from the source as a function of TNT-equivalent charge weight.

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1. Introduction

The detonation of explosive charges in shallow water from marine construction activities and navy training exercises generates high amplitude, broad-band noise levels, some of which are potentially hazardous to nearby marine life.[1] The lowest frequencies generated by such explosions (1–20 Hz) typically propagate along the interface between the water and the seabed as Scholte waves, which are the focus of this paper.

In a homogeneous medium, where the shear wave speed is constant with depth, Scholte waves are non-dispersive, whereas dispersion can occur when the shear wave speed in the seabed is depth dependent.[2] In unconsolidated sediments that are un-layered and of uniform composition (e.g., sands and clays), theoretical[3–5] and experimental[6] studies suggest that the shear wave speed increases continuously with depth into the seabed according to a power law

$$c_s(z) = c_o z^{\nu}. \tag{1}$$

In Eq. (1), $c_s(z)$ is the depth dependent shear wave speed, z is the depth below the water-sediment interface, c_o is a constant equal to the shear wave speed at a depth of 1 m, and ν is a parameter between 0 and 1 that controls the rate at which the shear speed increases with depth.

In a previous paper,[7] measurements of the noise produced by the detonation of explosive charges in shallow water were presented. During this experiment, Scholte waves generated by a C-4 charge with 3 kg-TNT equivalent weight (e.g., 1 kg of C-4 explosive is equivalent to 1.34 kg of TNT) detonated at 11.6 m, and a C-4 charge with 6 kg-TNT equivalent weight detonated on the seabed at 16 m, were measured on a vertical hydrophone array that sampled the water column between 6.4 and 12.1 m.

The main goal of this work is to assess whether the explosion-generated Scholte waves traveling in the sandy seabed at the measurement site can be modeled using a power law dependent shear wave speed profile. This will be accomplished using the dispersion of the Scholte waves and Eq. (1) to determine the shear wave speed profile in the seabed through a forward modeling approach.

Furthermore, in this study we also employ an empirical source model from Chapman[8,9] that determines the pressure time-series of an explosion at 1 m from the source as a function of TNT-equivalent charge weight. It is particularly appropriate for this study given that this source model was developed using multiple measurements collected in shallow water and can be applied to varying charge weights. This approach differs from previous studies involving Scholte waveforms that have used, for example, source functions based on a causal band limited function representative of an arbitrary source with a 10 Hz center frequency and which are less directly connected to TNT-charge weight,[10] and a volume seismic source with strength estimated using adiabatic bubble theory.[11]

2. Measurement description and environmental model

The underwater explosion measurements were conducted on September 11, 2012 during a training exercise for a Navy ordnance disposal team. The measurement site was located 7 km off the coast of Virginia Beach, VA during which the tidally dependent depth was 16 m. Due to recent storm activity the water column was well mixed, and profiles of the sound speed versus depth in the water column put the sound speed at an approximately constant 1528 m/s. As part of an unrelated sand-mining study conducted at a nearby site, 22 seabed core samples were collected over a 16 km^2 area. These core samples contained a range of materials from stiff clays to very coarse sands and gravels.[12]

Scholte waves generated by the detonation of a 3 kg-TNT equivalent and a 6 kg-TNT equivalent charge were measured on a nine-element vertical line array at a range of 430 m with an uncertainty of ± 50 m owing to vessel drift. All measurements discussed in this paper were recorded on the deepest hydrophone, 12.1 m below the surface. Additional details on the experiment can be found in Soloway and Dahl.[7]

As the exact composition of the seabed is unknown, we have assumed a laterally homogeneous seabed with a depth dependent shear wave speed described by Eq. (1). Following previous studies, we will assume that the density in the seabed is constant with depth[10,13] which we set equal to 1700 kg/m^3. Similarly, the compressional wave speed, which has little influence on the Scholte wave dispersion, is assumed to be 1700 m/s. Finally, a shear attenuation factor of 1.0 dB/λ and a compressional wave attenuation factor of 0.2 dB/λ have also been assumed.

3. Methodology

Previous investigations have determined the shear speed profile through two main methods; matching the group and phase speeds of Scholte waves,[14,15] and matching of the measured data to synthetic time series.[10] Here we will use the latter approach and find values for c_o and ν in Eq. (1) that give the best fit to our data using a forward modeling technique that iterates through a predetermined parameter space for c_o and ν. The best fit will be given by the model parameters that minimize the L^2 norm calculated from the difference of the measured and modeled data. Since the spectrum of the measured Scholte wave is in the range of 1 to 10 Hz, the data have been first bandpass filtered between 1 and 15 Hz and then down-sampled from 62 500 to 200 samples/s. Processing the data in this way greatly reduces the computation time for each forward model run.

During the experiment the source and receiving equipment were not synchronized, so an alternate method had to be employed to determine the source-receiver timing. By assuming the first water arrival corresponds to the peak pressure, the source-receiver time could be determined using the measured water sound speed, 1528 m/s, and the measurement range, 430 m. This puts the peak pressure arrival at time 0.28 s.

Forward modeling is achieved using the OASES seismo-acoustic wave propagation code[16] which computes the frequency dependent Green's function for a given environment. The forward modeling iterates over a parameter space of c_o in the range 90 to 110 m/s with 1 m/s discretization, and ν in the range 0.2 to 0.4 discretizing by 0.001. Outside this parameter space, the spectra of the modeled Scholte waves were in poor agreement with the measured data and were therefore not considered in the forward modeling. The time series are then computed by taking the inverse Fourier Transform of the Green's function weighted by the spectrum of the empirical source model from Chapman,[8,9] also sampled at 200 samples/s. As OASES describes the environment using a series of horizontally stratified layers, the continuous seabed described by Eq. (1) will be discretized using an equal layer travel time approach originally described by Godin and Chapman.[4] The seabed will be modeled using 78-layers with a homogeneous half-space beginning at 150 m below the water-sediment interface.

4. Results and discussion

Through iterative forward modeling, we have found the best fit model for the 3 kg-TNT equivalent charge is $c_s(z) = (102 \pm 7)\, z^{(0.375 \pm 0.008)}$ and for the 6 kg-TNT

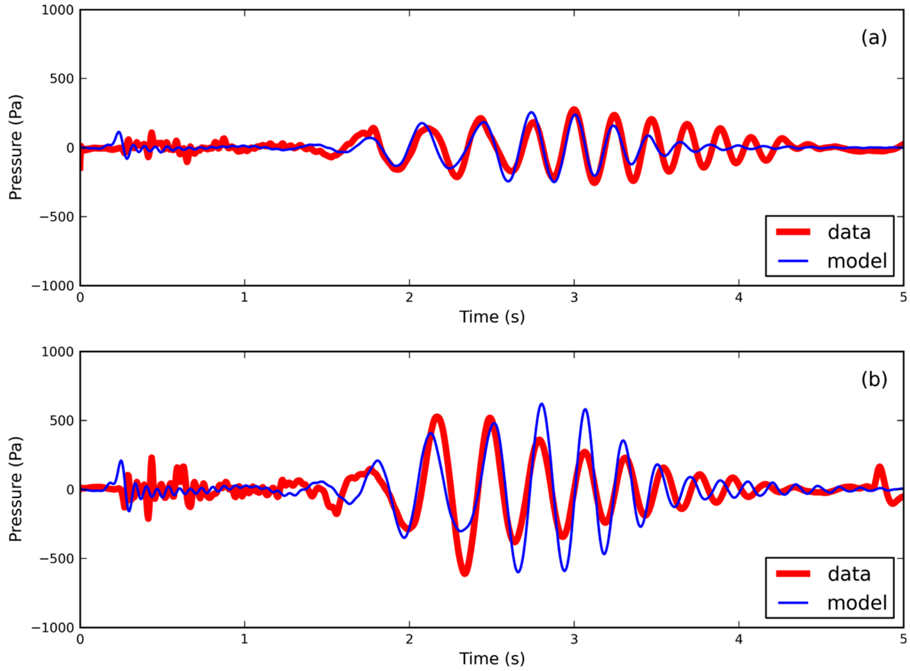

Fig. 1. (Color online) (a) Measured data (thick line) compared to best fit model (thin line) for the 3 kg-TNT equivalent charge given by $c_s(z) = 102z^{0.375}$, and (b) measured data compared to best fit model for the 6 kg-TNT equivalent charge given by $c_s(z) = 102z^{0.367}$. The region starting at 0.28 s represents the main waterborne arrival, the level for which is highly reduced in this frequency range.

equivalent charge, $c_s(z) = (102 \pm 7)z^{(0.367 \pm 0.007)}$. The resulting time series of these model results are compared to the band-passed filtered data (Fig. 1), with reasonable agreement in both magnitude and phase evident.

In this study we have assumed that the main contribution to the error is from uncertainty in the source-receiver range, so our error bounds are given by the best fit model parameters at ±50 m from the measurement range of 430 m (Fig. 2). In the future, a more robust approach that includes measurement range as a model parameter may be employed. For the purpose of this paper, however, we feel that the method used is sufficient for demonstrating that the explosion-generated Scholte waves traveling in the sandy seabed at the measurement site can be modeled using a power law dependent shear wave speed profile.

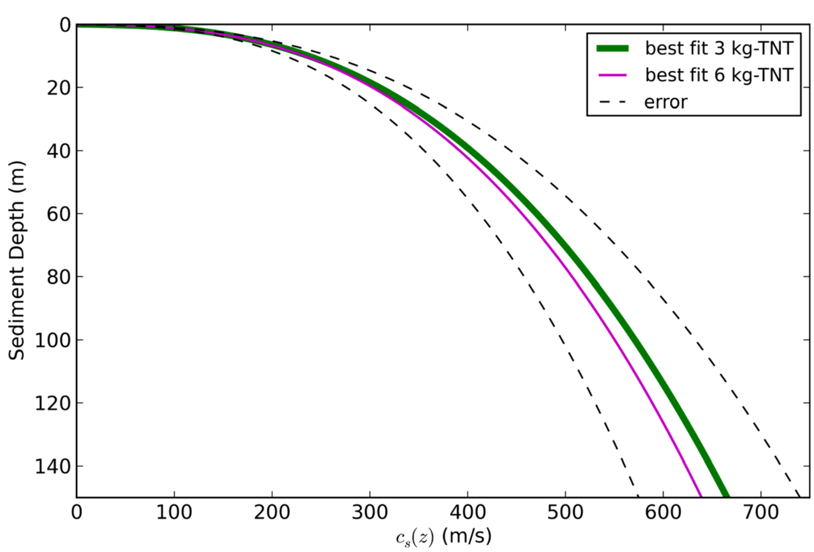

Fig. 2. (Color online) Best fit shear wave speed profile for the 3 kg-TNT equivalent (thick solid line) and the 6 kg-TNT equivalent (thin solid line) charges at 430 m range. The error bounds (dashed lines) shown in the figure represent the overall minimum and maximum profiles for the two charges. The lower error bound is given by the best fit profile for the 6 kg-TNT equivalent charge at 380 m, and the upper error bound is given by the best fit profile for the 3 kg-TNT equivalent charge at 480 m.

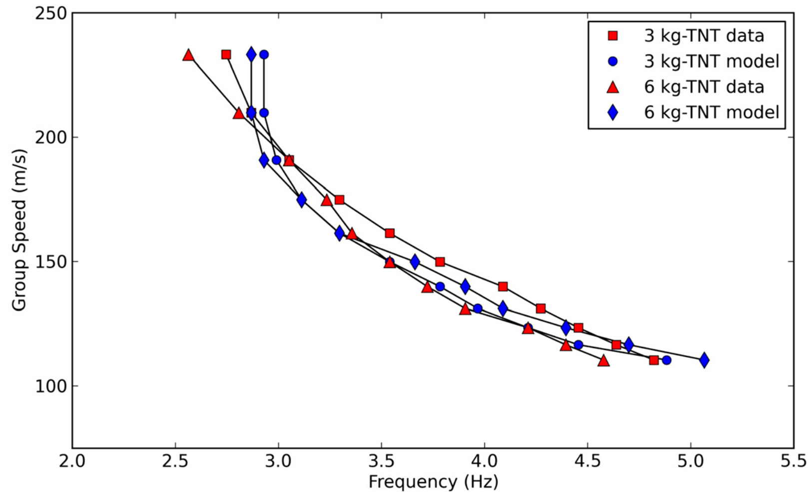

Fig. 3. (Color online) Comparison of the group speeds for the measured data (squares, triangles) and the best fit model results (circles, diamonds) for the 3 kg-TNT equivalent and the 6 kg-TNT equivalent charges.

As an additional check on our results, the group velocity curves for the modeled and measured data (Fig. 3) have also been computed following the method of Ohta.[17] The basic dispersion properties seen in the data are captured by the model results, although the comparison is limited to frequencies less than 4.5 Hz owing to low signal levels at higher frequencies.

5. Summary and conclusions

In this paper we have used a forward modeling approach and an empirical source model from Chapman[8,9] to show that the explosion-generated Scholte waves traveling in the sandy seabed at the measurement site can be modeled using a power law dependent shear wave speed profile. The model results for the best fit shear wave speed profile, determined through waveform matching, are in good agreement with both the measured data as well as previous studies that put ν in the range of 0.3 to 0.4.[6,14] Having determined that the shear-wave speed in the seabed can be modeled using Eq. (1), we plan to investigate the validity of the constant density assumption that went into our current forward modeling approach.

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