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Numerical simulations of wavefields generated by UXO counter-mining: study of the transition from shallow to deep water

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ABSTRACT

Explosive devices from World War II are discovered almost every week on the French coasts and they must be destroyed by the French Navy Mine Warfare Office. The consequences of the counter-mining on the marine environment are complex to evaluate. In a previous work, we focus on the impact of the seismoacoustic waves generated by such explosions on the infrastructures located on the coast and illustrate the importance of interface waves in this context. In this presentation, we address a different perspective of this problem and analyze the wavefields generated by the counter-mining of unexploded ordnances towards deep waters. For this purpose, we performed several numerical simulations using 2D time-domain spectral-element software which allows for accurate handling of the characteristics of the complex marine environment (complex bathymetry and elastic sediments). We will focus on the role of the steep transition from shallow to deep water which takes place in the area where the counter-mining is triggered and on the influence of a thin sedimentary layer on the generated wavefields.

Keywords: Counter-mining, UXO, Wave propagation, Interface wave, Numerical modeling

1 INTRODUCTION

Historical unexploded ordnances (UXO) from World War II are discovered almost weekly near the coasts of northwest and southeast France. Soon after their discovery, they must be destroyed to ensure the safety of divers and ships. The preferred method of destruction is counter-mining, i.e. the use of a higher-order detonation carried out by the explosion of an additional donor charge placed near the UXO. Depending on whether the UXO can be safely moved, this counter-mining takes place at specific safe locations or at the discovery site. In a previous work [1, 2], we evaluated the risk of damage to buildings on the adjacent shoreline induced by the detonation of highly charged UXO in a variable shallow water environment. The importance of environmental characteristics was emphasized and in particular the need to consider the elasticity of marine sediments to account for interface waves. In this extended abstract, as a complement to that work, we study the structure of acoustic wavefields generated towards the deep water to investigate how acoustic energy is distributed in the water column in that direction.

In this extended abstract, we first build a 2D model corresponding to the transition from shallow to deep water in the same area where we previously performed experiments. Then, this model is used to perform numerical simulations in the time domain of acoustic and seismic wave propagation. Finally, the results of these numerical simulations are analyzed and some conclusions are drawn.

2 CONFIGURATION

We first identified a bathymetric profile corresponding to a transition path to deep water in the rade d'Hyères (Mediterranean Sea), where the experiments reported in previous works [1, 2] took place. This path is shown in Figure 1. Note that there is a steep transition from shallow to deep water. At the beginning of the path, the depth of the water column is almost constant and equal to 46m. Towards the middle of the path, the depth is 240m to finally ends at 800m. After designing the computational domain, a mesh of it is created using quadrilateral elements with the Gmsh software [3].

Numerical simulations are then performed using the open-source software SPEC-FEM2D¹ which implements a spectral-element method. It is based upon a high-order piecewise polynomial approximation of the

¹<https://github.com/geodynamics/specfem2d>

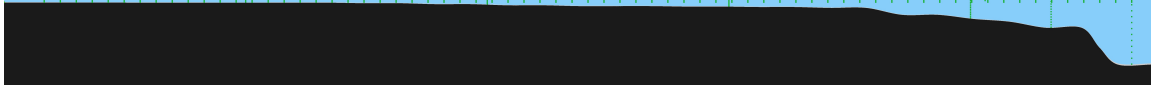


Figure 1. Bathymetry towards deep waters used in the numerical simulations. The green points represent the position of the receivers considered in the numerical simulation.

weak formulation of the wave equation and combines the accuracy of the pseudospectral method with the flexibility of the finite-element method. 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 a 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. This is a very important feature in our configuration since the influence of an interface wave of the Stoneley-Scholte type is known to be important. The numerical simulations are performed using the cylindrical coordinate system.

Two source positions are considered. The first position is “proud on the bottom”. In this configuration the charges are placed on the sea bottom. This position corresponds to the majority of the experiments which were done. The second position is “under barrel”. In this position, the UXOs are gathered in a barrel immersed at a depth of 11m under the sea surface. This source position is used to avoid the generation of vibrations at shore but is likely to generate more acoustic energy inside the water column.

We consider Very Low-Frequency acoustic propagation (VLF) by using a source time signal of the Ricker wavelet type with a central frequency of 25 Hz.

The bottom of the ocean is considered as an elastic medium. The physical characteristics are :

- Water: $\rho = 1000 \text{ kg/m}^3$, $c_p = 1477 \text{ m/s}$
- Bottom: $\rho = 2600 \text{ kg/m}^3$, $c_p = 4100 \text{ m/s}$, $c_s = 2700 \text{ m/s}$

where ρ , c_p and c_s are respectively the density, the velocity of longitudinal waves and the velocity of shear waves.

3 NUMERICAL RESULTS

In this section, we present the numerical results obtained with the configuration presented in section 2. Figure 2 represents snapshots of the acoustic energy distribution in the water column for two source positions, namely “proud on the bottom” and “under barrel”. It can be seen that, when the water depth increases strongly, the way the acoustic energy is spreading into the water column is very different depending on the source position suggesting a very different structure of the acoustic wavefield.

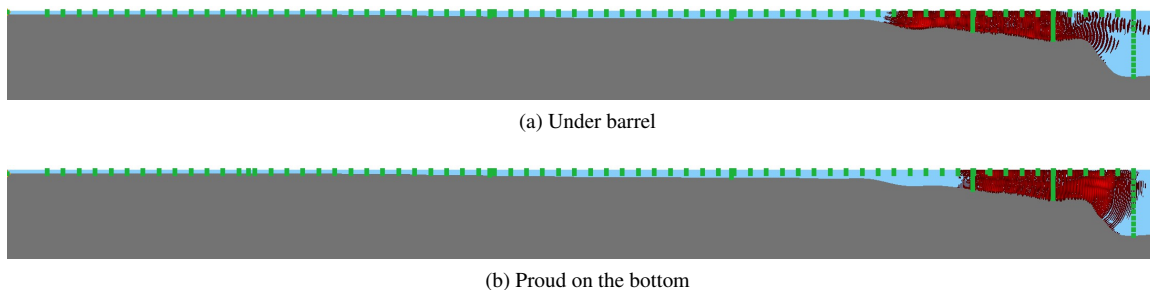


Figure 2. Snapshots of the acoustic wavefield for two source positions.

3.1 Analysis of simulated time signals

To investigate more in detail the structure of the acoustic wavefield which is generated with the two source positions, we present in Figure 3 the signals received at several vertical arrays situated along the path towards deep waters. The vertical arrays have different lengths because they span the entire water column at different distances from the source for which the water depth is different.

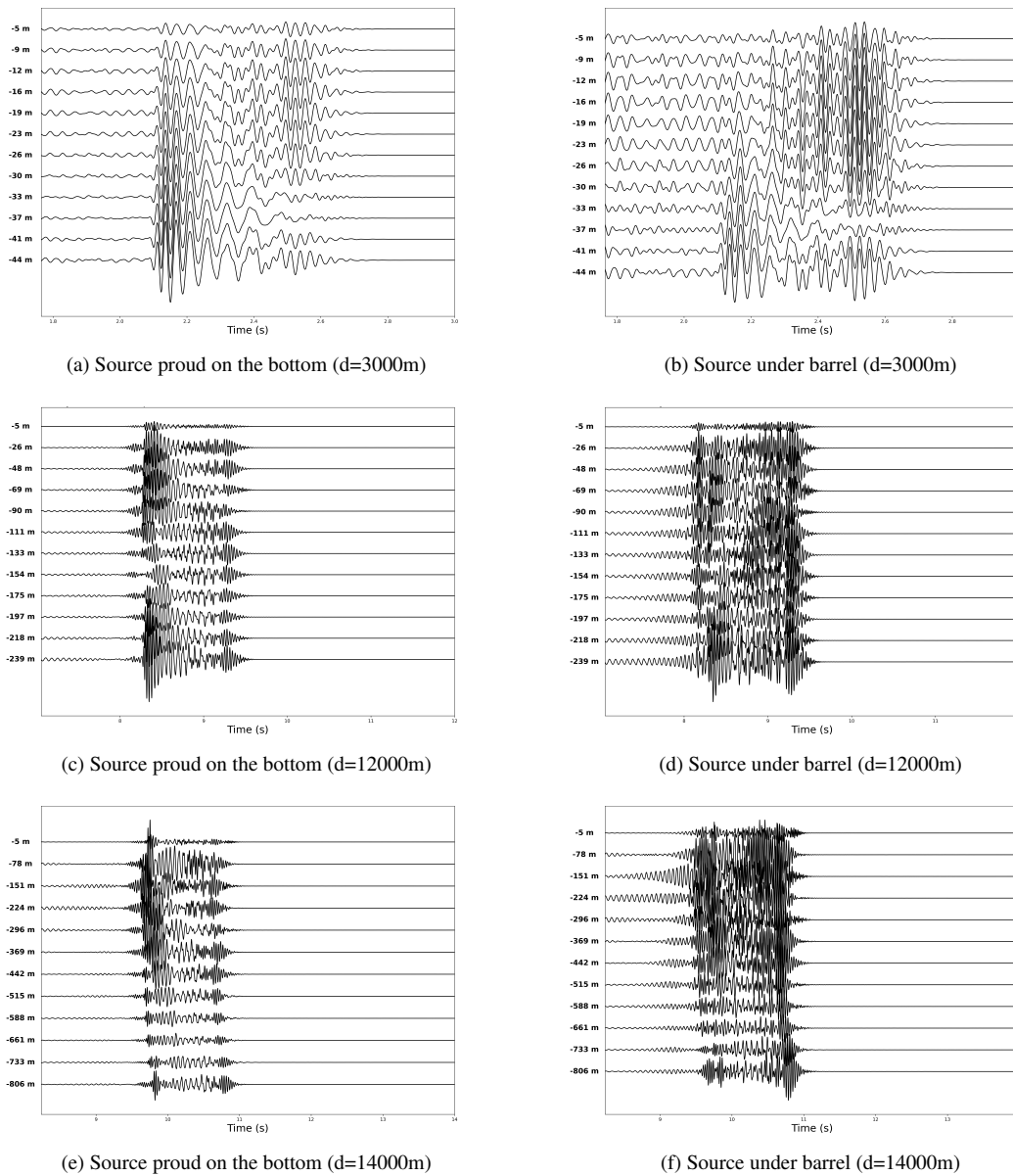


Figure 3. Signals received on three vertical arrays spanning the entire water column at three different distances

It can be clearly seen a strong first arrival which occurs when the source is “proud on the bottom”. This first arrival corresponds to the Stoneley-Scholte interface wave propagating at the water/bottom interface. It is always present even when the water depth increases. When the source is “under barrel”, this arrival is weaker because the source is far from the interface but is still present. In addition, it can be noted that the first arrival in the last vertical array (d=14000m), situated in deep waters, shifts in time with depth indicating an effect of the curvature of the interface due to the steep transition from shallow to deep water which occurs in this configuration.

3.2 Sound exposure levels

The Sound Exposure Level (SEL) is another physical parameter useful for the evaluation of the impact of the acoustic wavefield on the marine fauna. This parameter is given by the following relation:

$$SEL = 10 \log \left(\int_0^T p^2(t) dt \right)$$

where T is the length of the time signal.

It can be easily evaluated from time domain numerical simulations. In this subsection, we compare the SEL variations for the two source positions (“proud on the bottom” and “under barrel”).

We first evaluate the SEL variations with depth on several vertical arrays situated at different distances to the source (see Figure 4).

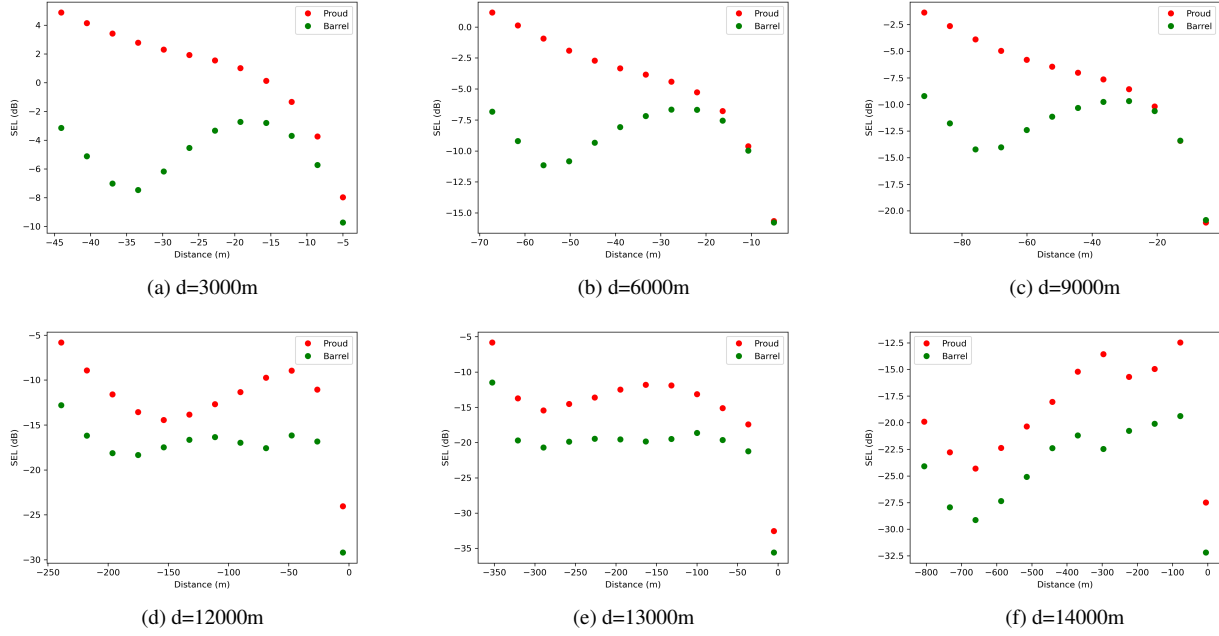


Figure 4. Variation of the SEL on vertical arrays spanning the entire water column for six different distances to the source

For all vertical arrays, it can be noted that the SEL values for the “proud on the bottom” source are always greater than the SEL values for the “under barrel” source. This results is counter intuitive and puts in light the strong effect produced by the interface wave. A 10 dB gap is present in the vicinity of the interface between water and sediments. In addition, a variation with depth of the SEL values is observed suggesting that it cannot be considered as constant in this configuration as usually guessed in the literature.

In a second step, we investigate the evolution of the SEL values with range at a given depth.

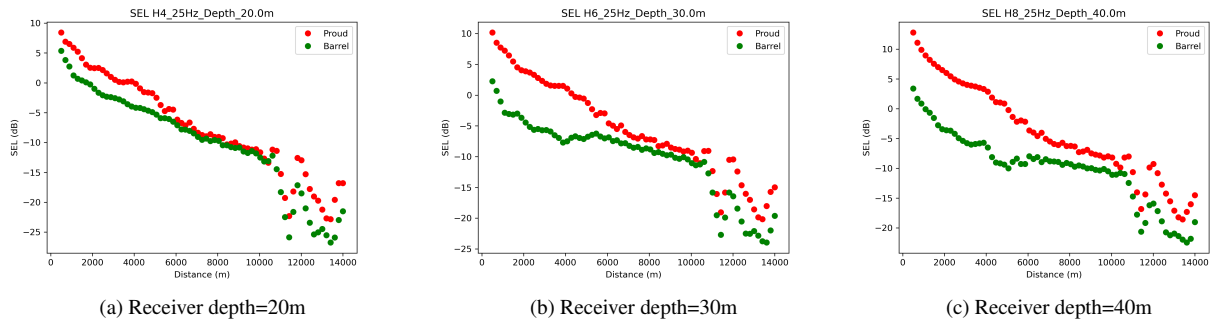


Figure 5. Variation of SEL with source-receiver distance for three different depths

Figure 5 confirms the results of Figure 4 showing that when the receiver gets close to the interface the difference between the SEL produced by the two sources can be more than 10 dB. This difference is higher in the shallow water zone but remains non negligible even when reaching deeper waters.

4 CONCLUSION

In this extended abstract, we studied the propagation of acoustic waves generated by the counter-mining of UXOs in shallow water. Specifically, we investigated the structure of the acoustic wavefield which propagates towards deep waters. It was found that the interface waves generated during disposal are critical highlighting the absolute necessity of considering the elasticity of sediments in this type of studies.

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