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SEISMO-ACOUSTIC WAVE PROPAGATION IN THE RADE OF HYÈRES (FRANCE) GENERATED BY COUNTER-MINING OF EXPLOSIVE DEVICES: RISK ASSESSMENT FROM THE COMPARISON BETWEEN NUMERICAL SIMULATIONS AND REAL EXPERIMENTS

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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. Depending on the environment geology, the explosive charges and their localization, the seismoacoustic waves generated by the explosion may cause damage to infrastructures located on the coast, and under specific conditions small submarine landslides. The ANR ASTRID POSA project proposed to address the risk assessment issue on the Mediterranean coast. The main originality of this project lied in the approach used that combines geological measurements, acoustic data recorded within the sea coastal zone and seismic data recorded on the coast, together with numerical simulations of seismo-acoustic wave propagation. We propose here to present the results of such a methodology applied to the counter-mining campaign that occurred in the Rade of Hyères (France) in December 2018. We focus more specifically on the numerical simulations of seismo-acoustic wave propagation from the location of the device explosion to several seismometers deployed on the coast of Hyères. From topographical and sedimentary measurements performed in the Rade of Hyères, physical and geometrical characteristics of the marine seabed have been carefully selected as input data for numerical simulations. In addition, a particular attention has been paid to the measured characteristics of the device explosion (source). The numerical simulations have then been conducted using a spectral-element method. The impact of the explosive device charge and its location (on the seabed or in the water column), together with the impact of the marine environment properties, on the simulated signals have been studied. Finally, the numerical results have been compared with the real signals recorded by the seismometers. The

risks of land degradation have been evaluated afterwards.

1. INTRODUCTION

Explosive devices from World War II are discovered every week on the French coasts. In a short time after their discovery, they must be destroyed by the French Navy Mine Warfare Office. If the risks are well known by mine warfare experts, the consequences of detonation on the marine environment are much more complex to evaluate and expertise is then required. Depending on the environment geology, the explosive charges and their localization, the seismo-acoustic waves generated by the explosion may cause damage to infrastructures located on the coast, and under specific conditions, small submarine landslides. The POSA project, led by SHOM, and which includes LMA, Geoazur and LPG Nantes, focuses on the Mediterranean coast and proposes to address the upstream risk management issue of such detonation operations in the marine field. The goal is to identify these risks for specific configurations and to develop a decision support tool for their control.

The underwater explosions have been widely studied especially after World War II [1] [2] [3] [4] [5]. They have the advantage of providing a pulse source of great power, and containing broadband frequencies. The main originality of the POSA project lies in the approach used to assess the risks arising from the underwater explosion detonations. This approach combines numerical simulations of seismo-acoustic wave propagation and the coupling between acoustic data recorded within the coastal zone at sea and seismic data recorded on the coast, together with sedimentary measurements. We present here the results of such a methodology applied to the detonation campaign conducted in the Rade of Hyères (France) in December 2018. We focus more specifically on the numerical simulations of seismo-acoustic wave propagation in this area.

As a first step, from topographical and sedimentary measurements performed in the Rade of Hyères, physical and geometrical characteristics of the marine seabed (i.e., sediments and rock basement) have been carefully selected to serve as input data for numerical simulations. In addition, particular attention has been paid to the source parameters. The source time function is estimated from in situ acoustic signals recorded by hydrophones located around the detonation location. Taking into account these input data (i.e., characteristics of the seabed and the source), numerical simulations of seismo-acoustic wave propagation, from the source to several seismometers deployed on the coast of Hyères and surrounding islands, has been then conducted using a spectral-element method based software SPECFEM [6] [7]. The seismic data recorded on the coast are used to calibrate the numerical simulation and to evaluate the impact of different marine environments.

The paper is organized as follows: First, we present the experiment setup. We then show some hydroacoustic measurements and seismic measurements. Finally, we address the numerical modeling and show how the marine environment, in particular the sedimentary layer, impacts the signal.

2. EXPERIMENT LOCATION AND GEOMORPHOLOGY

A series of 8 underwater explosions with 4 different charges of 80-680 kg equivalent TNT were detonated on December 2018 in the Rade of Hyères in France in 2 locations 3TY and 3TZ, with charge depths of 46 m and 26 m respectively (Fig.1). The distance from the explosion location to stations on the coast varies in the range 6-14 km. A detailed bathymetric map is shown in Fig.2. The sediment depth map (Fig.3) shows that the sediment depth in the experiment area varies in the range 0-30 m and reaches its maximum on the west side of the area. The physical properties of the sediments and the basement are shown in Fig.4 and Fig.5. It should be noted that the density, the P-wave velocity and the P-wave attenuation factor in the sediments are measured, but the S-wave velocity and the corresponding S-wave attenuation factor are missing and need to be estimated. The physical properties of the rock are estimated from terrestrial geological maps, field observations and some information from fragments of rocks in the samples, which results in significant uncertainties for the numerical modeling.

3. HYDROACOUSTIC AND SEISMIC MEASUREMENTS

3.1 Hydroacoustic measurements

A hydroacoustic measurement system, including a near-source shock probe (~200 m) and two hydrophones (~400 m and ~3000 m) was used for recording acoustic data. Detonations in shallow water produce seismic waves bearing data features caused by a source effect (bubble oscillation) and a path propagation effect (reverberations). The

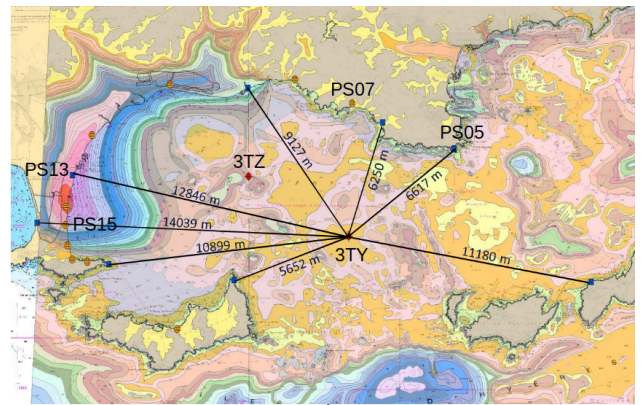


Figure 1. The explosion locations 3TY and 3TZ and the distances from 3TY to ground motion recording sites on the coast.

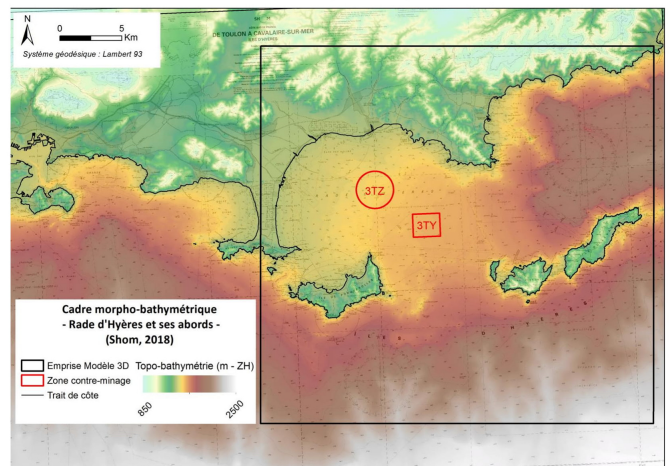


Figure 2. The bathymetry map of the studied area.

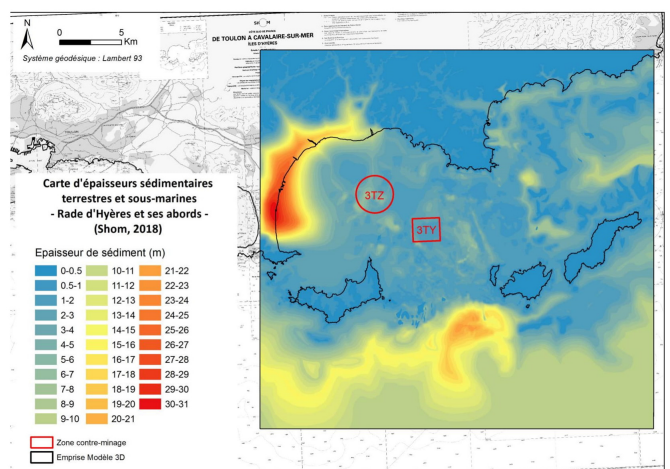


Figure 3. The depth of sediments in the studied area.

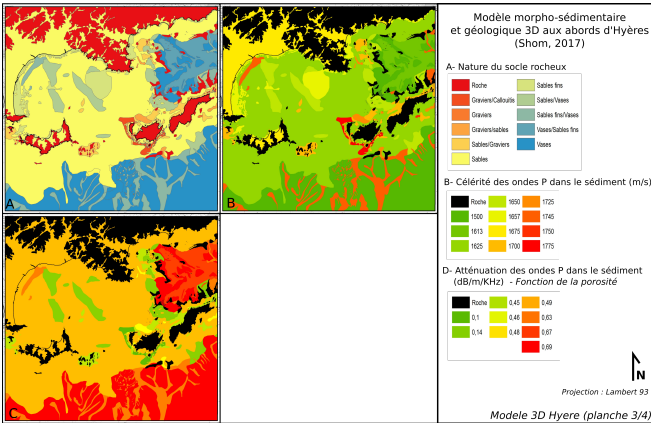


Figure 4. The physical properties of the sediments in the studied area. A. The nature of sediments. B. The P-wave velocity in the sediments. C. The P-wave attenuation factor in sediments.

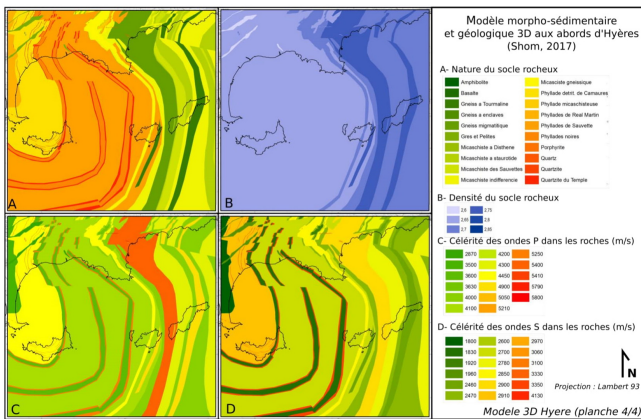


Figure 5. The physical properties of the basement in the studied area. A. The nature of rock. B. The density of rock. C. The P-wave velocity in the rock. D. The S-wave velocity in the rock.

pressure-time history recorded by the shock probe during one of the explosives of 80 kg in 3TY is shown in Fig.6. We can observe the shock wave at 0.16 s, the reverberation wave at 0.162 s and the first bubble pulse at 0.46 s. The spectral analysis of the shock probe and hydrophones measurements for the charge of 200 kg in 3TZ is shown in Fig.7. We note that the spectrum is broad band. A first maximum is located between 40 Hz and 100 Hz, and a second maximum is around 200 Hz. These near source observations are used to estimate source parameters of the explosions.

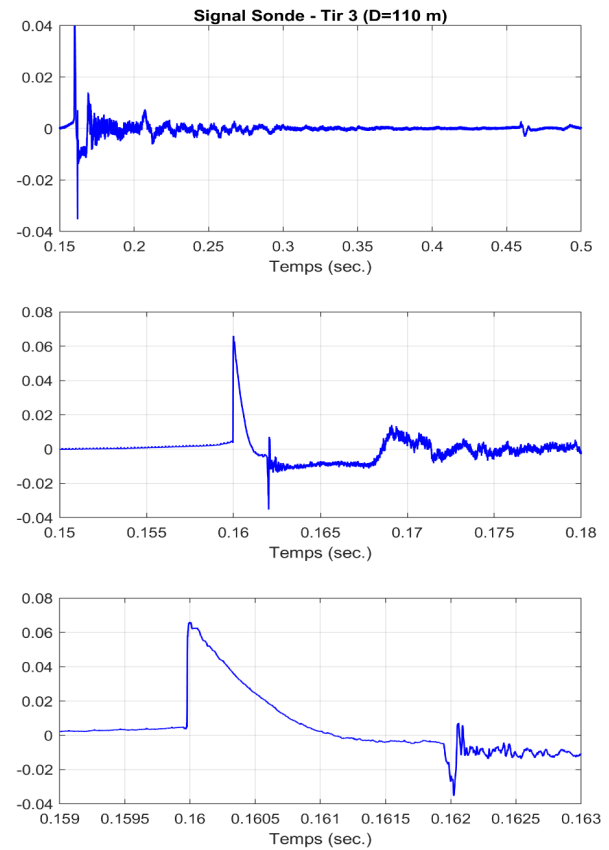


Figure 6. The pressure-time data recorded by the shock probe for the 80 kg charge (Time is relative to the beginning of the record).

3.2 Seismic measurements

Seismic data are recorded by 17 three-component broadband velocimeters or accelerometers along the coast. These records help to study the impact of different marine environments on signals. Fig.8 and Fig.9 show for the same explosive of 680 kg in 3TY, the signals recorded at the stations PS05, PS07, and PS13 (indicated in Fig.1). The major difference between the wave propagation paths to PS05/PS07 and PS13 are the distance and the thick sedimentary layer near PS13. We can observe the presence of stronger surface wave starting from 60s in the data

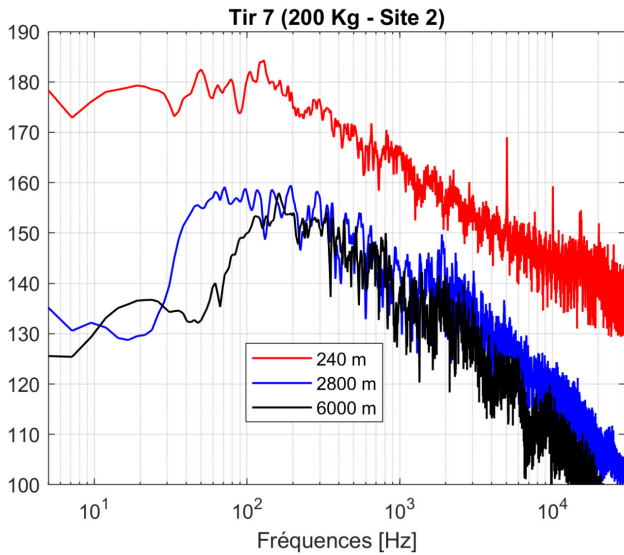


Figure 7. The spectrum of data with duration of one second recorded for the 200 kg charge by the shock probe at 240 m (red) and two hydrophones at 2800 m (blue) and 6000 m (green).

recorded at the station PS13. And its spectrum is enhanced on the low-frequency part around 1-6 Hz.

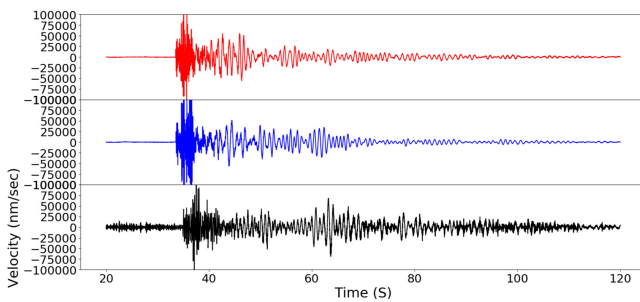


Figure 8. The recorded velocities at the station PS05 for the N-S component (red), PS07 for the N-S component (bleu) and PS13 for the E-W component (black). Time is relative to the beginning of the record.

4. NUMERICAL MODELING

Physical properties of the marine environments provided by SHOM, for example, the density, the P-wave velocity and the S-wave velocity in the rock, together with the density, the P-wave velocity and attenuation factor in the sediments are taken into account as input data for the numerical modeling of seismo-acoustic wave propagation. The S-wave velocity in the sediments is not provided and is assumed to be 260 m/s by considering the shallow depth of sediments. The S-wave attenuation factor is calculated accordingly. We choose to simulate wave propagation from the source 3TY to the station PS15 on the west side of the area (Fig.10). The choice of this station is motivated by the presence of a thick sedimentary layer near the coast, up to 30 m. The water layer depth in this area is 46 m in the

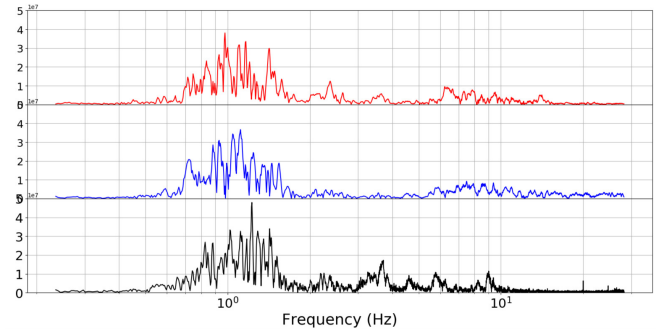


Figure 9. The spectra of recorded velocities shown in Fig.8, at the station PS05 for the N-S component (red), PS07 for the N-S component (bleu) and PS13 for the E-W component (black).

source location and gradually decreases when approaching the coast.

As shown in Fig.7, the data energy is significant in the range 0-300 Hz. If we consider this range of frequency and 260 m/s as the S-wave velocity in the sediments we need to set a very small time step to 2×10^{-5} s during the numerical simulation to ensure numerical stability. The 3D simulation with this time step for a propagation distance of 13 km and a S-wave velocity of 260 m/s is beyond our actual computational capacity. As a result, we propose to start with the 2D simulation and we limit the frequency range to 0-30 Hz, for which the infrastructures on the coast are mainly sensible. For the source waveform, we are still working on its estimation and we propose to neglect the shock wave, which is rather high frequency, and use the first bubble pulse as the source time function. At the same time, we use a Dirac delta function as the source time function to produce a broad-band data and we will just need to convolve the data with the estimated source waveform once we have it. The numerical simulation has been then conducted using a spectral-element method implemented in a software named SPEC-FEM [6] [7], which is a full-wave method combining the accuracy of a pseudo-spectral method with the flexibility of a finite-element method.

There are mainly three types of waves propagating in the model. The first one is the modal propagation in the water layer. The second one is the surface waves propagated along different medium interfaces. The third one is the body waves in the rock.

The modal wave in the water is relatively high frequency as the water layer depth is too small compared with the wavelength of low-frequency wave. And the number of modes gradually decreases with the decreasing of the water layer depth. After calculation, we estimate the critical depth for modal propagation is 20 m, meaning that after the location where the water layer depth is 20 m, there are no more modal propagation in the water.

The body waves propagating in the rocks can reach the seismic stations deployed along the coast, since there usually exists a velocity gradient with depth in rocks. Nevertheless, even if the stations actually record such waves, we cannot model their propagation, since rocks properties are

considered as constant with depth in our numerical simulations.

The surface/interface waves contain both relatively (very) low-frequency Rayleigh waves and Rayleigh-Sezawa modes and relatively high-frequency Stoneley-Scholte waves. Their existence, their generation and their conversion (from a Stoneley-Scholte wave to a Rayleigh wave or Rayleigh-Sezawa modes) mainly depend on the sediment height/wavelength ratio. Thin sediment layers then may have a greater impact on the high-frequency components of the interface/surface waves, while thick layers may have an impact on the low- and high- frequency components. As a consequence, areas located in the [2-4.5] km and in the [8-13]-km ranges (see Fig.10) probably have a great impact on interface/surface waves of Stoneley-Scholte wave and Rayleigh-Sezawa mode types.

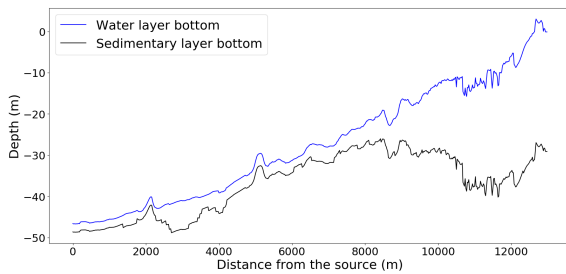


Figure 10. The selected 2D model for the numerical modeling. (Blue) Bottom of water layer. (Black) Bottom of sedimentary layer.

The impact of the marine environment properties, especially the influence of the sediments on the simulated data has been studied. From Fig.11 and Fig.12 we can follow the signal and spectrum evolution along the whole propagation path. We note that approaching the coast, where the sediments become thicker, the amplitudes are amplified and the spectra gradually shift to the low-frequency range. From Fig.13 we observe that at a distance of 8500 m from the source, where the water layer depth is 19 m and the sedimentary layer depth is 7 m, the energy is focused in the sedimentary layer, and in the water layer low frequencies are much weaker than that in the sediments and rock (Fig.14), as the energy is focused in sediments for surface wave along the water-sediment interface. The results agree with our previous analysis. The simulated data are compared to the real data (Fig.15 and Fig.16). We note that the real data duration is longer and in the real data spectrum, there is one peak around 1.5 Hz, while in the simulated data, there are several peaks around 2 Hz and 7 Hz. The difference mainly comes from 3 factors: the 3D to 2D simplification, the inaccurate source waveform used, and the uncertainties related to the estimated marine physical properties, especially the S-wave velocity in the sediments which affects the signal duration significantly. This is still an ongoing work.

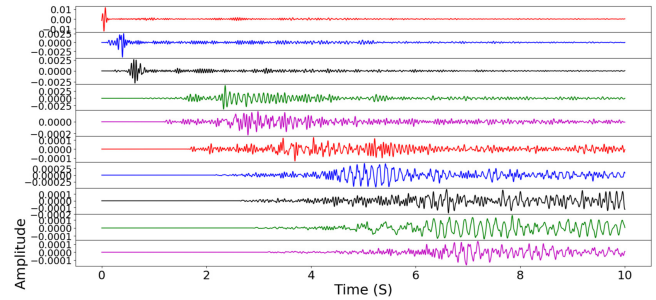


Figure 11. The simulated data for receivers situated at a horizontal distance of 100 m, 500 m, 1000 m, 3000 m, 5000 m, 7000 m, 9000 m, 1100 m, 12000 m, 12801 m respectively from the source and 2 m below the water-sediment interface.

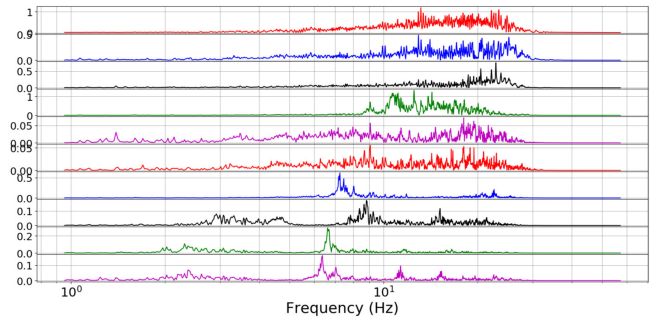


Figure 12. The corresponding spectrum of the data shown in Fig.11.

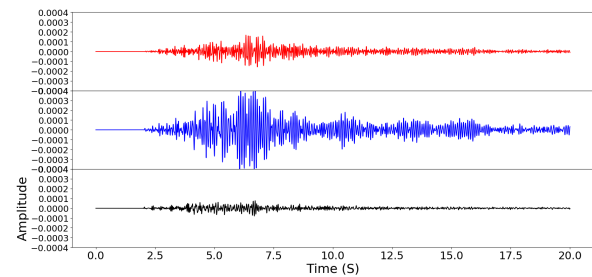


Figure 13. The simulated data for receivers situated at a horizontal distance of 8500 m from the source and with varied vertical positions, respectively in the water (top), in the sediment (middle) and in the rock (bottom).

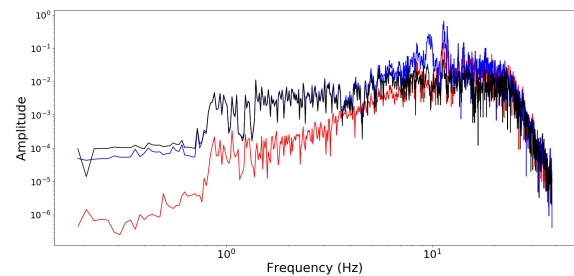


Figure 14. The corresponding spectrum of the data shown in Fig.13. (red) Receiver in the water, (blue) receiver in the sediment, and (black) receiver in the rock.

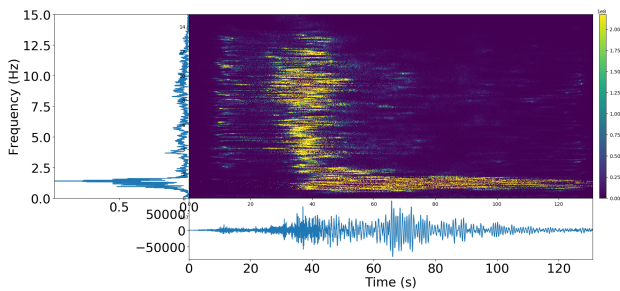


Figure 15. The spectrogram of the real data recorded at the station PS15 for the charge 680kg. The signal is filtered 0-10 Hz.

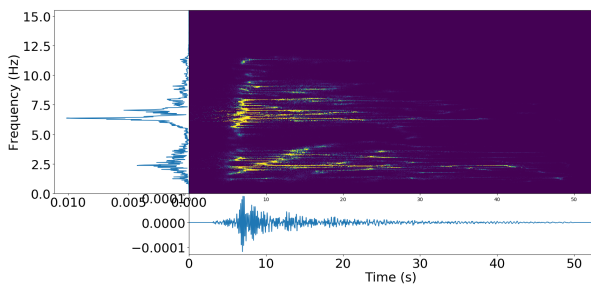


Figure 16. The spectrogram of the simulated data in the 2D model from the source location 3TY to the station PS15. The signal is filtered 0-10 Hz.

5. CONCLUSIONS

The underwater explosion in the Rade of Hyères provided a variety of data. The hydroacoustic measurements presented interesting phenomena such as the arrival of the shock wave, the reverberation wave, and the bubble pulsation. The near-source hydroacoustic measurements were used to estimate source parameters. The seismic measurements help to study the impact of marine environments on data recorded on the coast. Numerical modeling was conducted to better interpret propagation phenomena and to provide risk evaluation tools for future detonations. Both the seismic measurements and numerical modeling data show that thick sedimentary layers amplify the data amplitude and enhance the low frequencies. This is a phenomenon that is well-known in seismology, namely the site effect. However, further studies that we have conducted, but that are not reported here, show that the amplitude amplification together with the low-frequency shift do not lead to big earthquakes on the coast. Our in-situ measurements highlight small blast-induced earthquakes with a magnitude of up to 2.8 (for the biggest charges, namely of 680-kgs TNT-equivalent weight).

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