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# Numerical simulation of pile-driving induced-noise propagation into the ocean: effects of sedimentary basins and interaction of two distant pile driving operations

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## ABSTRACT

Pile driving is a major source of the noise generated by human activities in the ocean. The complex wavefield which is generated by this activity depends not only on the water column characteristics but also on the structure of the sediment layers beneath. In general, this structure is considered horizontally stratified with a gradient of mechanical properties. In this presentation, we propose to investigate a sediment configuration with a heterogeneous structure including two sedimentary basins. For this purpose, we performed several numerical simulations using a 2D time-domain spectral element method which allows for accurate handling of the characteristics of the complex marine environment (complex bathymetry and elastic sediments). We emphasize the presence of interface waves of the Stoneley-Scholte type. Additionally, we propose a method to generate 3D interaction maps of two distant pile driving operations using only one 2D simulation. Our results show the importance of taking into account the phase of the signals to correctly evaluate the interferences between the two operations.

Keywords: Pile driving, Wave propagation, Interface waves, Numerical modeling

## 1 INTRODUCTION

Pile driving is a major source of anthropogenic noise in the ocean. Many studies have been conducted on this topic, see for example the review article by A. Tsouvalas [1] and the references cited in this paper. Accurately predicting the noise levels generated in the water column by this type of source is fundamental for a reliable assessment of its potential hazards. In order to improve the understanding of the distribution of the ocean noise level generated by a pile-driving operation, this work aims to study the influence of a complex geological environment on the observed signals. Usually, a nearly horizontally stratified environment with a velocity gradient is considered, but this configuration may not reflect some situations where the sedimentary layer structure comes from a more complex geology. For example, sedimentary basins are known to strongly modify the acoustic wave field in the water column [3].

In this work, we chose to consider an ocean floor with two sedimentary basins and study how their presence can affect the propagation of acoustic waves in the water layer.

In a first step, a 2D model is built and used to perform numerical simulations in the time domain of acoustic and seismic wave propagation. Then, in a second step, the results of these numerical simulations are analyzed and some conclusions are drawn.

## 2 CONFIGURATION

We first design a 2D model of the structure of the ocean bottom with two sedimentary basins (see Figure 1) lying on a rock basement. The length of the model is 13 km. The first sedimentary basin is 10m deep with an extension of 3 km while the second sedimentary basin is 3m deep with a 2 km extension. In the vicinity of the pile, the sediment layer thickness is 2m. The water depth increases steadily with distance starting at 15m and ending at 50m. At the end of the model, far from the source, the layer structure is range independent.

In order to perform the numerical simulations, the entire domain is meshed with quadrilateral elements using the Gmsh Software[4].

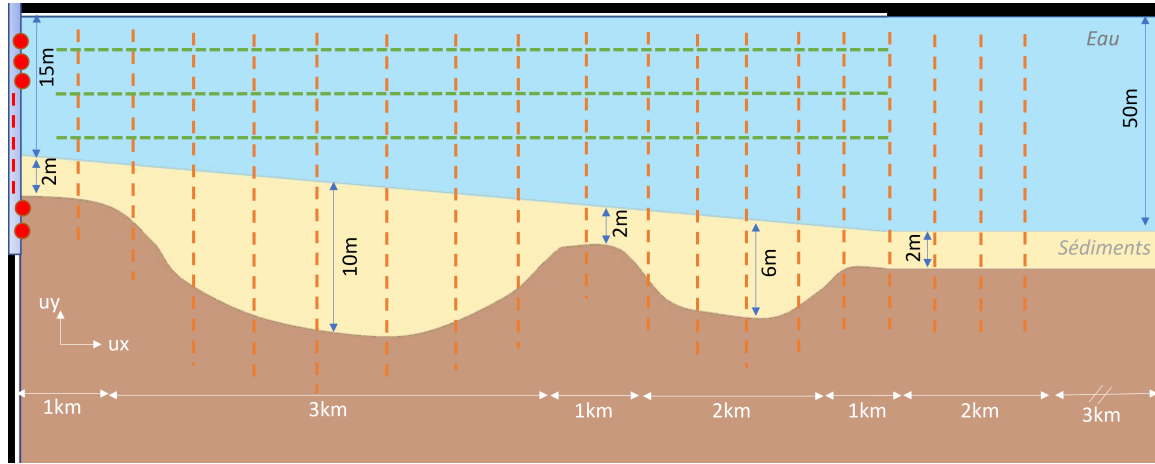


Figure 1. Bathymetry.

The numerical simulations are performed using the open-source software SPEC-FEM2D<sup>1</sup>. SPEC-FEM2D implements the spectral-element method. It is based upon a high-order piecewise polynomial approximation of the weak formulation of the wave equation. It 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 interface waves (Stoneley-Scholte, Leaky Rayleigh, etc.) is known to be important. The numerical simulations are performed using the cylindrical coordinate system.

The source model of pile driving is taken from reference [2]. The source signal is a Ricker wavelet with a central frequency of 85 Hz. This means that the maximum frequency which is considered in the numerical simulations is 212.5 Hz.

The bottom of the ocean is considered as an elastic medium with the following physical characteristics:

- Water:  $\rho = 1000 \text{ kg/m}^3$ ,  $c_p = 1450 \text{ m/s}$
- Sediment:  $\rho = 2200 \text{ kg/m}^3$ ,  $c_p = 1750 \text{ m/s}$ ,  $c_s = 600 \text{ m/s}$
- Basement:  $\rho = 2700 \text{ kg/m}^3$ ,  $c_p = 3550 \text{ m/s}$ ,  $c_s = 2200 \text{ m/s}$

where  $\rho$ ,  $c_p$  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. First, we show the results of the evaluation of the Sound Exposure Level (SEL) at a depth of 14m. This parameter is given by the following relation:

$$SEL = 10 \log \left( \int_0^T p^2(t) dt / p_0^2 \right)$$

Then, we present the spectra of several signals recorded along the path from the source and finally the evaluation the interaction of two pile driving operations is presented. Finally, the interaction between two distant pile driving operations is studied.

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

### 3.1 Sound exposure levels

The amplitude of the source is adjusted to give an SEL value of 190 dB at a distance of 100 m from the source.

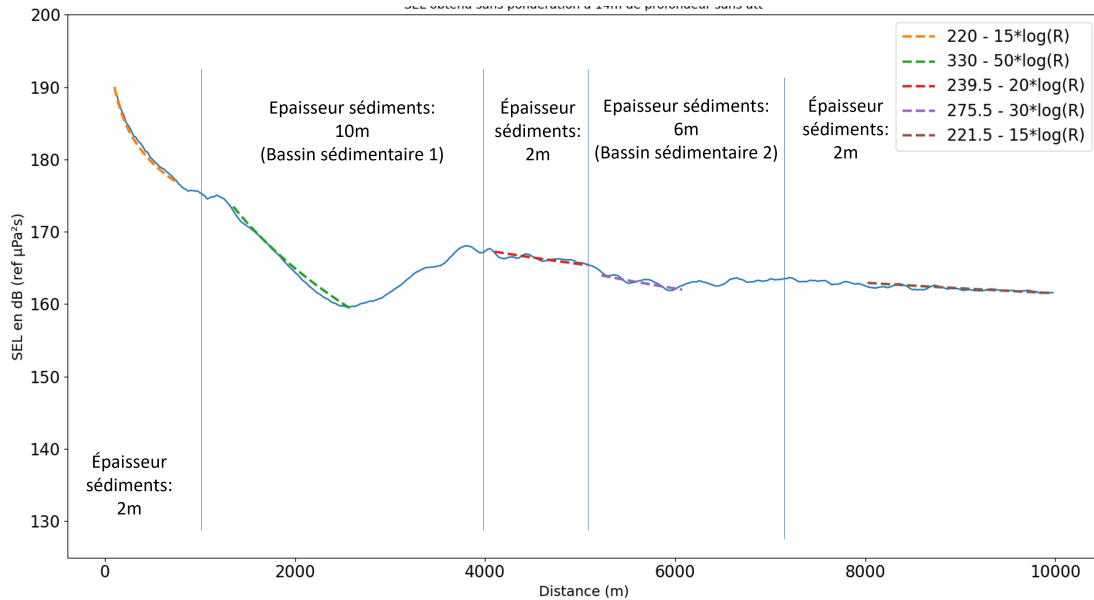
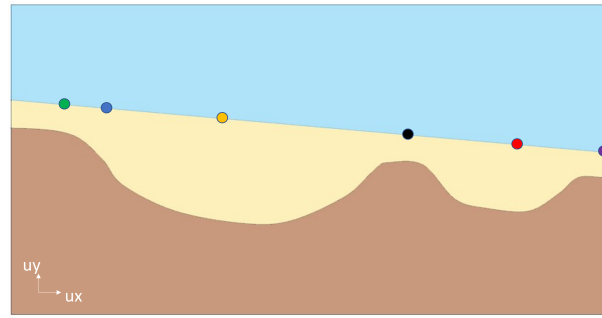


Figure 2. Variation of the SEL values with the distance to the source for receivers situated at a depth of 14m

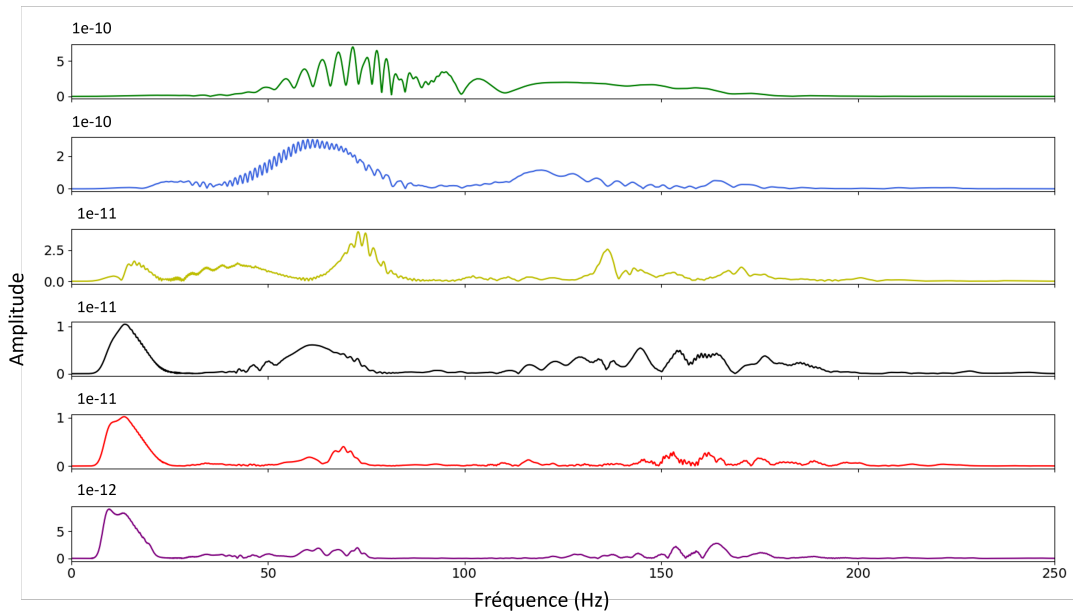
A strong decrease followed by a strong increase in SEL values can be observed in the first sedimentary basin. The increase reaches a value of 10 dB at the end of the first sedimentary basin. The effect of the second sedimentary basin is much smaller with a slight increase in SEL values. Nevertheless, it is clear that a site effect occurs, radically changing the behavior of the sound pressure decay. A complex geometry of the sedimentary structure can strongly affect the distribution of acoustic energy in the water column.

### 3.2 Spectrum evolution

In addition, it is also interesting to analyze how the spectral content of the signals evolves with the distance to the source. Indeed, it is known that site effects are characterized by a shift towards low frequencies of the spectra of the signals and also by a lengthening of the signal duration [5]. In this extended abstract, we will only tackle the frequency aspect of the site effect.



(a) Receiver positions



(b) Spectra

Figure 3. Spectra evolution of the horizontal component of the displacement. The color of the points indicated in subfigure a) corresponds to the color of the plots in subfigure b)

Figure 3 depicts the evolution of the spectral content of signals recorded at several receivers situated on the interface between water and sediments (see Figure 3a for the receiver positions). The shift towards low frequencies starts to be seen in the middle of the first sedimentary basin. At the end of the first sedimentary basin, it is very clear and this shift remains afterward. The frequency interval where the acoustic energy is the strongest shifts from the interval [30Hz-70Hz] to [10-15Hz]. It confirms the presence of a site effect due to the presence of a sedimentary basin.

This site effect may be due to the conversion of interface waves that may exist in this configuration. Depending on the frequency, the sedimentary basin may or may not affect wave propagation depending on its relative size to the wavelength of the interface wave and thus an energy transfer between the existing interface waves may be generated. In this configuration, we can have a Stoneley-Scholte wave at the water-sediment interface, a Stoneley-Scholte wave at the water-basement interface, and, a leaky Rayleigh wave at the water-basement interface. With the increase of the depth of the first sedimentary basin, we make the hypothesis that the high-frequency part of the leaky Rayleigh wave at the water-basement interface may be converted into a Stoneley-Scholte wave at the water-sediment interface while the low-frequency part remains unchanged. This, of course, needs to be confirmed by a more in-depth analysis.

### 3.3 Interaction of two distant pile driving sources

As a preliminary step to the study of the interaction of two distant pile driving operations in 3D, we propose to generate pseudo 3D SEL maps from a single 2D simulation in cylindrical coordinates. For this purpose, we consider a common area corresponding to the planar part of the 2D simulation where we evaluate the interaction between the signals emitted by the two distant sources. We first store the signals received by 80 receivers located, in what we defined as the common area, between 8 km and 10 km at a given depth. Then, we construct the 3D map by adding these signals as shown in Figure 4. The resulting non-uniform 3D spatial sampling is made uniform using "Nearest Neighbor" interpolation.

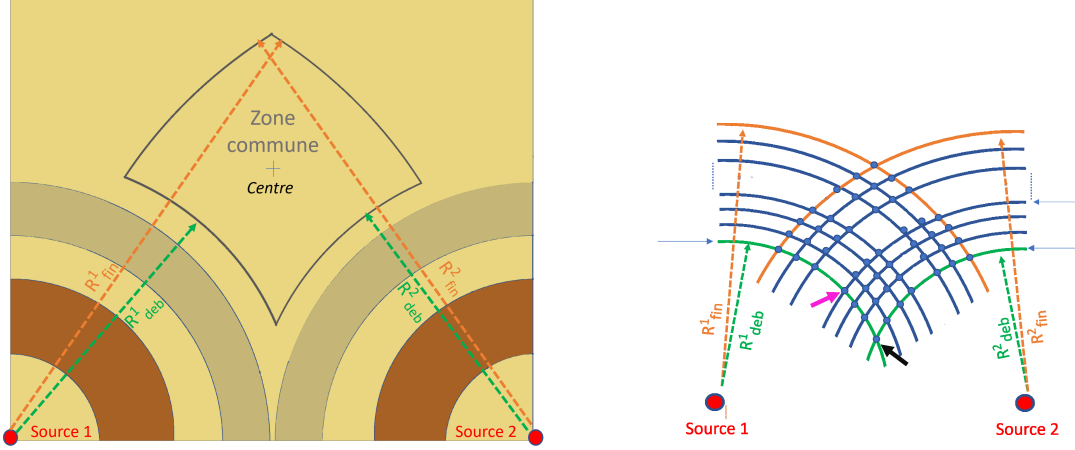


Figure 4. Schematic of the construction of a 3D map from one 2D simulation

The SEL maps are built in two ways to show the importance of taking into account the phase of the signals when there is an interaction. If  $p_1$  and  $p_2$  are respectively the sound pressure generated by Source 1 and Source 2, then the SELs can be evaluated using the following relation if we take into account the interaction between the two signals:

$$SEL = 10 \log \left( \frac{\int_0^T (p_1(t) + p_2(t))^2 dt}{p_0^2} \right)$$

Alternatively, if we do not take into account the interaction, the SELs are evaluated using:

$$SEL = 10 \log \left( \frac{\int_0^T p_1^2(t) dt + \int_0^T p_2^2(t) dt}{p_0^2} \right)$$

The generated pseudo-3D maps are shown in Figure 5. Figure 5a represents the SELs for two sources which are at the same distance to the center of the common area. Stronger SELs are observed along and near the diagonal of the image corresponding to the places where constructive interferences between the two emitted signals occur. Figure 5b represents the SELs for two sources whose distance to the center of the common area is different. One of the sources is moved back by a distance of 250m. This results in a shift of the line where constructive interferences occur.

If the SELs are evaluated without taking into account the interaction between the signals the SEL map is very different (see Figure 5c). The SELs are uniform.

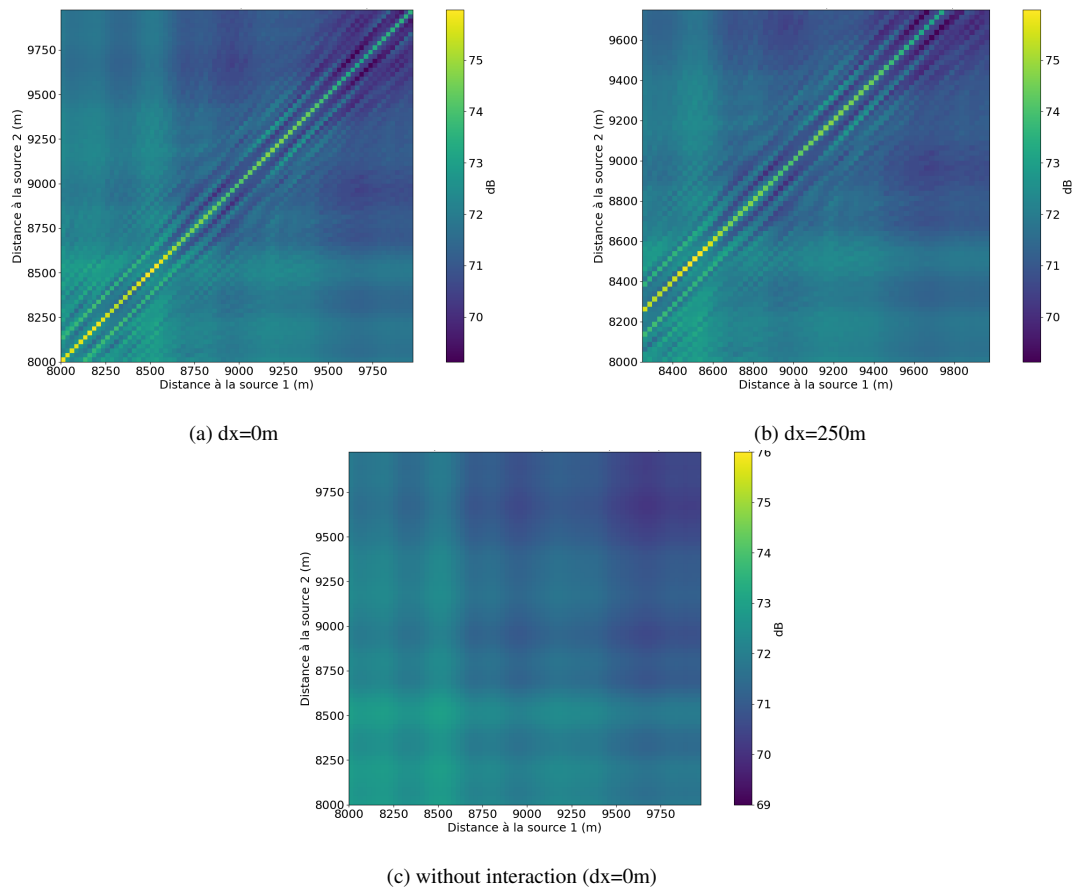


Figure 5. 3D SEL maps at a depth of 14m in the common area

## 4 CONCLUSION

In this expanded abstract, we investigated the structure of the acoustic wavefield generated by pile driving in the presence of a complex sediment structure. It was shown that the presence of sedimentary basins can strongly affect the distribution of acoustic energy on the water column both in terms of amplitude and frequency content. In addition, we generated pseudo 3D SEL maps of the interaction of two distant pile driving operations using a single 2D simulation in cylindrical coordinates. These maps highlighted the importance of taking into account the interference of the two emitted signals.

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