NUMERICAL ANALYSIS OF PILE DRIVING DISTURBANCES INTO WATER AND SOIL FOR OFFSHORE WINDFARM CONSTRUCTIONS

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Abstract: *Underwater noise during offshore wind farm construction goes along with significant disturbances that potentially harm marine mammals in the vicinity. There is limited information on the scale of such disturbances, knowing that each implantation site is different from the other. Therefore, it has become important to lead upstream numerical analysis in order to predict pile driving effects and better understand the physical behavior of radiated acoustic waves. As part of the offshore wind farm project in the area of Dieppe-Le Tréport, in France, 11 monopile foundations were driven into the ground during May 2017, where the sedimentology is the same as the future offshore site. Acoustic measurements have been done to serve as a starting point for the development and calibration of a simple 2D finite element model (FEM) for future offshore implementation.*
With our 2D FEM model, we predicted and investigated sound pressure level and sound exposure level (SEL) in the water, as well as radial displacement in the different sedimentary layers. We showed that more than half of the radiation in the water comes directly from the seabed itself. We then investigated existing solutions for underwater noise reduction, like an air-bubble curtain or low acceleration pile driving. It showed good results on noise reduction, by lowering the SEL by 10 dB at only 50 meters away (upstream). This is significant information that should be considered when planning offshore pile driving and looking for noise reduction solutions.

Keywords: *Underwater noise, pile driving, modeling, offshore wind farm, sound exposure level*

1. INTRODUCTION

In the last decades, offshore wind industry and associated Offshore Wind Farms (OWF) has grown significantly, in connection with an increasing demand for renewable energy: since 1991 and the world's first OWF in Denmark, this industry has grown on average 52% each year [1]. This growth led to bigger constructions, larger wind turbines and stronger wind profiles [2]. However, offshore constructions may come along with significant disturbances that potentially harm marine mammals in the vicinity [3]–[6]. Therefore, underwater noise during OWF constructions, and specifically during pile driving, became a research topic on its own [7], in addition to existing studies on harmful human activities [8], [9].

Pile driving consist of delivering a series of vertical blows to the head of the pile with a hydraulic hammer in order to fixed it into the ground. There are many different pile driving formulas in use, limited models and therefore limited information on the scale of such disturbances because every implantation site is different from the other [10]. That's why it has become important to lead upstream numerical analysis on each site in order to predict pile driving effects on radiated acoustic waves.
First, the context of this study is described in section 2. Then the 2D-FEM approach of pile driving is presented in section 3. Next, the numerical results will be shown and discussed in section 4. Finally, the conclusions of the paper and perspective of the results are presented in section 5.

2. CONTEXT

As part of a new OWF project between Dieppe and Le Tréport in Normandy (France), a research project called RESPECT[1] gave rise to collaboration between our team and the *Quiet Oceans* Company. This project aims to:

- Validate a proper finite element model (FEM) of the pile driving operation.
- Deepen the knowledge of the acoustic wave propagation acquired during the former phase of the project.
- Leading investigations on new and existing noise reduction solutions.

In order to calibrate the FEM, experimental pressure measurements has been made by *Quiet Oceans* company into the ground [11]. The measurements have been realized during a pile driving operation where sedimentological ground properties are equivalent to the location of the future OWF. In this location, 11 piles of 30 meters long and 1.22 meters of diameter were first vibro-driven and then pile-driven up to 20 meters deep into the soil. Piles are 22.7 mm thick, made of 8000 kg/m^3 density steel with 200 GPa Young's modulus. These parameters will be used to simulate pile driving operation into the sea, in order to limit scaling problems, although the final dimensions of the pile will be larger.

[1] RESPECT: *Réduction des Empreintes Sonores des Parcs Eoliens en mer: Comprendre pour de nouvelles Technologies*; (Reduction of Sound Footprints of Offshore Wind Farms: Understanding for New Technologies).

3. FINITE ELEMENT MODEL

The measurement campaign allowed to collect data (pressure, applied force, dimensions) in order to set up and calibrate a numerical finite element model through the commercial software ANSYS Mechanical APDL™ [12].
Once calibrated and close enough to experimental results (among other, by using the right sedimentary attenuation parameters [13]–[15]), an extrapolation of this model has been made to a pile driving problem into the sea. A 5 meter water layer is added, above a 3 meter sand layer. Every parameter used in this simulation can be seen on ***Table 1***. Regarding the pile itself, the applied attenuation is 2 dB/λ [15].

Layers	h [m]	E [GPa]	α [dB/λ]	ρ [kg/m^3]	c_l [m/s]
Water	5	2.2	-	1000	1500
Sand	3	0.194	0.8	2000	1800
Marly chalk	5	1.5	0.6	2000	1060
Medium chalk	2	12.15	0.4	2500	2700
Compact chalk	7+	15.68	0.2	3000	2800

Table 1: Parameters of each layer used in our 2D-FEM model.

In order to better understand the radiation of the pile, the contribution of the seabed is separate from the entire contribution of the pile itself, which radiates in water as much as in soil. In our model, for a normal situation, every node in the water (FLUID29) has 3 degrees of freedom (DOFs) which is 2 displacements (UX, UY) and fluid pressure. In order to predict the seabed contribution only, the DOFs of each node is blocked in a vertical line, at one meter distance from the pile, knowing that there may be some reflections, but without considering it for the moment. The pressure is picked up along a further vertical line in the water, at 50 meters away, as it can be seen on the *Fig.1*.

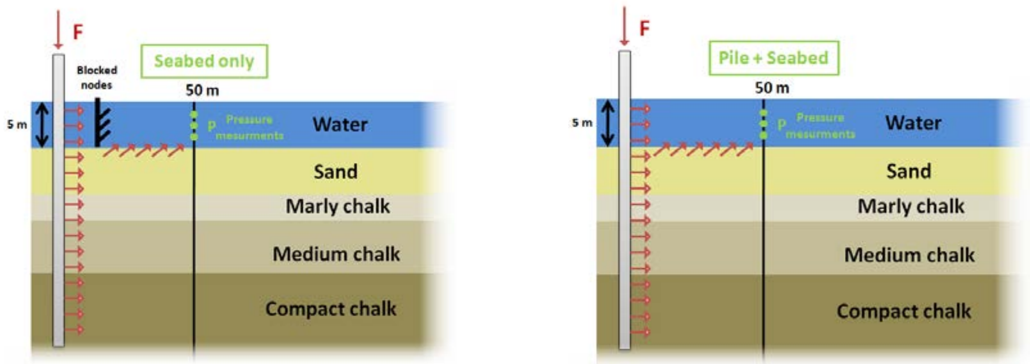

Fig.1: Measurement of the pressure at 50 meters by blocking the pile radiation in the water (left) and without blocking anything (right).

4. RESULTS AND DISCUTIONS

After separating the contribution, the pressure is calculated at 50 meters away from the pile, on a vertical line, over the entire depth of the water layer (5 meters), at the end of the pile driving operation. Then the SEL is plotted under both conditions, and results are discussed.

The effects of a noise reduction technique on the SEL with a low acceleration pile driving can be seen.

4.1. SEPARATION OF ACOUSTIC RADIATION

The calculated pressure at 50 meters at the end of the pile driving operation is plotted in the *Fig.2*. On the left graphic, the radiated sound pressure remains important even if the pile is not radiating into the water. In proportion, by a maximum amplitude ratio between both graphs, the seabed radiation is responsible for at least 50% of the pressure at 5 meters depth.

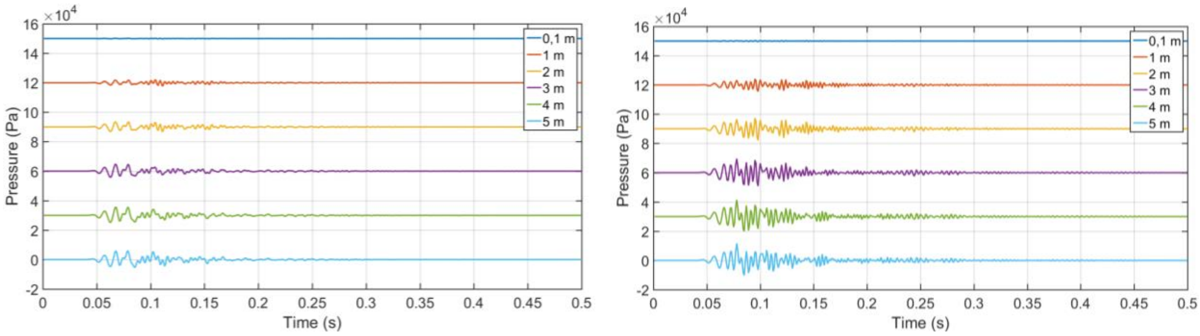

Fig.2: Sound pressure at 50 meters by blocking the pile radiation in the water (left) and without blocking anything (right).

The Sound Exposure Level (SEL) according to the depth is plotted on the *Fig.3*, and show the radiation from the seabed (red plot) being almost important as the entire SEL at 1 meter (blue plot), with a bigger contribution at 50 meters. This result suggests that long-range radiation should mainly relate to seabed radiation itself.

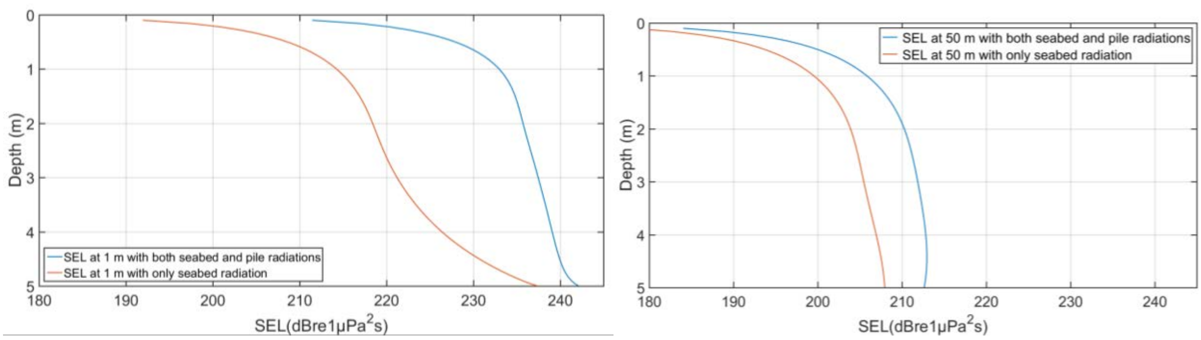

Fig.3: SEL at 1 meter (left) and 50 meters (right) by blocking the pile radiation in the water (red plot) and without blocking anything (blue plot).

This study shows that more than half of the radiation in the water comes directly from the seabed itself, which is significant information when studding noise reduction solutions. Hence, it could be noticed that an upstream noise reduction solution is more suitable than downstream technique. This is what is going to be shown in the next section.

4.2. NOISE REDUCTION SOLUTIONS

Classical and widely used noise reduction systems allowed between 10 and 14 dB (SEL) noise reduction, depending on the frequency range [16]–[19]. But those techniques only work as a downstream technique, and as we just have seen, the radiation of the pile in the water represents only a small part of the radiation. That is why upstream techniques could reduce way more significantly the underwater noise during pile driving. One of them allowed a noise reduction between 4 and 25 dB (SEL), depending on the scale and the frequency range [20]–[22]. This technique has been applied in our model, by using the same hammer force, but spread over a period of 100 ms instead of the initial 10 ms. SEL results according to the depth are plotted in the *Fig.4*. This technique reduces by almost 11 dB (SEL) the underwater noise at only 50 meters away from the pile. This is significant information that should be considered when planning offshore pile driving and looking for noise reduction solutions.

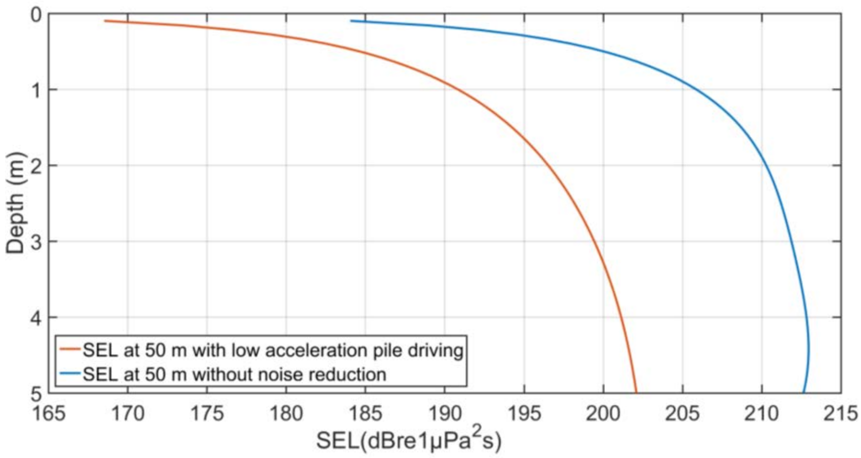

Fig.4: SEL at 50 meters from the pile using a soft pile driving (red plot) and without any noise reduction (blue plot).

5. CONCLUSIONS AND PERSPECTIVES

Our 2D-FEM model allowed us to easily separate radiation contributions and show that seabed itself is responsible of more than a half of the total radiation in water. Hence, reducing underwater noise should be better by lowering upstream signal, with optimized hammer for instance, than lowering downstream radiation, as downstream technique does. Existing upstream solution may offer a reduction of 11 dB (SEL) at 50 meters, which is not negligible.

In order to going further, it could be interesting to add friction in the model, losses in water, anisotropy and heterogeneities in the soil. It’s also important to have a better knowledge of the stratigraphic distribution under the pile driving zone. Indeed, the thickness of a layer, specifically the first one, as a significant impact on the radiating wave’s behavior into water.

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