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ADVANCED FAR-FIELD VIBRO-ACOUSTIC MODELING OF UNDERWATER PILE DRIVING FOR OFFSHORE NOISE MITIGATION

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ABSTRACT

Offshore pile driving generates substantial underwater noise, requiring advanced methods to assess and mitigate its impact on marine ecosystems. This study presents one of the first fully detailed numerical model for vibroacoustic noise propagation over 750 meters radial distance (as expected from ISO/CD 7605). Unlike traditional approaches, this model integrates all critical aspects: hammer excitation, pile vibrations, precise soil modeling, and airborne sound propagation. To address the complexity of propagation mechanisms, a dual-part modeling approach was developed. A near-field model captures detailed interactions close to the pile, while a far-field model extends predictions over longer distances. The methodology leverages an extensive bibliographic review to adopt the most robust techniques for each component. This work sets a new benchmark for vibro-acoustic modeling in underwater environments, offering a powerful tool for designing sustainable noise mitigation strategies while advancing offshore construction practices.

Keywords: *underwater, far-field, pile driving, numerical modeling, noise mitigation*

1. INTRODUCTION

Underwater noise pollution from offshore pile driving is a major environmental concern due to its impact on marine ecosystems (Fig. 1). Marine mammals and other aquatic species rely on sound for communication, navigation, and survival, making them highly vulnerable to anthropogenic noise (Ref [1-2]).

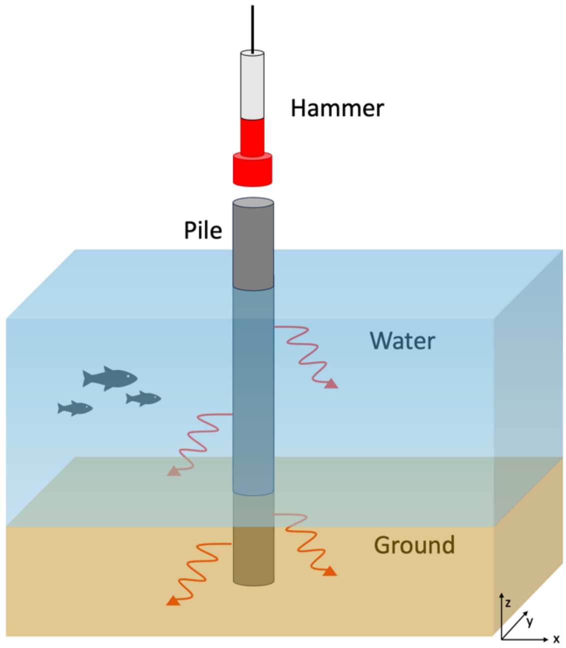

Figure 1. Schematic view of pile driving

The increasing awareness of wildlife needs and the emergence of new regulations (Ref [3]) emphasizes the necessity for accurate prediction models to assess the noise emitted from pile driving.

Traditional measurement approaches, while valuable, present significant limitations: full-scale in-situ measurements are costly and complex, whereas laboratory-scale experiments often fail to replicate real-world conditions. Consequently, accurate numerical tools are essential for predicting emitted noise. This study introduces an advanced numerical model that

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bridges this gap while maintaining computational efficiency.

In the following sections, we present the development of a numerical model designed to evaluate the noise levels generated by pile driving at a distance of 750 meters radial distance. This model is also employed to assess the effectiveness of various mitigation solutions, providing valuable insights into their performance in realistic offshore conditions.

2. FAR FIELD UNDERWATER NUMERICAL MODEL OF PILE DRIVING

2.1 Fast computing numerical model

The numerical model developed in this study consists of two distinct computational steps: one dedicated to the near-field region (0 m – 50 m) and another for the far-field propagation (50 m – 750 m) (Ref. [4]). Both are computed in the frequency domain, significantly reducing computational time (Fig. 2).

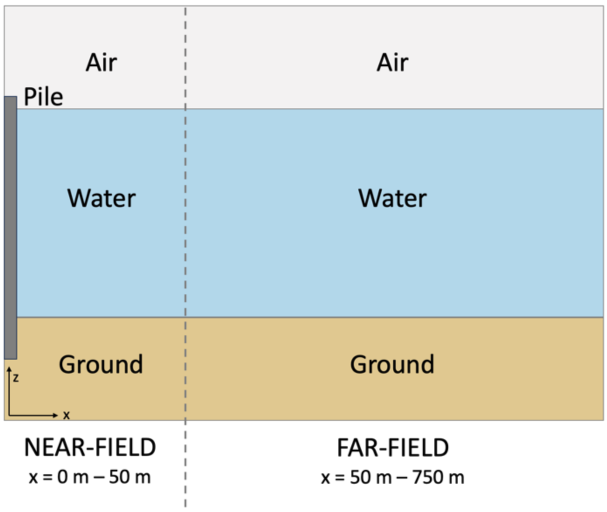

Figure 2. Overview of the model developed

For the near-field step (0 m - 50 m), the pile is explicitly represented with a 2D axisymmetric model (Fig. 3). Due to its small thickness but significant height, a highly refined mesh is required to accurately capture the physical interactions with its environment. Extending such a detailed mesh over 750 m would be computationally prohibitive. To address this limitation, the near-field simulation is performed only up to 50 m. The far-field model then extends the computation from 50 m to 750 m, simplifying the meshing process by representing the environment with three main layers: water, air, and seabed (Fig. 4).

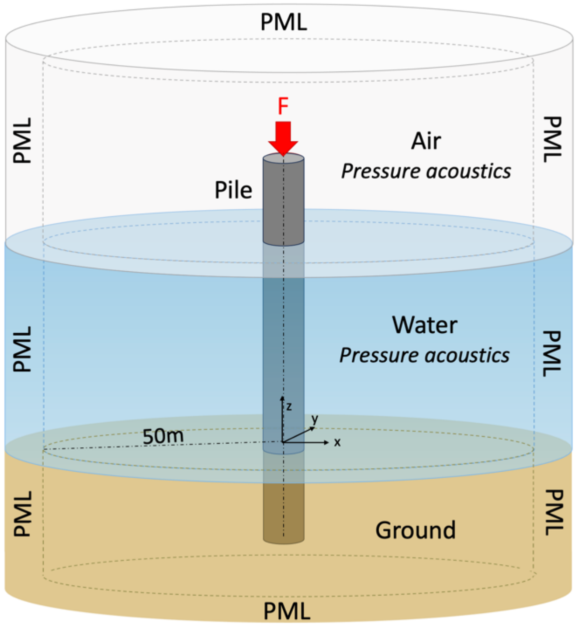

Figure 3. Near-field model for pile driving noise

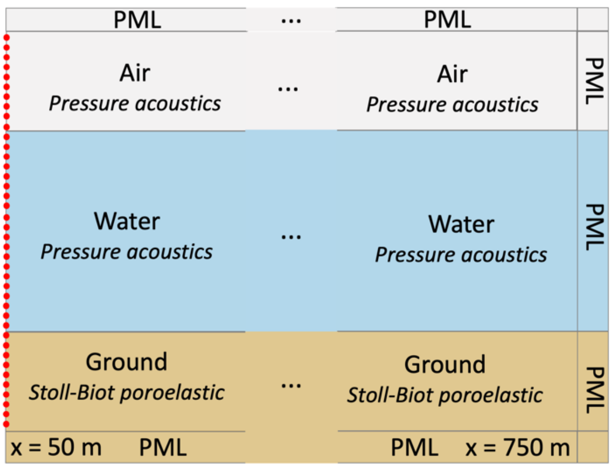

Figure 4. Far-field model for pile driving noise

Perfectly matched layers (PML) are applied at each model boundary (Figs. 3 and 4). The water column is modeled by incorporating hydrostatic pressure and variations in sound speed with depth. Oceanic attenuation is considered, as it significantly differs from atmospheric attenuation in the air domain.

For the seabed, the Biot-Stoll model is employed to describe poroelastic behavior, accommodating different sediment types, including fine or medium sand, soft sediment, or medium silt, based on established references (Ref. [5-6]). This approach provides a more accurate representation of the seabed's acoustic properties than classical solid elastic domains or fluid equivalent models.

In the near field model, excitation is performed by applying a force representative of the hammer behavior on the top of the pile. After computation, the pressure levels in air, water and ground are extracted and used as acoustic sources in the far-field model, illustrated by red points in Fig. 4. The final acoustic pressure fields obtained with the far-field model are illustrated in Fig. 5 (100 Hz) and Fig. 6 (500 Hz).

The pressure fields indicate that the water domain is the primary contributor at 750m. However, the ground and air domains play a crucial role, as evidenced by the multiple reflections between water and the other two domains, particularly at 500Hz.

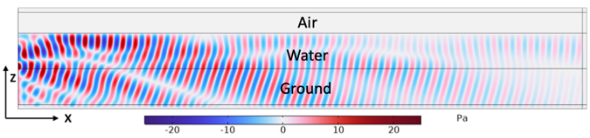

Figure 5. Acoustic pressure field at 100 Hz

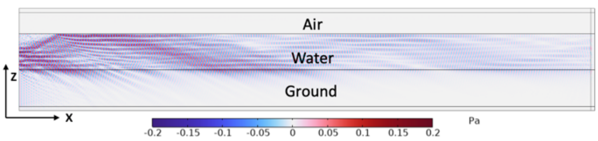

Figure 6. Acoustic pressure field at 500 Hz

This developed numerical model has been validated on a confidential experimental case showing very cohesive results.

2.2 Application of a noise mitigation system

A widely used system to mitigate pile driving noise is the air bubble curtain. However, implementing an air-bubble curtain requires extensive engineering and numerous components, such as air compressors, distribution lines, air emitters, introducing potential on-site challenges. Consequently, simpler designs that eliminate the air injection system can be preferable.

One such alternative is the hard bubble curtain (Ref. [7]), consisting of 17-inch-diameter balls filled with air. The balls have a High-Density Polyethylene (HDPE) shell and are aligned within a heavy-duty fabric sleeve designed to withstand large loads. Ballast is applied to one side to submerge the barrier (Fig.8).

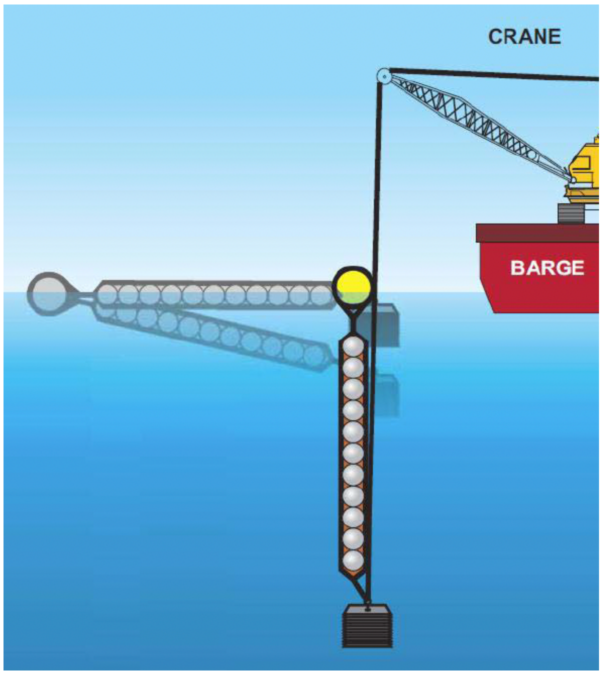

Figure 8. Computed acoustic pressure field – Frequency domain

The reference study (Ref. [7]) developed a simplified model to estimate the performance of a full-scale barrier. A plane wave was generated at one hand of the tube, and absorbing boundary conditions are applied at each end (Fig. 9).

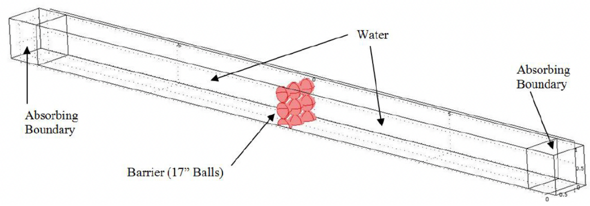

Figure 9. Simplified model of the hard bubble system

We replicated this model and estimated the insertion loss of this mitigation system. The results, shown in Fig.10, demonstrate a global match with the reference [7], with a peak shift around 150 Hz attributed to uncertainties in modeling the HDPE shell material as the parameters used were not shared in the reference article.

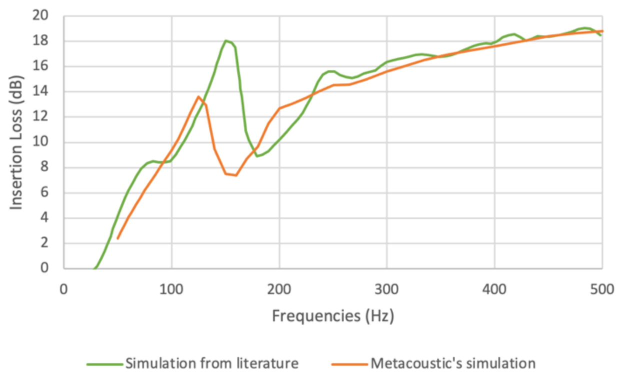

Figure 10. Insertion loss obtained with the simplified model

The hard bubble curtain was then implemented in the developed model (Fig. 11). Simulations were performed with and without the mitigation system to evaluate insertion loss at 750 m radial distance from the source (Fig. 12).

Results indicate that higher insulation than the simplified model can be expected (Fig. 10) with a gain up to 40 dB at 400 Hz for a realistic application on offshore pile-driving scenario. The model enables the assessment of spacing effects between balls:

- Direct contact or 5mm spacing: Minimal impact on insertion loss.
- 5cm spacing: Performance degradation above 200 Hz.

Additional mitigation techniques will be explored in future work, offering a broader perspective on noise reduction strategies for offshore applications.

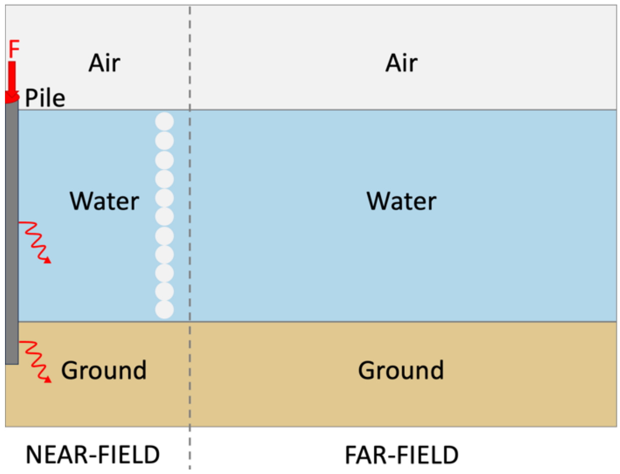

Figure 11. Application of the solution on the developed model

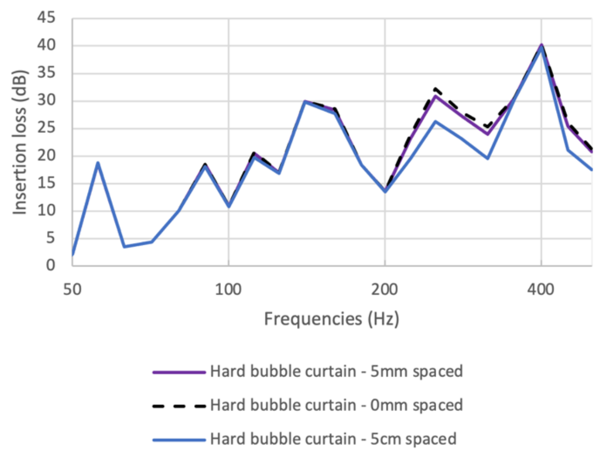

Figure 12. Acoustic pressure at 750m from the source with and without hard bubble curtain

2.3 Computational efficiency

The total calculation time, including near-field and far-field simulation, demonstrates high efficiency. A full simulation requires only 30 minutes on a system equipped with an 8-core processor (3.8 GHz), 80 GB of DDR4 RAM, and a dedicated 8 GB GPU.

3. CONCLUSION

This study introduces an advanced numerical model for underwater noise propagation generated by pile driving, addressing new regulatory requirements. By adopting a two-step approach, with a detailed near-field model and an optimized far-field model, we demonstrated predictions of acoustic levels up to 750 meters from the source while maintaining computational efficiency.

The application of a hard bubble curtain illustrates the model's relevance. Comparing the performance of a simplified water-only model with the full environmental model highlights the importance of realistic simulations.

The results represent a significant advancement in vibro-acoustic modeling, providing a powerful tool for assessing and optimizing underwater noise mitigation solutions. Future presentations will showcase additional mitigation strategies to further refine offshore noise reduction techniques.

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