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UNDERWATER SOUND MODELLING AND SOUND MAPPING IN VIBRATORY PILE DRIVING

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The installation of foundation piles for offshore wind turbines using traditional hydraulic impact hammers raises concerns about the impact of underwater noise on marine life. To address this issue, the offshore wind industry investigates the use of alternative driving techniques, such as vibratory pile installation, to reduce sound levels and expedite installation. This paper discusses a method for modelling underwater sound generated in vibratory piling and presents sound maps of broadband sound levels. The complete model comprises sub-models, including the generation of the source field and the propagation of the sound in range-dependent shallow water environments. The sound source model utilizes a non-linear three-dimensional pile–soil-water modelling framework tailored for vibratory pile installation in layered media, capturing the coupled pile-soil-water interaction at the source. The sound propagation model employed for generating sound maps is a normal mode model, designed to simulate propagation loss in range-dependent acousto-elastic half-spaces of varying bathymetry. The paper concludes with the theoretical case study of underwater noise emission from vibratory pile installation in the North Sea. Numerical simulations with the adopted modelling framework can be used by marine biologists to assess the environmental impact of underwater sound on marine species.

Keywords: vibratory pile driving, sound mapping, underwater sound

1. Introduction

With more offshore wind farms being constructed at greater water depths, the impact of anthropogenic noise is escalating due to the increased number of foundations of offshore wind turbines. To ensure the sustainability of offshore wind energy, underwater noise generated during pile installation is monitored and regulated. Various noise mitigation systems are implemented to lessen the impact of impulsive noise. Regulatory bodies impose standards, particularly in Germany, focusing on dual sound metrics such as SEL_{05} and $L_{p,pk}$ [1]. Environmental impact assessments are mandatory before offshore foundation construction to minimize threats to marine and other species [2]. These assessments require evaluation not only of the dual sound metrics at 750m from the pile but also of sound impact across broader areas, necessitating the generation of sound maps indicating noise impact on habitats of resident species. Quantitative assessment of sound exposure thresholds informs impact assessments, which often evaluate species-related quantities within effect zones and cumulative exposure to successive pile driving events. While acoustic modeling for shipping noise and seismic airguns is well-developed, focus on pile driving noise and its spatial propagation in the ocean environment is limited.

Sound modeling for environmental impact assessments often employs simplified models because most noise sources are situated in the water column or below the sea surface [3]. For modeling offshore pile driving noise, simplified approaches like cylindrical spreading models are common for evaluating marine species' effect zones [4]. Other models based on parabolic equation and wavenumber integration approach often approximate the seabed as an equivalent fluid medium [5, 6]. However, these models lack accuracy when specific soil conditions and seabed vibrations are considered, which affect the energy radiated into the water column and seabed. Seabed interaction is often disregarded in underwater noise sources such as shipping noise as its interaction with sound waves travelling in the sediment is limited. However, the significant uncertainties associated with these models can pose substantial risks when assessing the environmental impact of pile driving noise on underwater species.

To mitigate the high underwater noise levels induced by impact piling, alternative installation methods are also considered. Vibratory driving comprises one of the most promising techniques and is generally considered to lead to lower noise levels. This method utilizes centrifugal loads resulting from the counter-rotation of eccentric masses, thus driving the pile into the seabed by a harmonic/periodic force. Given the recent surge of interest in vibratory driving (by the offshore wind sector), the number of studies focusing on underwater noise generated by this method is limited. As a result, there are scarce field observations during offshore vibro-driving [7].

This paper discusses a method for modeling underwater sound generation from vibratory pile driving and presents sound maps of broadband sound levels. The model consists of sub-models, including source field generation and sound propagation in range-dependent shallow water environments. The sound source model utilizes a non-linear pile–soil model for axial vibratory pile installation combined with a near-field vibroacoustic model, to generate the underwater sound field and the seabed vibrations in the pile vicinity. Subsequently, the sound propagation model used for generating sound maps is a normal mode model designed to simulate propagation loss in range-dependent acousto-elastic half-spaces of varying bathymetry. A theoretical case study of underwater noise emission from a vibratory pile installation in the North Sea without a noise mitigation system is presented. Finally, numerical simulations employing the adopted modeling framework can be utilized by marine biologists to assess the environmental impact of underwater sound from vibratory pile driving on marine species.

2. Sound source modelling in vibro pile driving

The first phase of the overall approach consists of the sound generation module, from which the pile response and the associated wavefield in the surrounding fluid and soil are obtained. For that purpose, a coupled drivability-acoustic modeling framework is employed [8]. Specifically, the drivability module is a non-linear pile-soil interaction model (see Figure 1), where the pile is modelled as a thin cylindrical shell and the soil medium as a layered half-space via the Thin-Layer Method (TLM) coupled with

Perfectly Matched Layers (PMLs) [9]. The pile-soil interaction follows a history-dependent Coulomb friction model. Finally, the numerical solution of the described drivability model is obtained via the Harmonic Balance method (HBM). Upon obtaining the pile-soil interaction forces, these are substituted in an underwater noise prediction model [8]. In the latter approach, the internal and external fluid and soil domains are described by a boundary integral formulation, based on Green's functions for ring sources in the frequency domain. Furthermore, a modal summation of the in-vacuo modes represents the pile vibrations. In that manner, the pressure in the seawater fluid and the stress tensor in the seabed are computed, which serve as an input for the sound propagation module, as will be described below.

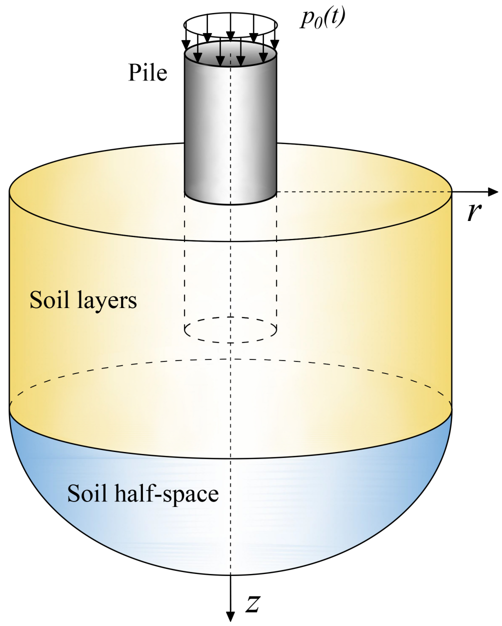

Figure 1: Geometry of the pile-soil model for the calculation of the soil reaction forces.

3. Sound propagation modelling in range-dependent environment

A crucial aspect involves appropriately assessing the soundscape by modeling the spatial and spectral distribution of sound radiated during pile driving. Predicting the Sound Exposure Level (SEL) or Sound Pressure Level (SPL) from pile-driving activities necessitates intensive computations for multiple sources and receiver point calculations across a broad frequency band, accounting for the hearing range and swimming depths of marine animals. To propagate the wave field at larger distances, up to hundreds of kilometers away from the noise sources, a detailed modeling approach is often required to capture variations in bathymetry, sediment properties, and wave speeds in range-dependent environments. Various modeling approaches, such as normal mode methods (NM) [10], parabolic equation approaches [11, 5], wavenumber integration methods (WNI) [12], ray tracing [13], and energy flux approaches [14, 15], have been applied in long-range sound propagation studies [16]. Depending on prevailing environmental conditions and the frequency range of interest, different approaches are preferred. In recent decades, propagation models have been commonly applied to analyze shipping noise, seismic airgun noise, and predictive sonar applications. With the growing demand for renewable energy, pile driving noise has begun to contribute to noise maps, necessitating specifically tailored approaches for modeling long-range sound propagation, particularly for low-frequency waves and sources embedded in the seabed at greater depths. These factors trigger more energy exchange and interaction with the sediment, varying considerably compared to other applications.

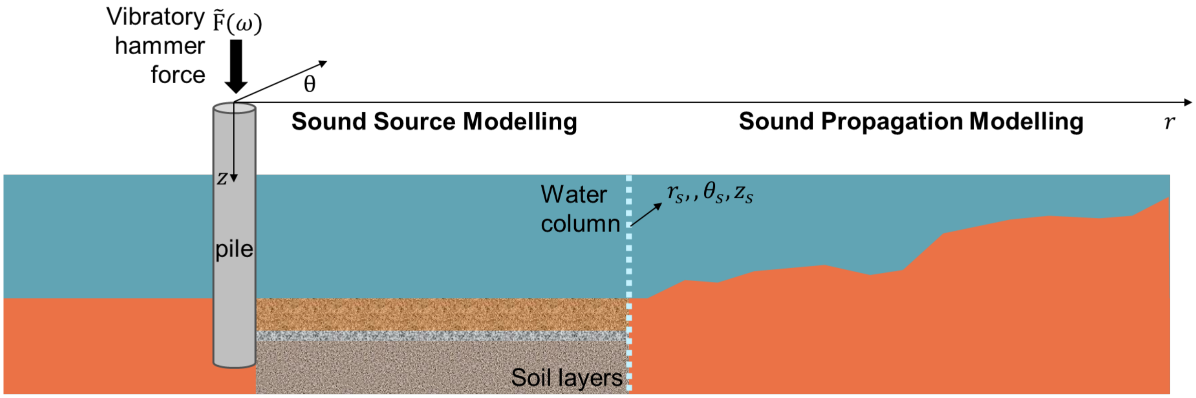

Figure 2: Geometry of the model for the simulation of the pile-driving noise: 1) noise generation model aiming at the sound source; 2) sound propagation model focuses on the coupling of the sound source model to the range-dependent propagating model.

In this section, a sound propagation model based on a normal mode approach in the range-dependent offshore environment is utilized to propagate the wave field generated from the detailed noise source model up to 750m away from the pile. This model describes the elastic properties of the seabed, allowing for the capture of energy emitted in the sediment layers.

As illustrated in Figure 2, the sound source modeling generates fluid and soil sources at the cylindrical surface $\boldsymbol{r} = \boldsymbol{r}_s$, e.g. at a horizontal distance of 750m from the pile, where the sound propagation model is coupled to the sound generation model. The sound sources in both the fluid and sediment are computed by the sound source model, which determines the amplitude of the fluid's pressure source and the soil's volumetric source at a coupling distance of 750 meters from the pile. This coupling depth encompasses the entire water column and extends to a certain depth below the penetration depth of the pile to ensure convergence of the results. The volumetric source level at $\boldsymbol{r} = \boldsymbol{r}_s$ in both the water column and the soil domain is defined as follows:

$$\tilde{P}_f(z_i, \theta_n, \omega) = \tilde{p}_f(r_s, \theta_s, z_s, \omega), \quad i = 1, ..., N_f; n = 1, ..., N_\theta \tag{1}$$

$$\tilde{P}_s(z_j, \theta_n, \omega) = -K\nabla^2\tilde{\phi}(r_s, \theta_s, z_s, \omega) = -(\lambda + \frac{2}{3}\mu)\nabla\tilde{u}_s(r_s, \theta_s, z_s, \omega), \quad j = 1, ..., N_s; n = 1, ..., N_\theta \tag{2}$$

In which N_f and N_s indicate the total number of sources in fluid and soil, respectively. The pressure $\tilde{p}_f$ in the water column and the displacement tensors in the soil are obtained from the noise generation model through a boundary element integration. The source level for each fluid and soil source is defined as follows:

$$\mathrm{SL}_{f,\theta_n,i} = 10\log_{10}\left(\frac{|\tilde{P}_f(z_i, \theta_n, \omega)|^2}{\tilde{p}^2_{\text{ref}}}\right), \quad i = 1, ..., N_f; \quad n = 1, ..., N_\theta \tag{3}$$

$$\mathrm{SL}_{s,\theta_n,j} = 10\log_{10}\left(\frac{|\tilde{P}_f(z_j, \theta_n, \omega)|^2}{\tilde{p}^2_{\text{ref}}}\right), \quad j = 1, ..., N_s; \quad n = 1, ..., N_\theta \tag{4}$$

For each source, the sound propagation model is conducted in an angular slice, assuming no energy channeling between different slices in the azimuthal direction. The received sound level is then given by

$(\xi = f, s)$,

$$\mathrm{RL}_{\xi,r,z,\theta_n} = \mathrm{SL}_{\xi,\theta_n} - \mathrm{PL}_{\xi,r,z,\theta_n},\ n = 1, ..., N_\theta \tag{5}$$

The final received sound level is the sum of all sources as,

$$\mathrm{RL}_{r,z,\theta_n} = 10 \log_{10} \sum_{\xi}^{N_f+N_s} 10^{\frac{\mathrm{RL}_{\xi,r,z,\theta_n}}{10}},\ n = 1, ..., N_\theta \tag{6}$$

To overcome computational problems in shallow waters, mode-flux model and NM model (KRAKEN) are both essential tools to model sound propagation. The energy flux model brings together the accuracy of the adiabatic range-dependent normal mode and the speed of Weston's flux theories for the shallow water propagation problems [17]. As a hybrid method based on the normal mode and flux theories[15], the model considers the bathymetric variations, range-dependent sediment properties, the sea surface and seabed influences. The accuracy of the model is verified against a detailed multi-model comparison based on the propagation loss calculations of various methods (adiabatic mode theory, coupled modes, ray tracing, parabolic equation, and flux theory)[15] and compared with the measurements for the noise stemming from shipping [14] and explosions [18]. The normal mode model used in this paper is based on KRAKENC [10], including the elastic properties of the sediments and adiabatic approximation for the range dependency. KRAKENC is a normal mode program designed for range-varying underwater acoustic environments and an extended version of KRAKEN that calculates complex eigenvalues, enabling the computation of leaky modes and accounting for material attenuation in elastic media. The results generated by the KRAKEN model provide a field represented as an array, considering a specified range and a series of source depths.

Range-dependent propagation modeling using KRAKEN can be employed to generate sound maps, offering insights into the L_E during offshore wind farm constructions. Sound maps can be computed based on a series of radial slices between the source location and the receiver point. Notably, the bathymetry slices reveal that range-dependent differences are typically minor at distances of 750 m, where a range-independent modeling approach is applied.

4. Numerical Implementation

In this section, a case study is examined of an offshore wind farm in the North Sea. The selection of the offshore wind farm location is based on potential sites outlined in the EMODNET Human Activities data portal [19], as depicted in the bathymetry map in Figure 3. The pile parameters are determined by realistic monopile properties detailed in [20, 8]. Specifically, the pile dimensions for the case study are set at a length of 76.9 m, a diameter of 8 m, and a wall thickness of 90 mm. The water depth at the piling location is measured at 40 m.

Initially, the pressure field is modeled using the sound generation model for sources in the vicinity of the pile. The Source Level (SL) is determined from the sound generation module in the near field and calculated for multiple receiver depth locations with a resolution of 1 m [8]. It is worth noting that this resolution may need refinement following convergence tests for improved accuracy. Beyond the 10 m range, assuming a vertical line source, sound propagation is computed using the normal mode method with adiabatic approximation. The sound pressure is then averaged over the depth.

The approach taken in this analysis to handle range dependency involves discretizing the range-dependent domain into multiple segments. When transitioning between these segments, the acoustic modes couple adiabatically, indicating no significant energy transfer to higher or lower modes. Additionally, the analysis computes the sound field on an azimuthal slice basis, assuming negligible energy

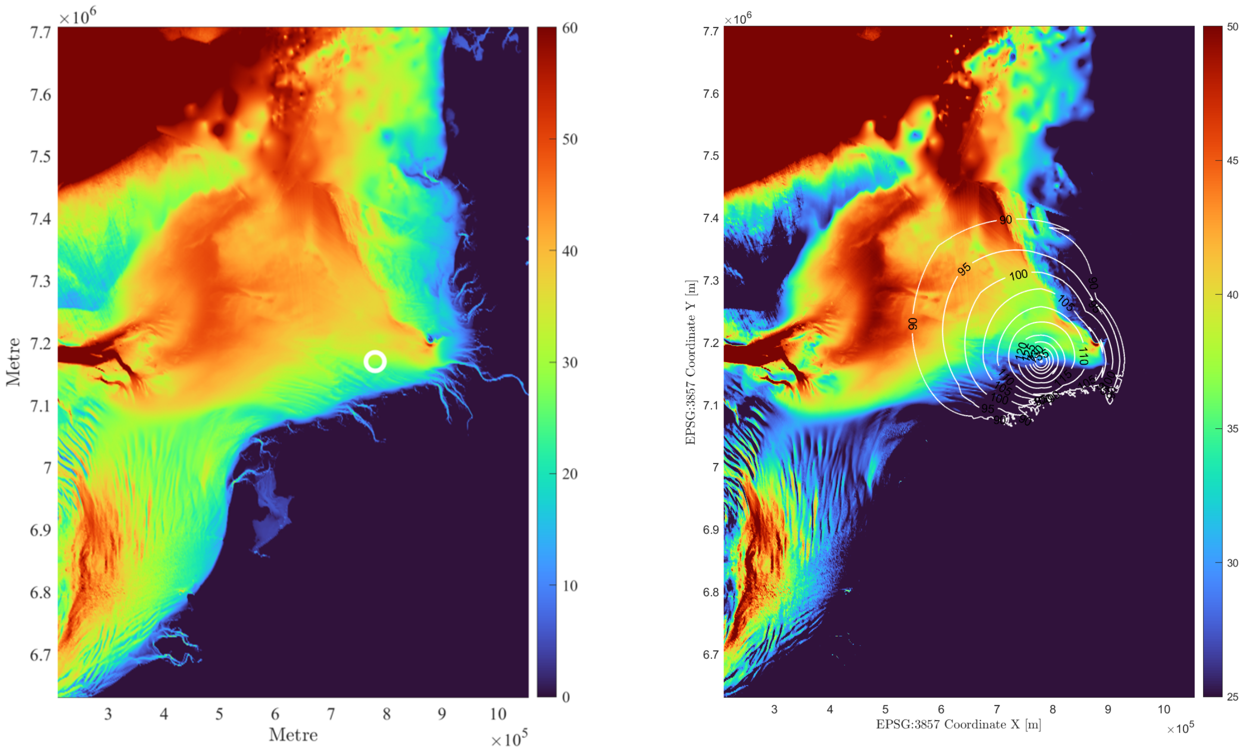

Figure 3: Bathymetry map and the location of the foundation in this analysis (left); L_E contour plot on top of the bathymetry map (right).

transition between different azimuthal slices. While these modeling assumptions may impact the results, they align with standard practices in underwater acoustics and have been demonstrated to offer a reasonable approximation of the Sound Exposure Level (L_E) at large distances from the acoustic source.

In the process of creating sound maps, the sound propagation model calculates underwater acoustic propagation for selected radial slices obtained from the bathymetry. The L_E is then computed for each radial slice with a 3-degree angular resolution, with each slice corresponding to distinct bathymetry and range-dependent sediment properties. A contour plot depicting the SPL for the pressure field is presented in Figure 3, superimposed on the bathymetry map, indicating a greater propagation of energy towards deeper water areas.

5. Conclusions

This paper introduces a methodology for modelling underwater noise mapping for vibratory pile driving. This model requires detailed noise source modelling for the regeneration of noise by vibratory driving, which is addressed by a coupled drivability-acoustic model. The proposed approach advocates the utilization of a diverse suite of mathematical models at distances that are both accurate and feasible to implement. The framework accounts for various environmental factors, such as elastic multilayered sediments and range-dependent water depth, crucial for accurately predicting sound propagation during offshore wind farm constructions.

REFERENCES

1. Stber, U. and Thomsen, F. Effect of impact pile driving noise on marine mammals: A comparison of different noise exposure criteria, *J. Acoust. Soc. Am.*, **145** (5), 3252, (2019).

2. Bailey, H., Senior, B., Simmons, D., Rusin, J., Picken, G. and Thompson, P. M. Assessing underwater noise levels during pile-driving at an offshore windfarm and its potential effects on marine mammals, *Marine Pollution Bulletin*, **60** (6), 888–897, (2010).

3. Brekhovskikh, L. The average field in an underwater sound channel, *Sov. Phys. Acoust*, **11** (2), 126–134, (1965).

4. Martin, S. B. and Barclay, D. R. Determining the dependence of marine pile driving sound levels on strike energy, pile penetration, and propagation effects using a linear mixed model based on damped cylindrical spreading, *J. Acoust. Soc. Am.*, **146** (1), 109, (2019).

5. Collins, M. D. The stabilized self-starter, *The Journal of the Acoustical Society of America*, **106** (4), 1724–1726, (1999).

6. Jensen, F., Kuperman, W., Porter, M. and Schmidt, H., *Computational Ocean Acoustics*, Springer New York (2011).

7. Dahl, P. H., Dall'Osto, D. R. and Farrell, D. M. The underwater sound field from vibratory pile driving, *The Journal of the Acoustical Society of America*, **137** (6), 3544–54, (2015).

8. Molenkamp, T., Tsetas, A., Tsouvalas, A. and Metrikine, A. Underwater noise from vibratory pile driving with non-linear frictional pile–soil interaction, *Journal of Sound and Vibration*, **576**, 118298, (2024).

9. Tsetas, A., Tsouvalas, A. and Metrikine, A. V. A non-linear three-dimensional pile–soil model for vibratory pile installation in layered media, *International Journal of Solids and Structures*, **269**, 112202, (2023).

10. Porter, M. B. The kraken normal mode program (draft), *Naval Research Laboratory, Washington DC*, (1992).

11. Collins, M. D. A split-step Padé solution for the parabolic equation method, *The Journal of the Acoustical Society of America*, **93** (4), 1736–1742, (1993).

12. Jensen, F. B., Kuperman, W. A., Porter, M. B. and Schmidt, H., *Computational Ocean Acoustics*, Springer New York (2011).

13. Porter, M. B. and Liu, Y.-C. Finite-element ray tracing, *Theoretical and computational acoustics*, **2**, 947–956, (1994).

14. Sertlek, H. O., *Aria of the Dutch North Sea*, Ph.D. thesis, University of Leiden, (2016).

15. Özkan Sertlek, H. and Blacquière, G. Effects of the rough sea surface on the signature of a single air gun, *IEEE Journal of Oceanic Engineering*, **44** (3), 575–581, (2019).

16. Etter, P. C., *Underwater acoustic modeling and simulation*, CRC press (2018).

17. Özkan Sertlek, H. and Ainslie, M. A. A depth-dependent formula for shallow water propagation, *The Journal of the Acoustical Society of America*, **136** (2), 573–582, (2014).

18. Salomons, E. M., Binnerts, B., Betke, K. and von Benda-Beckmann, A. M. Noise of underwater explosions in the north sea. a comparison of experimental data and model predictions, *The Journal of the Acoustical Society of America*, **149** (3), 1878–1888, (2021).

19. *EMODNET Human Activities data portal*. `www.emodnet-humanactivities.eu`, accessed: 2024-03-15.

20. Peng, Y., Tsouvalas, A., Stampoultzoglou, T. and Metrikine, A. A fast computational model for near-and far-field noise prediction due to offshore pile driving, *The Journal of the Acoustical Society of America*, **149** (3), (2021).