Document Version
Final published version

Citation (APA)
Sertlek, Ö., Peng, Y., & Tsouvalas, A. (2024). Modelling Pile-Driving Sound and Mitigation in Realistic Environments. In A. N. Popper, J. A. Sisneros, A. D. Hawkins, & F. Thomsen (Eds.), *The Effects of Noise on Aquatic Life: Principles and Practical Considerations* (pp. 277-288). Springer. https://doi.org/10.1007/978-3-031-50256-9_149

Modelling Pile-Driving Sound and Mitigation in Realistic Environments

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Contents

Abstract

Impact pile driving is a transient anthropogenic underwater sound source that can potentially affect marine life. Mathematical modelling tools are essential for predicting sound levels before installing new offshore wind farms. Different modelling approaches are required for modelling the sound generation in proximity to the pile, the mitigation of the noise with the use of air-bubble curtains, and the sound propagation at a larger distance. In addition, the interface and coupling between the different modelling approaches should be carefully considered without losing important details. In this work, a multi-model approach for estimating pile-driving sound in a realistic environment is described. The short-range predictions (up to 750 m) provide detailed spectral and temporal output in various metrics in the water (acoustic pressure, particle velocity) and the seabed (stress and displacement vectors). For the long-range predictions beyond 750 m, only the acoustic pressure metric is calculated, including the range-dependent

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A. N. Popper et al. (eds.), *The Effects of Noise on Aquatic Life*,
https://doi.org/10.1007/978-3-031-50256-9_149

properties of the acoustic environment. Based on the combination of short- and long-range models, sound maps can be created to identify the contribution of the pile driving to the underwater soundscape.

Keywords

Sound modelling · Impact · Propagation · Pile driving · Noise mitigation

Introduction

Anthropogenic offshore activities have raised serious concerns about their impact on marine life in different ways depending on the spatial, temporal, and spectral pattern of sound. One of the main impulsive underwater sound sources of concern is offshore pile driving due to the increasing numbers of offshore wind farms. Furthermore, in the next decade, it is expected that the number of offshore wind farms under construction will accelerate in European countries to provide alternative energy sources. To preserve the marine ecosystem and maintain sustainable development, many countries define noise thresholds at a specific distance in various metrics. Therefore, an environmental impact assessment that includes the prediction of noise levels is required prior to the construction of the installation of piles in most projects. Given the expected noise levels, appropriate noise mitigation systems (NMS), i.e., air-bubble curtains, hydro-sound dampers, or noise mitigation screens, are usually required to reduce the noise. To address this challenge, underwater sound modelling tools can assist in predicting potential sound sources and propagation characteristics.

There is no standard modelling approach for the pile-driving sound. Various computational methods (such as finite element, finite difference, semi-analytic and empirical models) have been used to predict the generated noise during pile driving and propagate the sound field to larger distances where the noise thresholds are defined (Tsouvalas 2020). These models should include the properties of the pile (i.e., length, thickness, hammer properties), the installation tool, and the site-specific environmental parameters (i.e., sediment type, sediment layers, water depth). Although finite element models can provide detailed results, they are computationally slow. In contrast, the fast empirical models are less detailed, especially when noise mitigation systems (NMS) are deployed. Air-bubble curtain systems have been widely used in many offshore projects to mitigate the impact pile-driving noise over the last decade. An accurate description of the acoustic characteristics of the air-water mixture is essential before modelling the noise mitigation mechanism in such cases.

In our work, a computationally efficient and validated pile-driving model is used to predict the generation and propagation of the sound field associated with impact piling at large (from the pile) distances, overcoming the limitations of earlier models (Tsouvalas 2020). In addition, the same model can be easily modified for various system configurations to investigate the water- and soil-borne noise transmission paths in a detailed and systematic way (Peng et al. 2021a, b). Furthermore, the sound source modelling tool can be combined with different sound propagation modelling approaches to include long-range propagation effects such as the variable bathymetry (Sertlek et al. 2019). The source and propagation modelling approaches are described in the following sections.

Sound Source Modelling in Impact Pile Driving

During pile driving, the sound propagates through the pile, water, and sediment layers after the source excitation by a hammer and interacts among these different domains (Tsouvalas 2020). In addition, low-frequency sound propagation in shallow waters can propagate long distances in vertical and horizontal directions. Therefore, the modelling approaches should consider the detailed composition of the sediment to capture the sound waves propagating through the multiple sediment layers. To achieve this aim, different modelling approaches have been used to model pile-driving sound such as:

- Finite element models (Reinhall and Dahl 2011; Zampolli et al. 2013)
- Finite difference schemes (MacGillivray 2013, 2015)
- Boundary element methods (Masoumi et al. 2007, 2009; Masoumi and Degrande 2008)
- Semi-analytical solutions by several authors (Tsouvalas and Metrikine 2014; Hall 2013, 2014, 2015; Deng et al. 2016a, b)
- Simplified formulas as damped cylindrical spreading (Duncan and Parsons 2011; Ainslie et al. 2014; Lippert et al. 2018a, b)

Some of these modelling approaches are compared during the COMPILE I Workshop (Lippert et al. 2016) to indicate their differences. In addition to the differences in the modelling of the sound generation, the assumptions related to the sediment play an essential role in the accuracy of model predictions. Some models describe the sediment as an equivalent fluid layer (Dahl and Reinhall 2011; Zampolli et al. 2013). Considering the elastic (Buckingham 2000) or poroelastic (Biot 1956a, b) properties of sediment could improve model accuracy (Tsouvalas 2020).

In this chapter, a semi-analytical solution that could provide a faster solution than the finite element method is used (Tsouvalas et al. 2015). This model assumes cylindrical symmetry for the pile and the surrounding environment. The pile is described as a cylindrical shell in an inviscid compressible fluid medium and horizontally stratified acousto-elastic half-space. The pile properties such as the pile length (L), radius (R), thickness (t), Poisson's ratio (ν), and density of the shell (ρ) are used as the model inputs. A time-dependent force function is applied to the pile head in the air. The mathematical background is based on the normal modes and branch line integrations for an axisymmetric ring source. The set of equations are implemented in the software package, SILENCE, providing various model options and outputs depending on the requirements of the specific problems. The near-source module calculates the wave field in the close to the monopile by

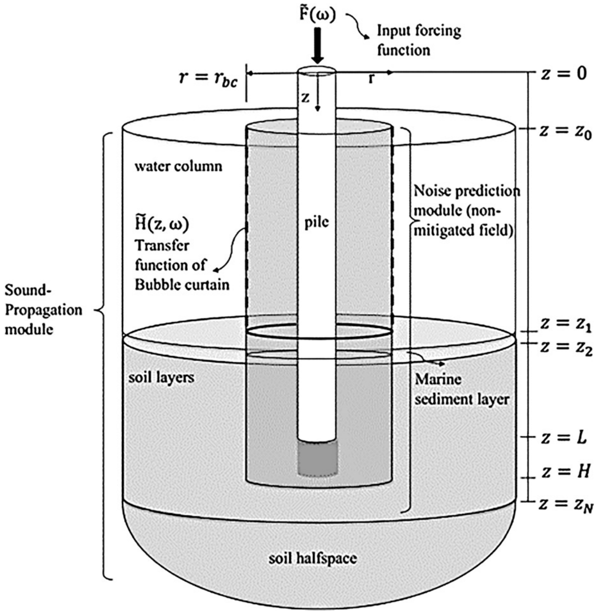

Fig. 1 The geometry of pile driving sound source model (SILENCE). F(t) is the time-dependent force function due to impact or vibratory hammer. F(w) is the Fourier transform of F(t) (This figure adapted from Peng et al. (2021a))

considering the interactions between the pile, fluid, and soil. Once the wave field at the close range ($r \leq r_0$) is calculated, the far-field module is used to propagate this field to the large distances ($r > r_0$). Since the detailed mathematical description of this model is given by Peng et al. (2021b), it is omitted for the sake of simplicity in this chapter. A basic version of pile-driving sound modelling software (SILENCE) is freely available on the TU Delft Webpage (http://ua.citg.tudelft.nl/) for research and educational purposes (Fig. 1).

In Fig. 2, the amplitude of the particle velocity in the water and sediment layers are shown for a pile with a diameter of 7 m and a length of 78 m (Tsouvalas 2020). Scholte waves propagating along the fluid-solid interface could be noticed in this figure. The vibratory piling can also be modelled with a similar modelling approach based on a vibratory hammer force function. However, since the acoustic energy enters the water column from all vertical angles due to the different temporal structure of the excitation, the coherent Mach cones would not be clearly visible for the vibratory piling.

The calculated sound field close to the pile is propagated over long radial distances with the far-from-source module based on the integral boundary equations considering the reciprocity theorem. The detailed derivation of the far-from-source module is described by Peng et al. (2021b). This model can provide detailed outputs including sound pressure, sound velocity, displacement, and stress in the sediment layers. The modelling of the particle motion in the water and top sediment layer is critical to assess the impact of the pile-driving sounds on fish, which are sensitive to both the pressure and particle motion.

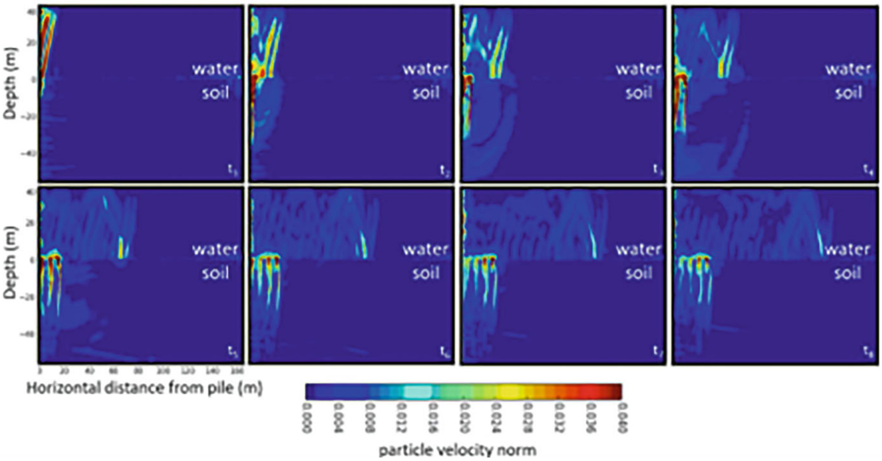

Fig. 2 The amplitude of the particle velocity after the hammer impact (6 s to 120 s). (This figure is adapted from Tsouvalas (2020))

Once the generated noise during pile driving is modelled, the performance of the noise mitigation systems could be simulated to discover their optimum configuration. Describing the acoustic properties of an air-bubble curtain with effective parameters such as effective wavenumber or sound speed simplifies the problem (Bohne et al. 2019). In our approach, the effective wavenumber formula of Commander and Prosperetti (1989) is applied based on the parameters of the air-bubble curtain (Bohne et al 2020) to estimate the variation of effective local wavenumbers over the entire water depth and frequency band. The bimodal bubble size distribution is introduced by Lethr et al. (2002) with observations of small and large bubbles (Bohne 2020; Milgram 1983). An example of effective sound speed profile evaluation with depth is shown in Fig. 3 for 125 Hz. It can be noticed that the sound speed in the air-bubble curtain is lower than the sound speed in the water. As a result of this difference, a large impedance mismatch at the water and air-bubble interface causes the reflection of the sound wave field back to the source and attenuation as they propagate through the bubble curtain. These transmission coefficients between water and bubble interfaces are calculated and coupled to the free-field noise prediction model through a boundary integral method. The water column and air-bubble curtain are divided into multiple regions along the depth coordinates. At each vertical domain, a one-dimensional problem is considered with an input incident wave and properties of the layers to determine transmission coefficients for depth direction. Once the solution is obtained for the depth-dependent fluid dynamic properties, the local effective wavenumber and the transmission coefficients of the air-bubble curtain are determined. The obtained results with the hydrodynamic model are processed, including the propagation modelling through air-bubble curtains, and the result is translated to the relevant acoustic metrics.

The modelling framework of the noise mitigation with air-bubble curtains should consider a detailed configuration of the mitigation system including the pneumatic

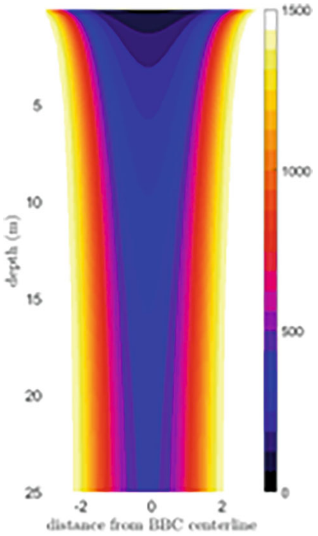

Fig. 3 The effective sound speed. This result is calculated at 125 Hz for a water depth of 25 m

model for the simulation of the air circulation and transport from the air-supplied vessel to the hose on the seabed. A hydrodynamic model calculates the effective wavenumbers and sound speed through depth and range in the air-bubble curtain. Next, the output of the hydrodynamic model is used to calculate the depth- and frequency-dependent transmission coefficients of the air-bubble curtain. Finally, the mitigated sound levels are calculated as a combination of individual simulation steps and propagated to larger distances by an acoustic modelling approach. More detailed description of the sound mitigation model is given by Peng et al. (2023).

As a summary, the mathematical models require inputs for the pile parameters, environment, and air-bubble curtain configuration. The pile parameters include the length, diameter, thickness, penetration depth, density, Young's modulus, Poisson's ratio, and damping of the pile. The big bubble curtain (BBC) parameters include the distance from the pile, nozzle diameter, nozzle spacing, and airflow rate through the nozzle. The BBC parameters should be calculated by the pneumatic and hydrodynamic models with the feed pressure, hose length and diameter, nozzle diameter, and spacing.

Sound Propagation in Range-Dependent Media

Long-range sound propagation requires the detailed modelling of the sediment properties, variations in bathymetry, and sound speed. Various modelling approaches (i.e., normal mode method, parabolic equation, ray tracing, energy flux) could be preferred depending on the environmental conditions and frequency range. Sound propagation modelling is usually required in shallow waters for impact pile driving.

Many EU countries (such as the Netherlands and Germany) define the noise criteria at 750 m (Heinis 2015; Heinis et al. 2019a, b; BSH 2011; 2013). Therefore, many modelling approaches ignore the range-dependent properties of waveguides due to the minor environmental changes up to 750 m. Instead, these models focus on the detailed modelling of elastic seabed properties that improve the accuracy of model predictions for pile driving due to the strong interactions between the water and sediment layer, especially at low frequencies. However, when sound propagation modelling is required at long ranges beyond 750 m, omitting the bathymetry changes could result in incorrect results. In this chapter, different modelling strategies are used in order to benefit from the advantages of different models. Up to 750 m, the sound pressure and particle motion are calculated, including the detailed sediment properties based on the range-independent waveguide assumption. Modelling sound propagation, including the detailed elastic properties of sediments, makes it possible to capture the sound energy in the sediment layer, which can tunnel under the bubble curtains and leak back to the water layer. This effect is usually critical for ranges up to 200 m where bubble curtains are typically deployed. Beyond 750 m, a sound propagation model of lower fidelity is used. Different propagation models could be chosen based on environmental conditions and frequency ranges, as shown in Fig. 4.

The parabolic equation model can use a starter field from sound source modelling tools and propagate this to larger distances, including the range-dependent variation in the water depth. Similarly, normal mode models, such as KrakenC (Porter 1991), could be used, including the elastic properties of the sediments and adiabatic approximation for the range dependency. If the elastic properties and layered sediments are ignored at high frequencies, mode-flux theory based on adiabatic approximation is an option. The wavenumber integration method can provide accurate results when the range dependency is weak. Comparisons between different propagation methods are investigated by Sertlek et al. (2019). At the interface of two different models, various approximations could be used (Reinhall and Dahl 2011:

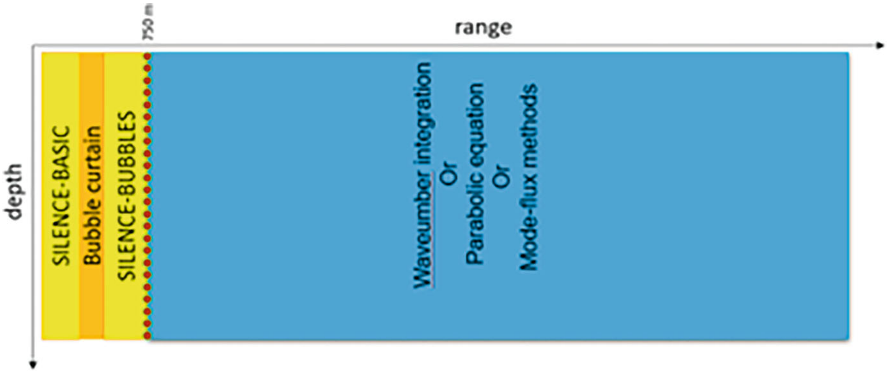

Fig. 4 Multi-model approach for the simulation of pile-driving noise. The detailed source and propagation model close to the pile (up to 750 m) with the sound pressure, velocity, displacement, and stress outputs. Beyond 750 m, propagation models only with sound pressure outputs are used

TNO report). The mathematical descriptions of these potential approaches are beyond the scope of this chapter. Range-dependent propagation modelling can be used for creating sound maps to provide insight into the sound exposure level (SEL) during the off-shore wind farm constructions. Sound maps can be calculated based on a large number of radial slides between the source location and receiver point as shown in Fig. 5.

As could be noticed from the bathymetry slices, the range-dependent differences are usually minor at 750 m where the range-independent modelling approach is used.

Figure 6 shows a sound map created based on the described steps for a single impact piling strike at 125 Hz. First, the pressure field is modelled with SILENCE up to 750 m. An artificial scenario was created to test the proposed approach in the Baltic Sea. The offshore wind farm location is chosen based on the possible wind farm locations as shown in the EMODNET Human Activities data portal (www.emodnet-humanactivities.eu). The pile parameters are also chosen based on the realistic pile properties from Peng et al. (2021a). The length, diameter, and wall thickness of the pile are chosen as 76.9 m, 8 m, and 90 mm, respectively. The water depth at the piling location is 39.9 m. The maximum blow energy is 1750 kJ. The pressure field at 750 m is calculated for multiple receiver depth locations with 0.1 m resolution. Beyond 750 m, assuming a vertical line source, the sound propagation is calculated using the normal mode method with adiabatic approximation. The sound pressure is averaged over the depth.

Sound mapping helps to predict the maximum impact distances based on the impact thresholds of the different marine animals (Southall et al. 2019). Furthermore, the sound maps could be weighted based on the marine animals' hearing sensitivities and swimming depths over a large frequency band to provide input for the biologists.

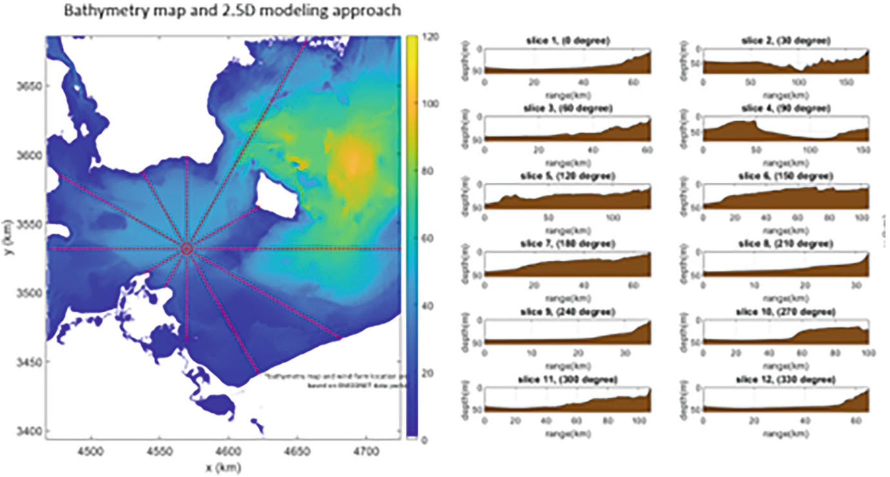

Fig. 5 The radial slicing of bathymetry as input of sound mapping (on the left panel). Selected water depth profiles from the same area (on the right panel)

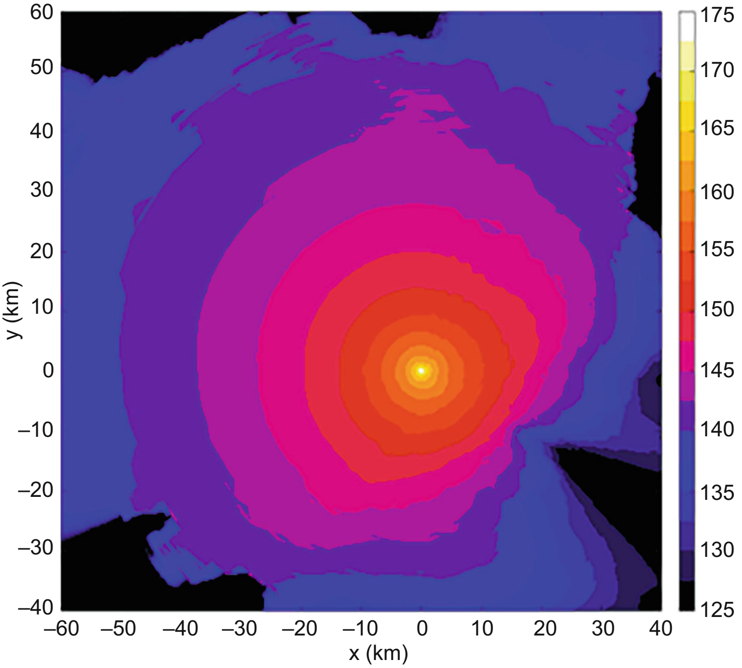

Fig. 6 Sound mapping based on the multi-model approach for the simulation pile-driving noise. The sound pressure is averaged over the depth. SEL is calculated for a single strike at 125 Hz

Conclusions

In this chapter, a framework for modelling underwater sound properties due to pile driving is described by considering the detailed environmental inputs, such as the elastic multilayered sediments and range-dependent water depth. As a general summary, the following procedure is followed to predict sound fields during offshore wind farm constructions:

- Modelling underwater sound during an impact pile driving with SILENCE
- Modelling the noise mitigation with a bubble curtain
- Modelling sound propagation up to 750 m with a high-fidelity sound propagation model considering elastic properties (including the particle motion and pressure)
- Modelling far-field propagation with a fast computational model beyond 750 m
- Sound mapping as combination modelling results for the individual radial slices

The proposed approach suggests using a set of various mathematical models at distances that can be accurately and practically implemented. The uncertainty in the environmental and pile parameters could be investigated individually for each region (source, near-field, and far-field). The pile-driving source model can generate outputs for the sound pressure, velocity, stress, and displacement in the sediment layers. These outputs could be critical for assessing the impact of sound on the fish and invertebrates. Due to the limited availability of the required inputs for the sediment properties and computational expenses, the particle motion, stress, and displacement outputs are only calculated up to 750 m in this work. However, more detailed propagation modelling tools at long distances could be used in future works. Furthermore, the sound propagation modelling approach for the air-bubble curtain could be improved considering the detailed backscattering effects and continuity conditions for the acousto-elastic waveguides.

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