TU Delft

Delft University of Technology

Document Version
Final published version

Licence
Dutch Copyright Act (Article 25fa)

Citation (APA)
Peng, Y., & Tsouvalas, A. (2025). Acoustic Monitoring and Validation of Noise Mitigation for Offshore Pile Driving. In Á. Cunha, & E. Caetano (Eds.), *Experimental Vibration Analysis for Civil Engineering Structures: EVACES 2025 - Volume 3* (pp. 46-53). (Lecture Notes in Civil Engineering; Vol. 676 LNCE). Springer Nature. https://doi.org/10.1007/978-3-031-96114-4_6

Important note
To cite this publication, please use the final published version (if applicable).
Please check the document version above.

Copyright
In case the licence states “Dutch Copyright Act (Article 25fa)”, this publication was made available Green Open Access via the TU Delft Institutional Repository pursuant to Dutch Copyright Act (Article 25fa, the Taverne amendment). This provision does not affect copyright ownership.
Unless copyright is transferred by contract or statute, it remains with the copyright holder.

Sharing and reuse
Other than for strictly personal use, it is not permitted to download, forward or distribute the text or part of it, without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license such as Creative Commons.

Takedown policy
Please contact us and provide details if you believe this document breaches copyrights.
We will remove access to the work immediately and investigate your claim.

This work is downloaded from Delft University of Technology.

Acoustic Monitoring and Validation of Noise Mitigation for Offshore Pile Driving

Yaxi Peng(✉) and Apostolos Tsouvalas

Delft University of Technology, Delft, South Holland, Netherlands
{y.peng,a.tsouvalas}@tudelft.nl

Abstract. Offshore wind energy is a key resource in the renewable energy sector, with a growing number of monopile foundations being installed for wind turbines. The installation of these piles generates high levels of underwater noise, which can pose risks to marine species. High-level experiment data sets are essential to quantify the pressure, particle motion in both seawater and seabed and vibration of the monopile, allowing for the monitoring of sound levels and the assessment of environmental impact. This is done by comparing measured noise to regulatory thresholds and auditory injury criteria for marine mammals, fish, sea turtles, and benthic communities. Noise mitigation systems, such as air-bubble curtains, play a significant role in reducing underwater noise. Ensuring their effectiveness requires monitoring key parameters, including the pressure distribution along bubble curtain hoses, which governs air flow through the nozzles and ultimately determines acoustic performance. In this study, medium-scale tests were conducted to measure pressure distribution along hoses at varying air flow rates and compare the results with numerical predictions. Additionally, acoustic measurements were performed during an offshore installation campaign in German waters, with hydrophones deployed at multiple locations and distances from the pile. The collected data serves as a benchmark for validating noise prediction models for offshore pile driving across various scenarios, including those with and without noise mitigation measures. These measurements enable the validation of modelling approaches and the evaluation of the effectiveness of applied noise mitigation techniques. Future work will focus on laboratory-scale tests to monitor particle motion in the water column and seabed vibrations. This will help assess the environmental impact on species that are particularly sensitive to these physical changes.

Keywords: Monopile foundation · Underwater noise · Noise mitigation

1 Introduction

The installation of offshore wind turbine foundations generates high levels of anthropogenic noise, raising concerns about its impact on marine life. During

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2025
Á. Cunha and E. Caetano (Eds.): EVACES 2025, LNCE 676, pp. 46–53, 2025.
https://doi.org/10.1007/978-3-031-96114-4_6

impact pile driving, energy from the hammer strike is transmitted into the monopile, and the surrounding water column and seabed. The resulting noise and vibration can pose risks to marine species, including mammals, fish, and benthic communities, potentially leading to behavioural disturbances, auditory injuries, or physiological stress. Regulatory noise thresholds are implemented to reduce the impact of offshore pile driving on marine species [3,10]. In Germany, regulations require that underwater noise levels do not exceed a 5th percentile single-event SEL (SEL05) of 160 dB and a peak sound level (Lp,pk) of 190 dB at a distance of 750 meters from the pile-driving site [11]. Taiwan has implemented similar regulations, setting an SEL limit of 160 dB at 750 meters and a warning threshold at 158 dB. Mandatory response measures are required if monitoring data approach or exceed this threshold [5]. In the Netherlands, environmental impact assessments for offshore wind energy projects compare predicted piling noise levels against thresholds for behavioural disturbance and noise-induced hearing loss in marine mammals [6]. These limits may also account for seasonal variations in species density and the cumulative effects of multiple pile installations. To comply with regulatory noise thresholds, various noise mitigation systems have been developed and implemented. Among these, air-bubble curtains and hydro-sound dampers (HSD) are commonly used to reduce noise propagation in the water column. Additionally, modifications at the noise source, such as impact hydraulic hammers with integrated noise reduction units and the use of vibratory pile driving as an alternative technique, are increasingly explored to minimize acoustic emissions. These measures are essential for balancing offshore wind energy expansion with the protection of marine ecosystems.

To understand the physics of noise generation and propagation, numerous noise prediction models have been developed over the past few decades, focusing on quantifying noise levels in both the near- and far-field from offshore wind turbine foundations. Evaluating the effectiveness of noise mitigation systems, particularly air-bubble curtains, requires accurate modelling approaches. In finite element models, the air-bubble curtain is often represented as a fully absorbing impedance boundary condition around the pile [4]. Alternatively, in semi-analytical models, it is treated as a homogeneous medium with a constant thickness over the entire water depth, incorporating frequency- and depth-dependent wave speed [12]. A more advanced integral approach was later developed to account for the local distribution of the air fraction within the bubble curtain [1,2]. This study considers the influence of water depth, nozzle configuration, and air volume injection on the local distribution of gas within the bubble curtain and the formation of bubbly flow.

Despite advancements in numerical modelling, noise reduction predictions for mitigation systems are still largely based on empirical data from past projects. Offshore measurements of bubble flow formation remain limited, particularly in terms of accuracy and availability. To address this gap, this study conducts medium-scale test campaigns to generate high-quality experimental datasets for validating numerical models and analysing pressure distribution along perforated hoses used in air-bubble curtain systems. Additionally, acoustic measurements

were performed during an offshore installation campaign in German waters, with hydrophones deployed at various locations and distances from the pile. This article is structured as follows: Sect. 2 discusses the field test campaign, detailing the measurements from the pneumatic system used to generate the bubble curtain. Section 3 presents the validation study based on data from an offshore installation campaign. Finally, Sect. 4 provides an overview of the main conclusions.

2 Field Test Campaign

A series of medium-scale tests were conducted in Sliedrecht, the Netherlands, in July 2022 [7]. The primary objective was to measure the performance of the pneumatic system used to generate the bubble curtain, with a focus on analysing pressure distribution along the hoses at varying volumetric airflow rates. The tests included multiple configurations, varying hose sizes, lengths, nozzle spacings, and nozzle diameters to assess their impact on system performance.

Table 1. Test configuration for the wet experiments.

Configuration	Value	Unit
Hose diameter	0.0124	m
Nozzle spacing	0.15	m
Nozzle diameter	0.001	m
Air Flow rate	76.7 to 200	m^3/hr
Hose length	45	m

This section presents test results for a selected configuration with varying airflow rates, highlighting their effect on pressure distribution along the hose. Throughout the measurement campaign, flow rate, pressure, and temperature data were continuously recorded. Within each time trace of flow and pressure measurements, steady-state intervals were identified, and statistical values were computed for each pressure sensor positioned at specific distances from the air injection point, as illustrated in Fig. 1. The test configuration for one of the field experiments is summarized in Table 1, with airflow rates ranging from 76.7 m/h to 200 m/h. This particular setup closely resembles current operational configurations when scaled appropriately. As shown in Fig. 1 (A) and (B), pressure decreases nonlinearly as the distance from the air injection point increases for each tested flow rate. Figure 1 (C) further illustrates the relationship between pressure amplitude and volumetric airflow for sensors positioned at different horizontal distances from the air injection point.

A comparison between experimental and numerical results, presented in Fig. 1 (BD), shows a reasonable agreement for pressure measurements below 3 bar. However, at higher pressures exceeding 4 bar, the numerical model underestimates the pressure near the air injection point across all flow rate cases. This discrepancy is likely due to the nonlinear pressure drop occurring closer to the

air source. Error bars in the figure indicate the deviation from the mean pressure values recorded at a constant flow rate. The observed nonlinear pressure variation suggests that airflow distribution influences both pressure and nozzle discharge in the azimuthal direction, significantly impacting the overall performance of the air-bubble curtain system. By analyzing different airflow rates for the given hose-nozzle configuration, results confirm that pressure at each sensor location increases nonlinearly with the injected volumetric airflow rate. These field test findings validate the critical role of airflow rate in shaping pressure distribution along the hose, further indicating that air-bubble curtain effectiveness varies significantly along its circumference.

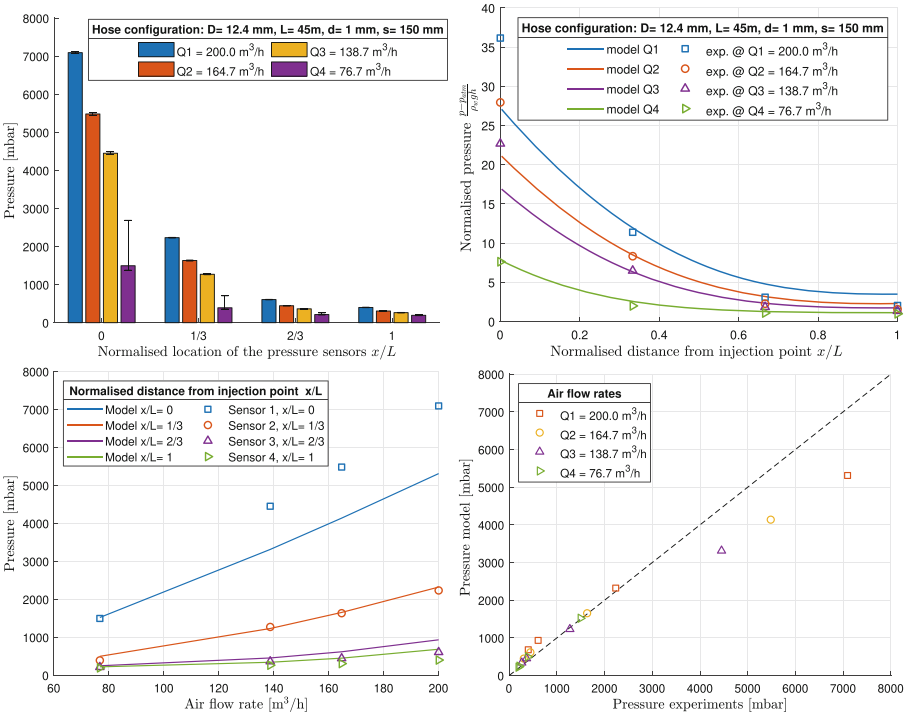


Fig. 1. Comparison of simulation and experimental results for the tested configuration at a water depth of 2.0 m (L = 45 m, D = 12.4 mm, d = 1.0 mm, s = 15 cm). (A) Experimental results (left, top). (B) Pressure distribution along the hose length (right, top). (C) Pressure vs. airflow rate (left, bottom). (D) Model vs. experimental comparison (right, bottom).

3 Offshore Installation Campaign

This section examines an offshore wind farm foundation installation campaign conducted in 2018 [8]. The material properties and geometric parameters of the

model are detailed in Table 2. The applied forcing function follows a smoothed exponential impulse, as illustrated in Fig. 2 (A), delivering approximately 2000 kJ of energy into the pile. The seabed at the installation site consists of a thin marine sediment layer overlying a stiff bottom soil half-space. The configuration of the double bubble curtain (DBBC) system used for noise mitigation is summarized in Table 3. In this setup, the inner bubble curtain is positioned 105 m from the pile, while the outer bubble curtain is placed at a distance of 145 m.

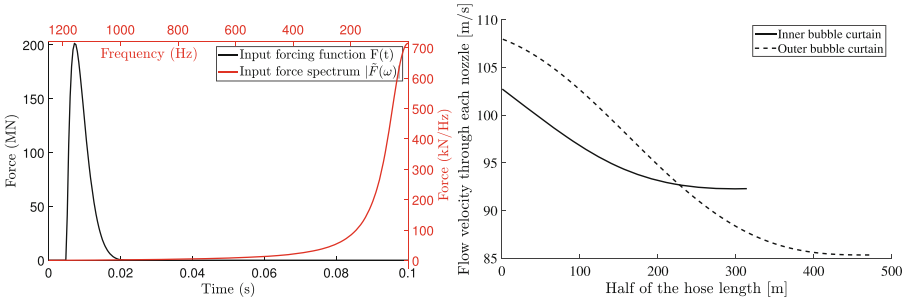


Fig. 2. OWF foundation: (A) input forcing function in time and frequency domain; (B) flow velocity through each nozzle along the hose with the solid line indicating the air flow at the inner BBC and the dash line being the outer one.

Table 2. Basic input parameters for the validation case.

Parameter	Pile	Parameter	Fluid	Marine sediment	Bottom soil
Length [m]	75	Depth [m]	40.1	1.5	∞
Density [kg/m^3]	7850	Density [kg/m^3]	1000	1621.5	1937.74
Outer diameter [m]	8	c_L [m/s]	1500	1603	1852
Wall thickness [mm]	90	c_T [m/s]	-	82	362
The penetration depth [m]	30.5	α_p [dB/λ]	-	0.91	0.88
Maximum Blow Energy [kJ]	2150	α_s [dB/λ]	-	1.86	2.77

The variation in the flow velocity through the nozzles is shown in Fig. 2(A), which is due to the drop of the pressure during the transportation of the air. In Fig. 3 (A), the evolution of the pressure field in time is shown for the point positioned 2 m above the seabed at 750 m radial distances from the pile. The arrival of the pressure cones is at around 0.5 s after the impact of the pile, which is in line with the expectations regarding the arrival time of the direct sound waves traveling with the speed of sound in the water at the distance of 750 m from the pile. The overall SEL and $L_{p,pk}$ for both unmitigated and mitigated fields are sumarised in Table 4. The zero-to-peak pressure level ($L_{p,pk}$) in dB re

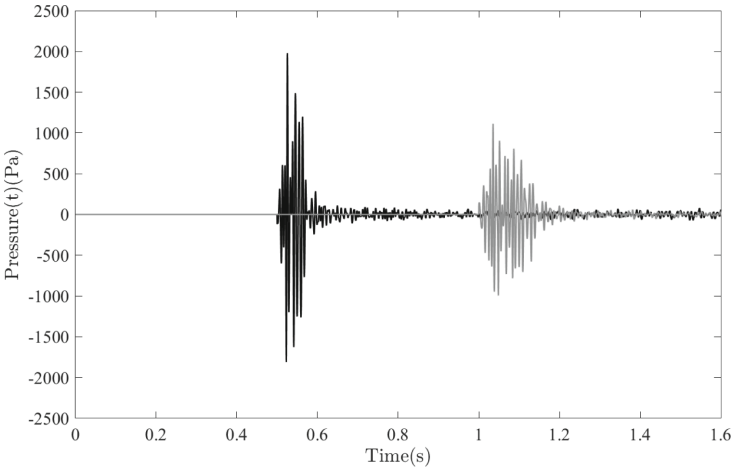


Fig. 3. OWF foundation: evolution of the pressure field for the mitigated field with the use of DBBC system at 750 m (black line) and 1500 m (grey line) from the pile.

Table 3. Basic input parameters of the air-bubble curtain system.

Parameter	Value
location of the inner bubble curtain r_{bc} [m]	105
location of the outer bubble curtain r_{bc} [m]	145
Nozzle diameter d_n [mm]	1.5
Nozzle spacing y_n [m]	0.30
Air flow rate q_{FAD} [m^3/min/m]	0.5
Spreading coefficient λ [-]	0.1

Table 4. Noise mitigation assessment at the foundation. All values are given at a distance of 750 m and 1500 m from the pile. SEL are given in the unit of dB re $1\mu\ Pa^2s$ and $L_{p,pk}$ in the unit of dB re 1μ Pa.

Scenarios @750 m	SEL	$L_{p,pk}$
Noise prediction for the unmitigated field	182	201
Noise prediction for the mitigated field with DBBC system	166±1	185±1
Measurement sound levels	165 168	184 187
Modelled noise reduction Δ_s	15 ±1	15±1
Measured noise reduction Δ_m	14 ∼17	14 ∼17
Scenarios @1500 m	SEL	$L_{p,pk}$
Noise prediction for the unmitigated field	178	196
Noise prediction for the mitigated field with DBBC system	164±1	181±1
Measurement sound levels	163 164	185
Modelled noise reduction Δ_s	14 ±1	15 ±1
Measured noise reduction Δ_m	14 ∼ 15	11

1 μPa and the sound exposure level SEL in units of dB re 1 $\mu Pa^2 s$ are defined as:

$$L_{p,pk} = 20\log\left(\frac{\max|p(t)|}{p_0}\right), \quad \text{SEL} = 10\log\left(\int_{T_1}^{T_2}\frac{p^2(t)}{p_0^2}dt\right) \tag{1}$$

in which T_1 and T_2 are the starting and ending of the predicted time signature with the sound event in between and pulse duration $T_0 = T_2 - T_1$ being 1 s and $p_0 = 10^{-6}\text{P}a$ is the reference underwater sound pressure.

The unmitigated sound field is predicted using the model developed in [9], with predictions falling within 12 dB of the measured sound levels, aligning with the accuracy of the measurement equipment. The recorded sound levels indicate that the DBBC system achieves a noise reduction of approximately 1417 dB at 750 m for both SEL and $\text{L}_{p,pk}$. This reduction is determined by comparing the modeled unmitigated sound field with the measured data collected during DBBC operation. The model for the unmitigated sound field was previously validated against an offshore measurement campaign conducted in 2018 [9].

At a greater distance of 1500 m from the pile, the DBBC system achieves a noise reduction of 14–15 dB for SEL and 11 dB for $\text{L}p, pk$. Modeling results predict an average reduction of 15 dB for both SEL and $\text{L}p, pk$ at 750 m, and 14 dB for SEL and 15 dB for $\text{L}_{p,pk}$ at 1500 m. Due to variations in flow velocity through the nozzles in different azimuthal directions, a deviation of approximately ±1 dB in noise reduction levels is expected. The upper and lower bounds of the sound levels indicate that the predicted results closely match the measured data across various horizontal distances from the pile, confirming the accuracy of the noise prediction model and the effectiveness of the DBBC system.

4 Conclusions

Acoustic monitoring and validation of noise mitigation techniques, particularly air-bubble curtains, are essential for reducing underwater noise during offshore pile driving. Medium-scale tests and offshore field measurements confirm that pressure distribution along bubble curtain hoses significantly influences noise reduction performance. Experimental data show that higher air flow rates lead to nonlinear pressure variations, affecting bubble formation and overall mitigation effectiveness. Offshore measurements further validate numerical models, demonstrating that double bubble curtain systems effectively attenuate noise, especially at lower frequencies. Future work will focus on laboratory-scale tests to assess particle motion and seabed vibrations, improving the understanding of noise impact on marine species.

References

1. Bohne T, Grießmann T, Rolfes R (2019) Modeling the noise mitigation of a bubble curtain. The Journal of the Acoustical Society of America 146(4):2212. https://doi.org/10.1121/1.5126698

2. Bohne T, Grießmann T, Rolfes R (2020) Development of an efficient buoyant jet integral model of a bubble plume coupled with a population dynamics model for bubble breakup and coalescence to predict the transmission loss of a bubble curtain. International Journal of Multiphase Flow **132**. https://doi.org/10.1016/j.ijmultiphaseflow.2020.103436
3. European Commission: Directorate-General for Environment: Guidance Document on Wind Energy Developments and EU Nature Legislation. Publications Office of the European Union, Luxembourg (2020). https://data.europa.eu/doi/10.2779/457035 Accessed 03 Mar 2025
4. Lippert S, Huisman M, Ruhnau M, Estorff O, van Zandwijk K (2017) Prognosis of underwater pile driving noise for submerged skirt piles of jacket structures. In: Proceedings of the UACE 2017 4th Underwater Acoustics Conference and Exhibition
5. Ministry of Environment, Taiwan (2018) Highly efficient eia review process for offshore wind power reaches a milestone in green energy, https://www.moenv.gov.tw/en/B005F3AAE9CEC1EC/76c5a811-e76d-43d9-b85d-dc6e67e43312 Accessed 16 Mar 2025
6. Netherlands Enterprise Agency (RVO) (2020) Summary environmental impact assessment for hollandse kust (west) wind farm sites vi and vii, version november 2020. Tech. rep. https://www.rvo.nl/onderwerpen/windenergie-op-zee/hollandse-kust-west Accessed 16 Mar 2025
7. Peng Y, Jarquin Laguna A, Tsouvalas A (2023) A multi-physics approach for modelling noise mitigation using an air-bubble curtain in impact pile driving. Frontiers in Marine Science **10**. https://doi.org/10.3389/fmars.2023.1134776, https://www.frontiersin.org/articles/10.3389/fmars.2023.1134776
8. Peng Y, Tsouvalas A, Stampoultzoglou T, Metrikine A (2021) 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):1772–1790
9. Peng Y, Tsouvalas A, Stampoultzoglou T, Metrikine A (2021) Study of the sound escape with the use of an air bubble curtain in offshore pile driving. Journal of Marine Science and Engineering 9(2):232. https://doi.org/10.3390/jmse9020232
10. Southall B, Nowacek D, Bowles A, Senigaglia V, Bejder L, Tyack P (2021) Marine mammal noise exposure criteria: assessing the severity of marine mammal behavioral responses to human noise. Aquatic Mammals 45(5):421–464. https://doi.org/10.1578/AM.47.5.2021.421
11. Stöber U, Thomsen F (2019) Effect of impact pile driving noise on marine mammals: A comparison of different noise exposure criteria. The Journal of the Acoustical Society of America 145(5):3252. https://doi.org/10.1121/1.5109387
12. Tsouvalas A, Metrikine AV (2016) Noise reduction by the application of an air-bubble curtain in offshore pile driving. Journal of Sound and Vibration 371:150–170. https://doi.org/10.1016/j.jsv.2016.02.025