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Publication date
2024

Document Version
Final published version

Published in
Proceedings of the 30th International Congress on Sound and Vibration

UNDERWATER NOISE FROM GENTLE DRIVING OF PILES

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Underwater noise pollution during the installation of foundation piles offshore using large impact hammers can adversely affect marine fauna. In recent years, several vibratory techniques have been developed to drive large foundation piles offshore. One promising technology is called the gentle driving of piles (GDP). This technology uses a combination of high-frequency torsional excitation together with low-frequency vertical excitation at the pile head to drive the pile into the marine sediment. To date, most of the modelling developments have focused on the installation process with this new method, i.e., the development of the so-called driveability models. This paper discusses the underwater noise that is generated during the installation of piles using the GDP method. A case study is analyzed using experimental data to identify the excitation forces at the top of the pile. The prediction of the noise is then investigated using a linear vibroacoustic model in two cases: the classical installation with vertical excitation alone and the installation by means of the GDP method. The differences between the two methods are highlighted, and some conclusions are drawn that can be of added value for practitioners in the field.

Keywords: Underwater sound, Gentle Driving of Piles, Monopile installation, Vibratory Piling

1. Introduction

Wind power has gained recognition in Europe as a pivotal solution for transitioning towards renewable energy. For instance, the EU Offshore Renewable Energy Strategy advocates for a rapid increase in offshore wind deployment, targeting 60 gigawatts of capacity by 2030 and ambitiously aiming for 300 gigawatts by 2050 [1]. This strategy stresses the importance of reaching these targets while maintaining harmonious coexistence with marine ecosystems, thus requiring minimal ecological impact [2].

The installation of offshore wind turbine foundations generates noise that adversely affects marine life [3, 4]. Several models have been devised to forecast noise levels during the installation of monopiles using impact piling techniques [5, 6, 7, 8, 9, 10]; a comprehensive overview can be found in [11]. To mitigate noise levels, sound attenuation methods are implemented to impede sound waves, such as the utilization of large bubble curtains [12]. Alternatively, vibratory driving techniques have been developed to diminish noise emission at its source, with Gentle Driving of Piles (GDP) being one such method [13]. However, there is scant research available on noise prediction for vibratory piling [14, 15, 16].

The GDP project attempts to develop and showcase the advantages of an innovative vibratory pile installation technique that relies on the simultaneous application of vibratory loads in both the vertical and torsional directions. The GDP hammer has been designed with low-frequency and high-frequency vibrators applied in the vertical and torsional directions, respectively, with the intention of reducing the driving loads and noise generated during installation. The term "gentle" stems from the anticipated ability to reduce the noise generated during installation. The overarching objective is to develop the GDP technique, not to compromise the crucial aspects of pile penetration speed and soil-bearing capacity, which are indispensable for the stable operation of offshore wind turbines.

The experimental campaign consisted of two distinct phases. In the first phase, piles were installed, and in the subsequent phase, the lateral bearing capacity of the installed piles was examined. Throughout both phases, a comprehensive array of measurement equipment was employed to gather data on various parameters related to the piles. A detailed account of the experimental setup and the collected data during installation can be found in Tsetas et al. [17]. Furthermore, Kementzetzidis et al. [18] presented the results obtained from the post-installation lateral load experiments.

This paper provides noise predictions with the GDP method and a scientific justification of assumptions necessary to do so. These assumptions are based on the conclusions drawn by Molenkamp et al. [14, 15]. Based on the experimental findings, a hypothetical scenario is presented to compare the noise predictions for GDP with those for monopiles driven using a Vibro hammer.

2. Underwater noise predictions

The test campaign reveals numerous uncertainties that affect noise predictions during driving with GDP. As the installation tool is still under development, the frequencies and amplitudes of both hammer excitations may not accurately represent future designs. However, this chapter aims to predict the anticipated noise levels generated by GDP and compare them with those produced during driving with a traditional vibratory hammer (VH) under a specific set of assumptions, such as symmetry around the circumference. This comparison is based on the experimental campaign presented and the measurements taken.

Next, the pile and soil interaction plays a crucial role in noise predictions for vibratory devices [14, 15]. This chapter examines two extreme cases of pile-soil interaction: a scenario with no friction (NF) and another with perfect contact (PC) between the pile and the soil. Both pile-soil interface descriptions have their limitations but can serve as extreme cases. The NF case is presumably the most representative, while the relative velocity vector between pile and soil will have a component that is predominantly along the horizontal direction. This results in reduced frictional resistance in the vertical direction.

On the other hand, excitation of the vertical vibrations of the pile by friction forces at the torsional excitation frequency can occur due to the change in the effective friction angle. It is argued that the excitation of vertical pile vibration by friction is partly reflected in the measurements and thus accounted for indirectly. This assumption simplifies the GDP noise prediction model to be equivalent to the VH noise prediction model, with the differences being introduced via the forcing on top of the pile. The subsequent subsections will discuss the examined case study and compare the noise predictions for VH and GDP based on the PC and NF interface condition assumptions.

2.1 Case study

The case study considers a small pile with a diameter of 0.762 m and a length of 17.4 m driven into sediment. The water depth is 10 m. The case study is presented in more detail by Molenkamp et al. [14]. The case is employed to illustrate the differences in noise generation during pile driving with VH and GDP. The vertical forces applied atop the pile for both hammer types are deduced from empirical data and showcased in Fig. 1 [17]. The assumption of cylindrical symmetry leads to the omission of the rotational force component; nevertheless, its influence on vertical excitation is indirectly incorporated through the recorded vertical forces.

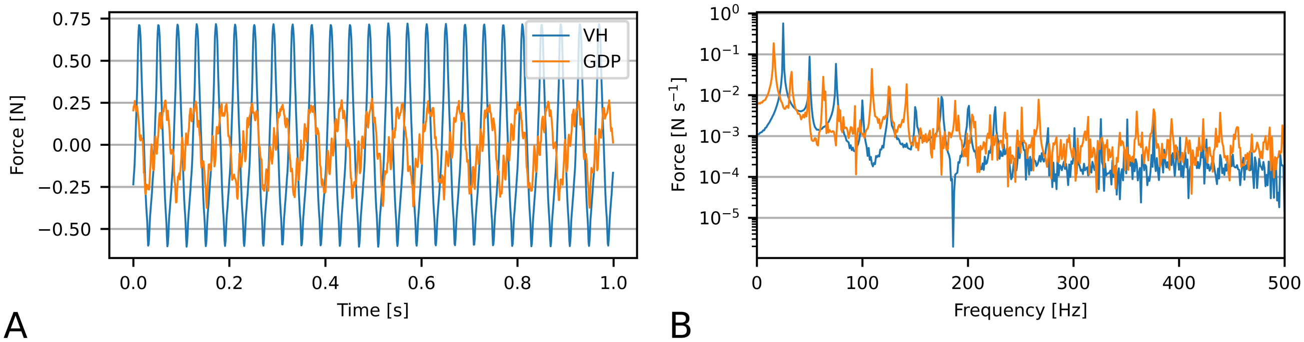

Figure 1: Radial, torsional and vertical measured acceleration on top of the pile for (A) the Vibro hammer-driven pile and (B) and (C) the GDP-driven piles

As displayed in Fig. 1A, the excitation induced by the GDP hammer exhibits decreased amplitude compared to the VH excitation. Furthermore, the signal appears less smooth, implying a relatively higher contribution of superharmonics relative to the primary driving frequency. This observation aligns with the spectral representation of the force profile depicted in Fig. 1B, where the GDP-induced force displays more peaks at superharmonics of relatively high amplitudes compared to the VH-driven forces, whereas the VH forcing has considerably higher amplitude at the primary driving frequency.

2.2 Noise predictions under the assumption of perfect pile-soil contact

This section explains the differences in expected noise emission between VH and GDP under the assumption of perfect contact between the pile and the soil. The conventional modelling of perfect contact between the pile and the soil is prevalent in impact pile driving models. However, despite the indications that perfect contact might not precisely forecast the noise propagation for vibratory devices [14, 15], the absence of empirical data necessitates exploring limiting scenarios.

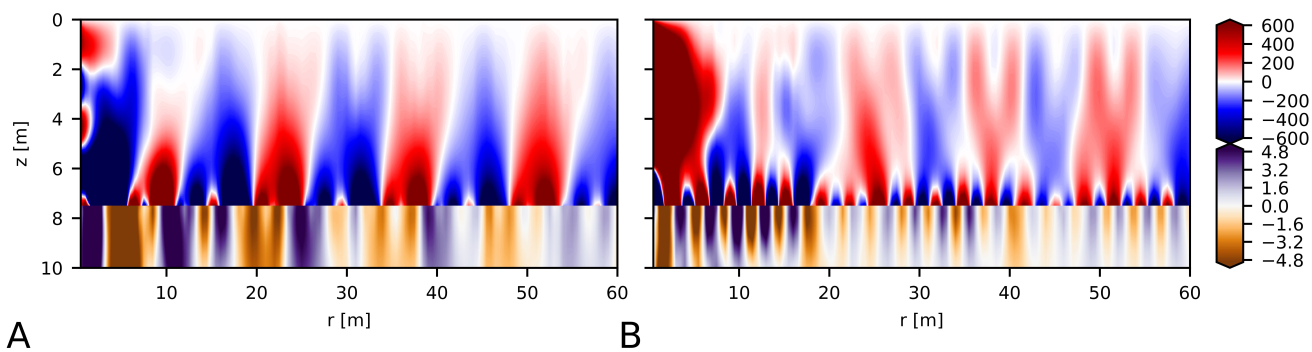

Figure 2: Snapshot of fluid pressure $[\mathrm{Pa}]$ and vertical soil velocity $[\mathrm{mm\,s^{-1}}]$ induced by VH (A) and GDP (B) hammer under perfect contact assumption.

Figure 2 presents a snapshot of the wavefield induced by both dynamic excitations, i.e. the sound pressure in the seawater and the vertical soil vibrations in the seabed. Upon initial examination, the fluid pressure exhibits comparable amplitudes except above the seabed, where the VH produces Scholte waves of greater magnitude that dominate the noise propagation. The seabed vibrations substantiate this observation, manifesting waves with greater amplitude and wavelength, correlated with Scholte waves excited at a lower frequency and present within the soil. In the case of GDP, Scholte waves with shorter wavelengths and smaller influence zones in the fluid medium are observed.

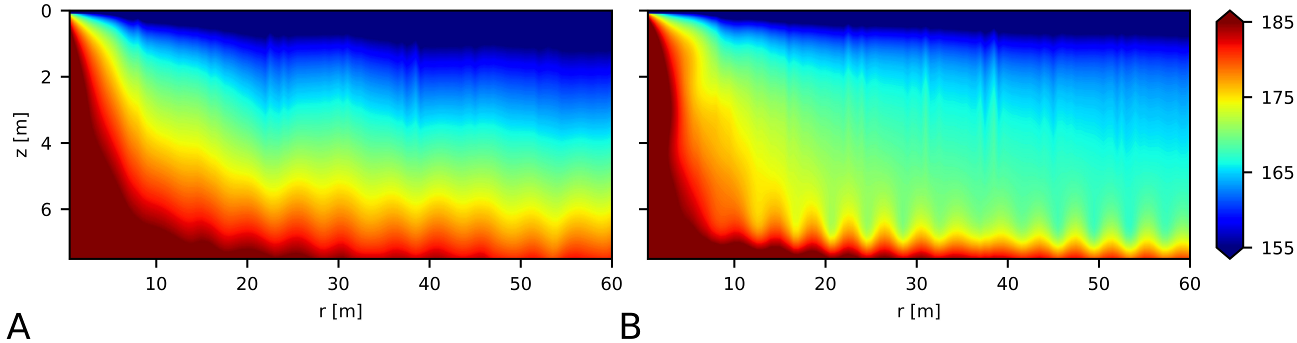

Figure 3: Sound exposure levels in dB integrated over 1 second due to VH (A) and GDP (B) hammering under perfect contact assumption.

The sound exposure levels in Fig. 3 corroborate the inference drawn from the time-domain plot. The highest noise levels materialise just above the seabed due to the propagating Scholte wave along the seabed. In the VH scenario, the influence zone is broader and characterised by higher amplitude. The dominant Scholte wave in the scenario of perfect contact aligns with literature [14, 15], where soil excitations are likely amplified due to the underlying pile-soil interface assumption.

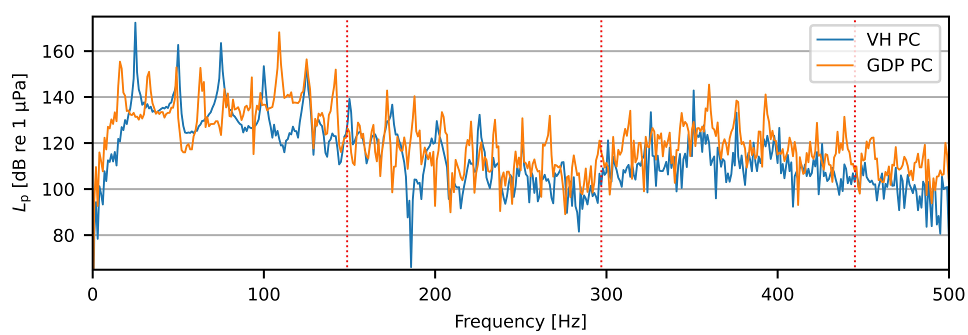

Figure 4: Sound pressure levels $0.25\ \mathrm{m}$ above the seabed at $r = 60\ \mathrm{m}$, with the red vertical lines indicating the in-vacuo eigenfrequencies of the pile.

The sound pressure levels above the seabed illustrate that the fundamental driving frequency dominates the noise field generated by the VH. In contrast, the highest noise levels in the GDP scenario are evident around $120\ \mathrm{Hz}$. This discrepancy accounts for the variation in wavelengths of the Scholte waves as observed in Fig. 2. Once again, the significance of the superharmonics demands emphasis, as both hammers exert considerable influence on the noise field.

2.3 Noise predictions under the assumption of no friction between pile and soil

All types of vibratory piling involve consistently vibrating the top of the pile, causing the pile to continuously move and shift within the soil. Past studies have indicated that frictional forces add to the noise produced during this process. However, in situations where the hammer's vibrations produce significant superharmonics, it can be reasonable to assume that friction plays a minor role. This assumption is made under the belief that the hammer's vibrations at higher harmonics outweigh the effects of friction. In the case of GDP, the assumption of no friction in the vertical direction seems even more suitable since the friction angle will mainly be governed by the torsional motion instead of the vertical motion, minimalising the contribution in the vertical component of the friction forces.

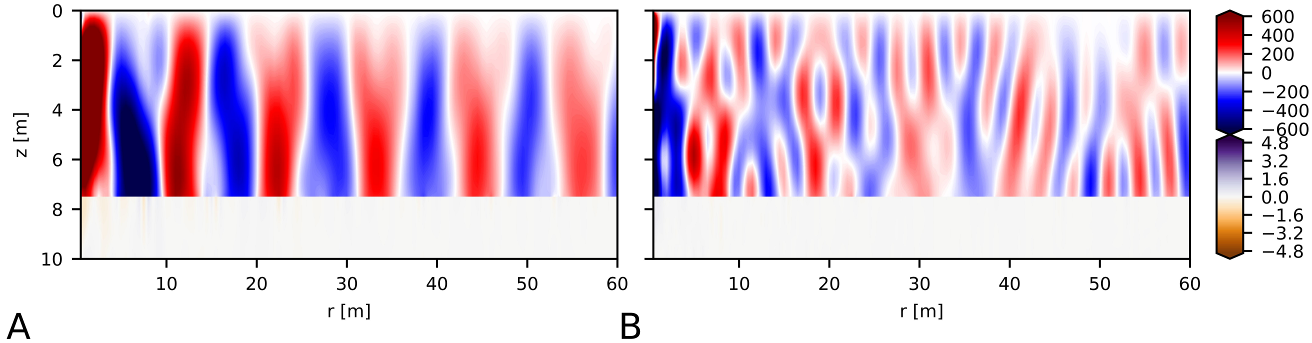

Figure 5: Snapshot of fluid pressure $[\mathrm{Pa}]$ and vertical soil velocity $[\mathrm{mm\,s^{-1}}]$ induced by VH (A) and GDP (B) hammer under no friction assumption.

Figure 5 offers a snapshot of the generated noise pattern and soil vibrations while assuming the absence of frictional forces. It becomes immediately apparent that the two noise profiles significantly differ, and both cases exhibit minimal soil vibrations. The lack of soil wave propagation is inherent to the frictionless assumption, where soil perturbations originate solely from the pile's radial deformation. This likely results in underestimating the soil vibrations without shear waves and Scholte interface waves.

The pressure field produced by the VH hammer is primarily governed by a wave that extends across the fluid column's height with the same phase. In contrast, the pressure field induced by the GDP hammer comprises numerous waves of varying shorter wavelengths, manifesting radially and vertically. This differential behaviour indicates distinct pile vibration modes, resulting in dissimilar noise emission mechanisms compared to the perfect contact scenario.

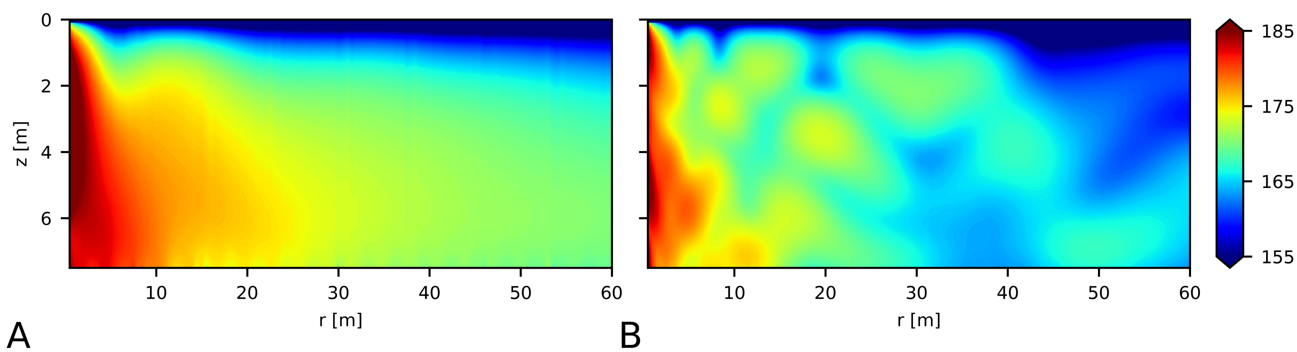

Figure 6: Sound exposure levels in dB integrated over 1 second due to VH (A) and GDP (B) hammering under perfect contact assumption.

The corresponding sound exposure levels depicted in Fig. 6 exhibit a gradual attenuation throughout the fluid column radially in the case of VH excitation. On the contrary, sound exposure levels associated with GDP excitation reveal a more oscillatory pattern characterised by a superposition of multiple waves.

Nevertheless, the noise levels emitted by the GDP hammer are markedly lower than those generated by the VH hammer. Evidently, the amplification of sound levels due to the Scholte wave above the seabed is absent in both cases.

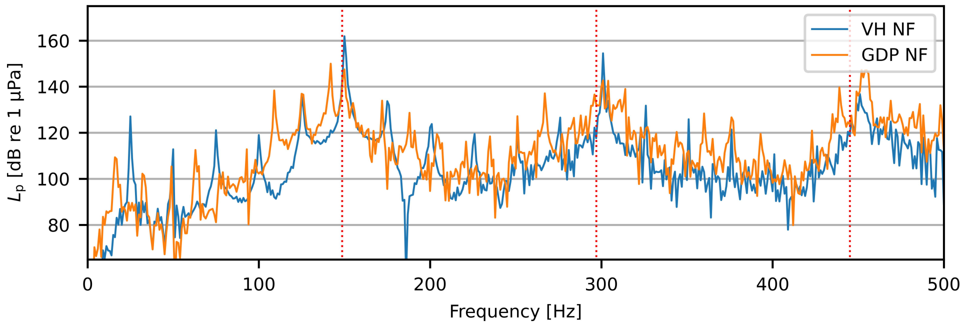

Figure 7: Sound pressure levels $0.25\ \mathrm{m}$ above the seabed at $r = 60\ \mathrm{m}$, with the red vertical lines indicating the in-vacuo eigenfrequencies of the pile.

Figure 7 presents the sound pressure levels, shedding light on the origins of the pressure fields. The sound pressure levels highlight the peak pressures around the in-vacuo eigenfrequencies of the pile, suggesting minimal shifts from in-vacuo eigenfrequency to resonant frequencies of the immersed pile due to the assumed pile-soil interaction. For both forces, the superharmonics of the excitation force aligning with the system's resonant frequencies cause the highest noise levels. Notably, the VH hammer generates substantially higher noise levels at the first resonant frequency than the subsequent two frequencies. The GDP hammer emits noise at the first three resonant frequencies with comparable amplitudes, contributing to a more frequency-rich noise field.

Once again, Fig. 7 emphasises the significance of adequately accounting for superharmonics in the forces. Small shifts in excitation frequency and superharmonics can result in substantial fluctuations in the sound levels. While the GDP hammer excites a more significant number of superharmonics due to its dual excitation, these are more likely to coincide with resonant frequencies. In contrast, the driving frequency and superharmonics of the VH hammer can, from an engineering perspective, be more straightforwardly adjusted and calculated. Nonetheless, the VH hammer generates significantly higher noise levels within the specified conditions than the GDP hammer.

3. Discussion

This chapter reflects on the potential of GDP as a silent vibratory pile-driving device. Despite the shaker being in its initial design iteration for the experimental campaign and the need for offshore and full-scale experimental data, the experimental data and numerical simulations presented substantiate the envisaged capabilities of the GDP shaker.

The experimental campaign emphasises that the GDP shaker requires significantly reduced vertical force to drive a pile into the soil at a comparable or heightened pace. The reduction in vertical shaker amplitude directly influences noise emissions. While the data reveal coupling between torsional and vertical driving frequencies, noise emission is not strongly affected by vertical and radial vibrations at the torsional excitation frequency.

The significant torsional movement in the GDP shaker is expected to lead to minimal vertical frictional resistance. As a result, the process of driving the pile encounters less resistance in the vertical direction, making it smoother and faster. However, this may also make the pile more susceptible to resonant responses, as the coupling between the pile and its surroundings is limited. Given the dual excitation frequencies of the GDP, there is a potential risk of resonance frequencies causing issues. Decreasing the energy in superharmonics has the potential to reduce noise emissions in all vibratory hammers, with particular emphasis on GDP.

In theory, friction couples both torsional and vertical excitation, yielding a multifaceted frictional reaction, engendering various combinations of superharmonics from both excitation forces, contingent on the pile's velocity angle. While this aspect has not been incorporated within this chapter, the frictional forces possibly excite pile vibrations at any combination of super- and subharmonics of the excitation frequencies. While the amplitudes are anticipated to be modest, this phenomenon can potentially initiate pile vibrations and consequent noise emissions at hard-to-predict frequencies.

The Scholte wave predominantly governs the noise emission in the numerical scenario where pile and soil interact via perfect contact. While acknowledging the non-physical nature of this scenario, this extreme case highlights that GDP is inclined to produce reduced noise emission via the Scholte wave mechanism due to the substantially reduced vertical force atop the pile.

Despite the assorted assumptions, the potential of GDP as a silent vibratory shaker is substantiated across all scenarios. Subsequent research should demonstrate the device's performance in offshore settings and at full scale. Reducing or mitigating energy in superharmonics and decoupling vertical and torsional excitations emerge as key facets for consideration in the future design of the GDP shaker. If executed adeptly, the GDP shaker is potentially a solution for noise generation in offshore pile driving.

4. Acknowledgments

This paper is associated with the GDP project in the framework of the GROW joint research program. Funding from *Topsector Energiesubsidie van het Ministerie van Economische Zaken* under grant number TEHE117100 and financial/technical support from the following partners is gratefully acknowledged: Royal Boskalis Westminster N.V., CAPE Holland B.V., Deltares, Delft Offshore Turbine B.V., Delft University of Technology, ECN, Eneco Wind B.V., IHC IQIP B.V., RWE Offshore Wind Netherlands B.V., SHL Offshore Contractors B.V., Shell Global Solutions International B.V., Sif Netherlands B.V., TNO, and Van Oord Offshore Wind Projects B.V.

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