Delft University of Technology

Noise and Vibration Suppression in Vibratory Pile Driving Using Locally-resonant Metamaterials

Farăgău, Andrei; Tsetas, Athanasios; Metrikine, Andrei; Tsouvalas, Apostolos

Publication date
2024

Document Version
Final published version

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

Citation (APA)
Farăgău, A., Tsetas, A., Metrikine, A., & Tsouvalas, A. (2024). Noise and Vibration Suppression in Vibratory Pile Driving Using Locally-resonant Metamaterials. In W. van Keulen, & J. Kok (Eds.), *Proceedings of the 30th International Congress on Sound and Vibration* Article 775 (Proceedings of the International Congress on Sound and Vibration). Society of Acoustics.
https://iiav.org/content/archives_icsv_last/2024_icsv30/content/papers/papers/full_paper_775_20240422160759489.pdf

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

Copyright
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.
For technical reasons the number of authors shown on this cover page is limited to a maximum of 10.

NOISE AND VIBRATION SUPPRESSION IN VIBRATORY PILE DRIVING USING LOCALLY-RESONANT METAMATERIALS

Andrei Fărăgău
Delft University of Technology, Department of Engineering Structures, Delft, the Netherlands
E-mail: a.b.faragau@tudelft.nl
Athanasios Tsetas
Delft University of Technology, Department of Engineering Structures, Delft, the Netherlands
Andrei Metrikine
Delft University of Technology, Department of Engineering Structures, Delft, the Netherlands
Apostolos Tsouvalas
Delft University of Technology, Department of Engineering Structures, Delft, the Netherlands

The increasing demand for renewable energy sources is driving a significant rise in the adoption of offshore wind energy. Offshore wind turbines are typically supported by large foundation piles driven into the seabed. The primary method of installation is by hydraulic impact hammers. However, this method generates excessive underwater noise among other drawbacks. Consequently, alternative techniques are being explored by both researchers and industry. One promising alternative is vibratory driving, which theoretically produces less underwater noise compared to impact driving. Nevertheless, there remains a substantial amount of energy transmitted into the water column, particularly from the higher harmonics of the driving frequency. While energy at the fundamental frequency is essential for efficient driving, the energy associated with higher harmonics does not contribute to this efficiency and can significantly increase radiated underwater noise. To address this issue, this study proposes a mitigation strategy to block energy transfer at super-harmonic frequencies in the pile-water-soil system. To selectively target these frequencies without affecting the fundamental one, a mitigation approach utilizing locally-resonant metamaterials is proposed. This involves integrating a transition piece between the vibratory hammer and the pile, that incorporates periodically inserted multiple-degrees-of-freedom systems. By manipulating the natural frequencies of these periodic inclusions, the transition piece forms band-gaps at the relevant super-harmonics. Initial findings indicate that this design has the potential to effectively mitigate noise and vibration at targeted frequencies. Nonetheless, further investigations employing more sophisticated models are necessary to confirm these outcomes.

Keywords: Metamaterials, Pile driving, Underwater noise mitigation, Vibration mitigation

1. Introduction

Motivated by ambitious climate goals aiming to reduce greenhouse gas emissions, the demand for energy generated by wind turbines has surged in recent decades [1]. Offshore wind power generators, unlike their onshore counterparts, typically yield higher electricity output due to the less turbulent and faster-flowing winds offshore [2]. Despite the diversity of available foundation concepts, monopiles stand as the predominant choice for wind turbines in shallow to intermediate water depths. Monopiles are installed by driving them into the seabed using hydraulic impact hammers or large vibratory devices. Regardless of the installation method employed, noise is emitted into the seawater, and elastic waves propagate into the seabed. The responses of marine mammals and fish to this noise and vibration pollution range from mild disturbance to outright avoidance of the construction site; in severe cases, permanent hearing impairment may occur [3]. Consequently, regulations have been enacted to limit underwater noise levels, necessitating mitigation measures to ensure compliance with threshold limits.

While the underwater noise generated by impact driving is extensively researched (e.g., [4, 5]), the studies on sound emission from vibratory pile driving remain relatively limited. This disparity is attributed to the fact that noise levels are generally less pronounced with vibratory methods compared to impact piling, and vibratory installation techniques are less frequently utilized offshore. Nonetheless, a handful of studies endeavor to quantify the noise levels of vibratory driving [6, 7] and evaluate its environmental impact [8, 9]. More recently, Molenkamp et al. [10, 11] demonstrated that the higher harmonics produced by vibro-piling, arising from nonlinearities in the system such as pile-soil interaction [12], can emit a significant amount of energy as noise radiation in the water column.

This study proposes a method to considerably reduce the energy in the higher harmonics generated during pile driving with vibratory devices. The mitigation device consists of a transition piece between the vibro-hammer and the pile that contains periodically placed resonators. This transition piece works as a locally-resonant metamaterial that absorbs the energy at these specific super-harmonics. This study serves as a theoretical proof-of-concept for this mitigation measure, in which a simplified model is used to determine the feasibility of such a measure. The model consists of a rod (representing the pile) partially supported by a visco-elastic foundation (representing the soil). The vibrating hammer is modelled as a point mass with an imposed multi-harmonic force at the top of the pile. The metamaterial resonators are modelled as single/multi-degree(s)-of-freedom (S/MDOF) systems. This initial investigation excludes the water and such it focuses only on the mitigation of the pile vibrations as a first phase of this investigation. Nonetheless, since the pile acts as the source, eliminating the energy at higher harmonics in the pile leads to the abatement of underwater noise as well.

Future studies will be conducted using more advanced models for both pile and soil, and their interaction to better assess the potential of this measure. Nonetheless, establishing the feasibility of the mitigation measure based on locally-resonant metamaterials (which is novel in offshore applications) to reduce energy at the super-harmonics of the driving frequency serves as a valuable starting point.

2. Model formulation and the meta-transition piece design methodology

To evaluate the feasibility of the mitigation measure based on locally-resonant metamaterial to reduce the system response at the higher harmonics (i.e., integer multiples of the driving frequency), this study employs a simplified model consisting of a rod with axial stiffness EA and mass per length ρA representing the pile, which is partially supported by a visco-elastic foundation with stiffness and damping coefficients k_{s} and c_{s}, respectively, which represents the soil. Additionally, a spring-dashpot element with coefficients K_{t} and C_{t} is imposed at the pile bottom to simulate the soil tip reaction. The vibrating hammer is modelled as a point mass M_{h} with an imposed multi-harmonic (i.e., $p\Omega$ with $p = 1, 2, 3, \dots$) force at the top of the pile. Since this study is theoretically oriented (and because the model employed is linear), the amplitude of each harmonic is chosen as unity, and only the response reduction relative to the force amplitude is presented. Although the water column can influence, to some degree, the pile vibrations, its influence is neglected in this preliminary study. This also means that the investigation focuses on the reduction of the noise source (pile vibrations) and does not investigate the underwater noise propagation. A schematic of the system is presented in Fig. 1 and its governing equations read

$$-EAw'' + \rho A\ddot{w} + \left(k_\mathrm{s} + c_\mathrm{s}\frac{\partial}{\partial t}\right) wH(z - L_\mathrm{emb}) = 0, \qquad L_\mathrm{mm} < z < L_\mathrm{p}, \tag{1}$$

$$-EAw'' + \rho A\ddot{w} + \sum_{i=1}^{N}\left(k_{\mathrm{i},1} + c_{\mathrm{i},1}\frac{\partial}{\partial t}\right)\left(w(z = z_i) - u_{\mathrm{i},1}\right)\delta(z - z_i) = 0, \quad 0 < z < L_\mathrm{mm}, \tag{2}$$

$$M_{i,j}\ddot{u}_{i,j} + \left(k_{i,j} + c_{i,j}\frac{\partial}{\partial t}\right)\left(u_{i,j} - w(z = z_i)\right) + \left(k_{i,j+1} + c_{i,j+1}\frac{\partial}{\partial t}\right)\left(u_{i,j} - u_{i,j+1}\right) = 0, \quad j = 1, \tag{3}$$

$$M_{i,j}\ddot{u}_{i,j} + \left(k_{i,j} + c_{i,j}\frac{\partial}{\partial t}\right)\left(u_{i,j} - u_{i,j-1})\right) = 0, \qquad j = N, \tag{4}$$

$$M_{i,j}\ddot{u}_{i,j} + \left(k_{i,j} + c_{i,j}\frac{\partial}{\partial t}\right)\left(u_{i,j} - u_{i,j-1}\right) + \left(k_{i,j+1} + c_{i,j+1}\frac{\partial}{\partial t}\right)\left(u_{i,j} - u_{i,j+1}\right) = 0, \quad j > 1, \tag{5}$$

where w is the axial pile displacement, $u_{i,j}$ is the displacement of the corresponding DOF of a single resonator element, L_emb and L_mm denote the embedded and the metamaterial transition piece lengths, respectively. Furthermore, $M_{i,j}$, $c_{i,j}$ and $k_{i,j}$ are the mass, damping and stiffness values of the indicated DOF of a single resonator element, with the index i corresponding to the position of the resonator in z-direction, while index j corresponds to the degree-of-freedom of a single resonator element (for example if a single-degree-of-freedom is used, $j = 1$, if a two-degree-of-freedom is used $j = \{1, 2\}$ and so on).

The response of the formulated model is obtained using a finite element (FE) discretization in space and the Newmark-β time-stepping scheme in time. A frequency-domain approach can also be used, which most likely would be more efficient computationally, but the above-mentioned approach is adopted to allow the implementation of nonlinear resonators in the meta-material zone in the future.

The procedure for designing the metamaterial is divided into two main stages. Firstly, the unit cell is designed as part of a structure consisting of an infinite number of identical cells, ensuring that its band gaps align with the expected super-harmonics of the loading frequency. The dispersion properties of this infinite periodic structure are determined semi-analytically (i.e., an infinite rod with periodically positioned resonators, see Ref. [13] for one way of determining the dispersion curves of such a system). Secondly, the designed unit cell is incorporated into the actual pile-soil model, where the zone with metamaterials is finite. This final step aims to determine the required length of the transition piece such that a significant amount of energy from the higher-harmonics is absorbed by the resonators. It must be emphasized that significant discrepancies can occur between the first and last steps; the preliminary metamaterial design is based on an infinite system that allows for propagating or evanescent waves, while the second step includes a finite model with standing waves. Consequently, iteration between these two steps is most likely necessary to ensure the optimal design of the transition piece.

3. Results and discussion

To propose an innovative countermeasure as a viable solution, it is essential to establish realistic design constraints. In this study, we choose to use the same material and dimensions for the transition piece as for the monopile. This choice is made to reduce the complexity of the transition piece at this investigation step; in future analyses, other designs and materials will be investigated. The parameters used for the results presented in this paper are given in Table 1.

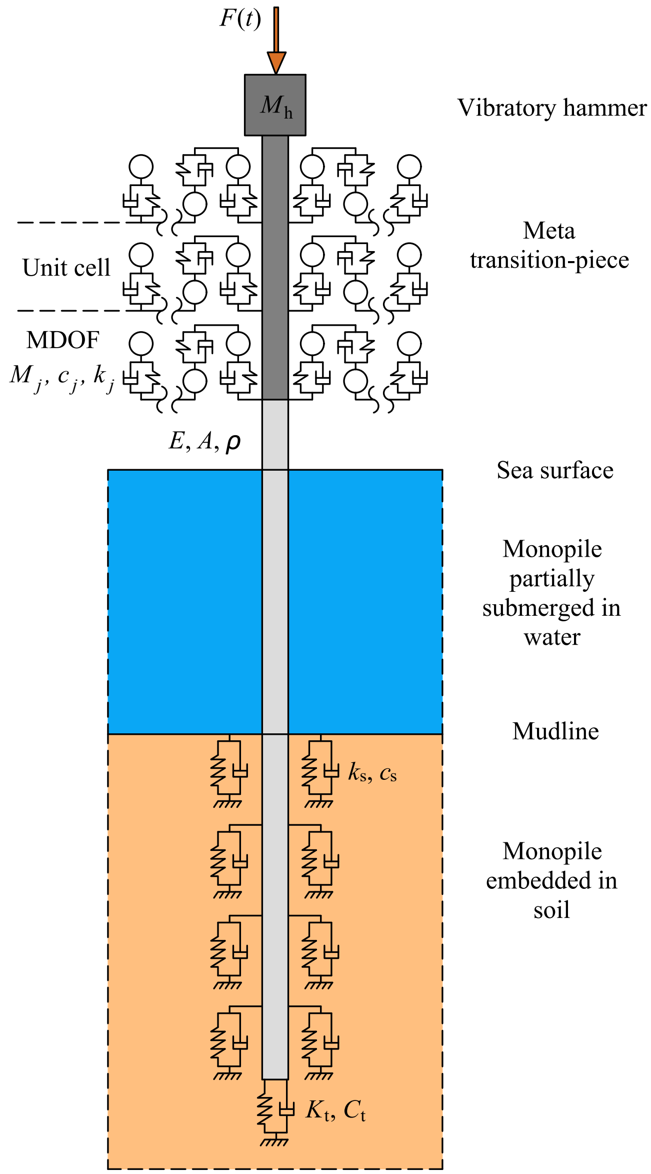

Figure 1: A schematic depiction of the problem considered: a monopile (modelled as a rod) partially embedded in soil (modelled as a Kelvin foundation) subjected to a vibratory hammer (modelled as a periodically excited point mass). Between the vibratory hammer and monopile, a metamaterial transition piece is placed to filter out higher harmonics from the vibratory hammer.

3.1 Proposed metawedge design

The transition piece presents periodic two-degree-of-freedom (MDOF) resonators rigidly connected to the transition piece. In addition to the fundamental forcing harmonic, two super-harmonics are imposed into the force acting at the top of the monopile. Consequently, to mitigate the two higher harmonics, two degrees of freedom are chosen for the MDOFs. The properties of the MDOF are tuned such that the resulting band-gaps are located at the forcing higher harmonics. The parameters of the transition piece are given in Table 2.

Following the design procedure described in Section 2, the dispersion curves of the longitudinal waves

Table 1: System parameter values except for the meta transition piece.

Parameter	Symbol	Value	Unit
Young's modulus	E	210	GPa
Mass density	ρ	7850	kg/m^3
Diameter	D	2.6	m
Thickness	h	40	mm
Length	L	50	m
Embedded length	L_{emb}	20	m
Hammer mass	M	88	tons
Shaft stiffness	k_{s}	30 $\times 10^6$	N/m^2
Shaft damping	c_{s}	150 $\times 10^3$	Ns/m^2
Tip stiffness	K_{t}	222 $\times 10^6$	N/m
Tip damping	C_{t}	222 $\times 10^3$	Ns/m

Table 2: System parameter values for the meta transition piece.

Parameter	Symbol	Value	Unit
Mass DOF #1	M_1	280	kg
Mass DOF #2	M_2	42	kg
Stiffness DOF #1	k_1	32 $\times 10^6$	N/m
Stiffness DOF #2	k_2	5.7×10^6	N/m
Damping DOF #1	c_1	474	Ns/m
Damping DOF #2	c_2	77	Ns/m
Resonators distance	d	0.5	m
Length	L_{mm}	10	m

are determined and presented in Fig. 2. The gray background represents the location of the stop-bands, i.e. frequency ranges associated with strong wave-amplitude decay. The imaginary part of the wavenumbers have a considerable magnitude in these frequency ranges, while it is nearly zero elsewhere, basically confirming the strong wave attenuation in these ranges. It can be seen that the two stop-bands generated by the inclusion of the resonators are located at the forcing higher-harmonics, while no stop-band is located in the vicinity of the forcing fundamental harmonic. The latter is desired since the monopile drivability should not be compromised.

It must be noted that other combinations of parameters can lead to similar stop-bands, but finding the most optimum set of parameters is outside the scope of this investigation.

3.2 Results

While dispersion curves are extremely useful in the preliminary design of the metamaterials, they consider an infinite number of identical unit cells. This deviates from the practical constraints and, thus, the response of the actual system is now investigated. Fig. 3 presents the frequency components of the pile response evaluated at 2 m above mudline for both the system with and without metamaterials. The top panel shows that the response at the forcing fundamental harmonic is almost unaltered, while the one at the higher-harmonics is significantly diminished, which can be more clearly seen in the bottom panel. Furthermore, the first super-harmonic is more efficiently mitigated than the second due to the stronger

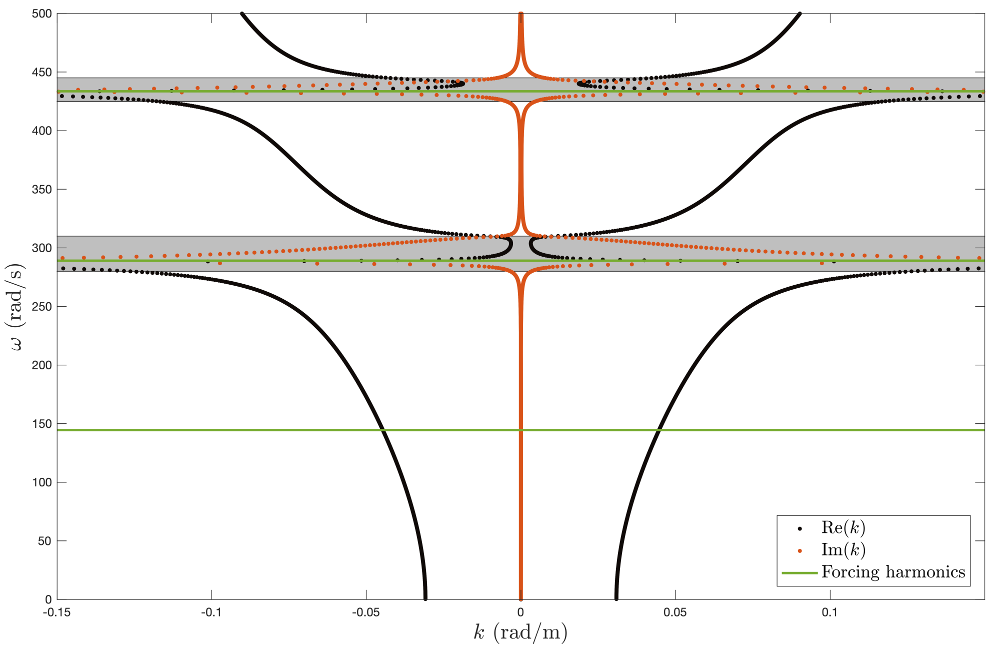

Figure 2: Dispersion curves for an infinite number of repetitive unit cells of the transition piece.

decay observed in the dispersion curves associated with this harmonic (i.e., the wavenumbers there have a larger imaginary part).

4. Conclusions

This study proposes a mitigation strategy to dissipate energy at super-harmonic frequencies for offshore pile driving using vibratory hammers. To selectively target the super-harmonic frequencies without affecting the fundamental one, a mitigation approach utilizing locally-resonant metamaterials was proposed. This involves integrating a transition piece between the vibratory hammer and the pile, that incorporates periodically inserted multiple-degrees-of-freedom systems.

The results show that the proposed mitigation measure is capable of significantly reducing the response at the super-harmonic frequencies. Future studies will investigate the optimal design to ensure that the higher harmonics are mitigated as much as possible. Also, since this study serves as a proof-of-concept, a simplified model has been used to generate these results. Future studies will involve higher fidelity models to confirm the potential observed in this preliminary investigation. Finally, this work aimed to showcase the potential and feasibility of metamaterials to address present and future challenges in the offshore wind energy sector.

REFERENCES

1. Kaldellis, J. K. and Kapsali, M. Shifting towards offshore wind energy-Recent activity and future development, *Energy Policy*, **53**, 136–148, (2013).

2. Bilgili, M., Yasar, A. and Simsek, E., (2011), *Offshore wind power development in Europe and its comparison with onshore counterpart*.

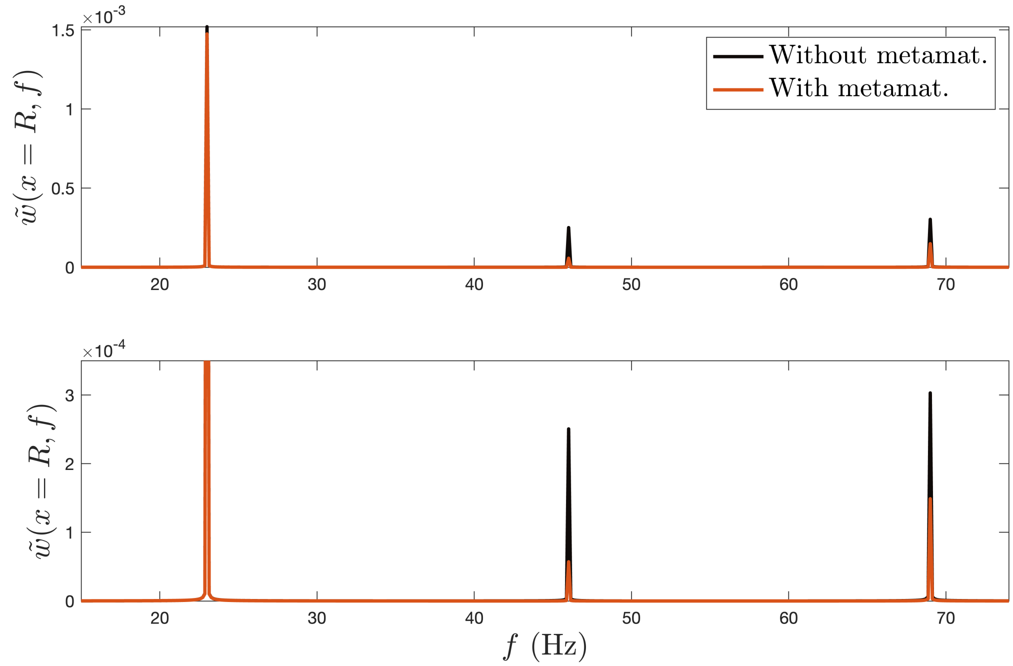

Figure 3: The frequency components of the pile response evaluated at 2 m above mudline for both the system with and without metamaterials. The bottom panel is a zoom-in version of the top panel.

3. Madsen P.T., Wahlberg M., Tougaard J., Lucke K. and Tyack P. Wind turbine underwater noise and marine mammals: implications of current knowledge and data needs, *Marine Ecology Progress Series*, **309**, 279–295, (2006).

4. 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), 1772–1790, (2021).

5. Peng, Y., Jarquin Laguna, A. and Tsouvalas, A. A multi-physics approach for modelling noise mitigation using an air-bubble curtain in impact pile driving, *Frontiers in Marine Science*, **10**, (2023).

6. 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), 3544–3554, (2015).

7. Tsouvalas, A. and Metrikine, A. V. Structure-borne wave radiation by impact and vibratory piling in offshore installations: From sound prediction to auditory damage, *Journal of Marine Science and Engineering*, **4** (3), (2016).

8. Paiva, E. G., Salgado Kent, C. P., Gagnon, M. M., McCauley, R. and Finn, H. Reduced detection of Indo-Pacific bottlenose dolphins (Tursiops aduncus) in an Inner Harbour channel during pile driving activities, *Aquatic Mammals*, **41** (4), 455–468, (2015).

9. Graham, I. M., Pirotta, E., Merchant, N. D., Farcas, A., Barton, T. R., Cheney, B., Hastie, G. D. and Thompson, P. M. Responses of bottlenose dolphins and harbor porpoises to impact and vibration piling noise during harbor construction, *Ecosphere*, **8** (5), (2017).

10. Molenkamp, T., Tsouvalas, A. and Metrikine, A. The influence of contact relaxation on underwater noise emission and seabed vibrations due to offshore vibratory pile installation, *Frontiers in Marine Science*, **10** (March), 1–14, (2023).

11. 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** (January), 118298, (2024).

12. 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).

13. Fărăgău, A. B., de Oliveira Barbosa, J. M., Metrikine, A. V. and van Dalen, K. N. Dynamic amplification in a periodic structure with a transition zone subject to a moving load: three different phenomena, *Mathematics and Mechanics of Solids*, (1), 1–21, (2022).