Slow-fast dynamics in vibratory pile driving: field tests and numerical modelling

Athanasios Tsetas*, Apostolos Tsouvalas* and Andrei V. Metrikine *
*Faculty Of Civil Engineering and Geosciences, Delft University of Technology, The Netherlands

Summary. This paper presents a study of vibration-based pile driving methods on the basis of field data and numerical modelling. Based on field data from an extensive field test campaign and existing results found in the relevant literature, the vibratory pile installation is shown to constitute a slow-fast dynamical process. Moreover, a three-dimensional numerical model for the analysis of vibratory pile driving is presented, comprised by a thin cylindrical shell (pile), a linear elastic layered half-space (soil) and a frictional interface. Based on the latter numerical model, the relevant experimental findings are discussed and compared in order to shed light into the complex pile-soil behavior during vibratory driving and the emergence of slow-fast pile motion.

Extended abstract

Presently, over 80% of the offshore wind turbines (OWTs) in Europe are founded on monopiles [1]. These foundations are most commonly installed by impact hammer, albeit this method poses a source of noise pollution, harmful to marine life, and can compromise the structural integrity and fatigue life of a monopile [2]. To this end, environmentally friendly alternatives are investigated for offshore monopile installation, such as vibratory methods. The standard axial vibratory pile driving is used onshore for decades, with advantageous features such as high installation speed and low axial pile loading. However, in the offshore industry the use of the vibratory driving technique is limited, due to the lack of field data and knowledge gaps related to the complex pile-soil behaviour during installation and the post-installation effects.
To further the potential of vibration-based methods a new technology – the Gentle Driving of Piles (GDP) – has been proposed by TU Delft [3]. The GDP method is based on simultaneous application of low-frequency/axial and high-frequency/torsional vibrations at the pile head and aims to improve installation performance and reduce underwater noise emissions. Medium-scale field tests have been performed at Maasvlakte II site, at the port of Rotterdam (see Fig. 1), in which different pile installation methods were investigated, with a focus on the classical vibratory and GDP methods.

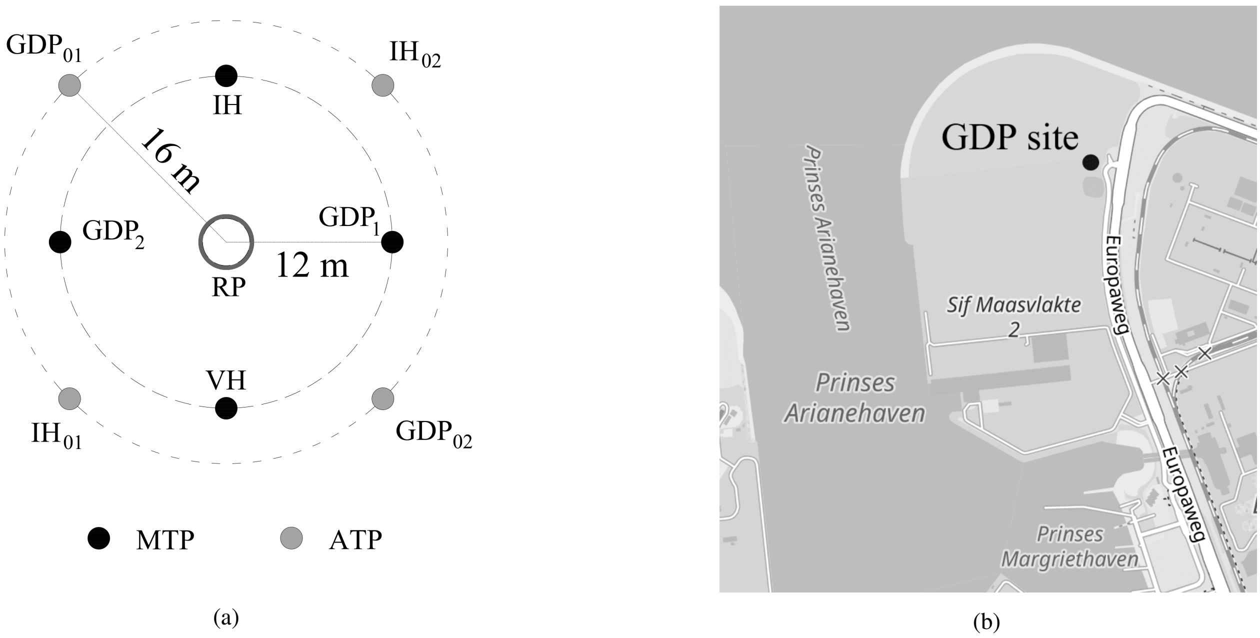

Figure 1: (a) Test pile layout and (b) GDP test site.

In this paper, the vibratory and GDP installation methods are studied and the emergence of pile penetration into the soil medium as a slow-fast dynamical process is presented. In principle, the pile is forced by the combination of a periodic excitation at the pile top and the self-weight of the pile and the vibratory device. The resulting motion can be distinguished into a slow motion of the rigid body type and a fast motion characterized by the fundamental driving frequency and its super-harmonics. The main findings of the installation tests and the comparison of the two methods are discussed. Furthermore, a three-dimensional model for the analysis of pile installation for the considered methods is presented. Specifically, the pile is modelled as a thin cylindrical shell, according to the Love-Timoshenko theory [4], in order to properly capture the pile motion. The soil continuum is modelled as an elastic layered half-space, by means of the thin layer method (TLM), augmented with perfectly matched layers (PMLs) [5]. Finally, a frictional interface is used to couple the pile-soil system and permit pile slip. The numerical solution of the presented model is based on the alternating frequency-time harmonic balance method, in order to address the problem with a computationally fast approach.

In the topic of vibratory pile driving two classes of models are employed, i.e. the engineering-oriented one-dimensional models and the advanced research-oriented three-dimensional models. The former describe in a simplistic manner the non-linear pile-soil interaction during driving, neglecting effects such as the non-local and frequency dependent soil-reaction. The latter models -although more rigorous- rely on a multitude of parameters for the soil constitutive model, which cannot be customarily obtained by *in situ* measurements. Therefore, their use in engineering practice remains unfeasible, especially considering their excessive computational cost. The model presented in this work aims to bridge the gap between the two classes, by employing a more physically sound soil reaction with reduced semi-empirical soil parameters, while retaining the computational efficiency required for use in engineering practice. To that end, the predictions of the developed model are validated with the field data; the latter is of great essence for the GDP method, which cannot be analysed by other existing numerical models.

Figure 2: Installation test of a pile driven by the GDP method.

References

[1] Ramírez, L., Fraile, D. and Brindley, G. (2021). Offshore wind in europe: Key trends and statistics 2020. *WindEurope*.

[2] Tsouvalas, A. (2020). Underwater noise emission due to offshore pile installation: A review. *Energies*, **13**(12), 3037.

[3] Metrikine, A.V., Tsouvalas, A., Segeren, M.L., Elkadi, A.S., Tehrani, F.S., Gómez, S.S., Atkinson, R., Pisanó, F., Kementzetzidis, E., Tsetas, A., Molenkamp, T., van Beek, K. and de Vries, P. (2020) GDP: A new technology for Gentle Driving of (mono)Piles. In *Proceedings of the 4th International Symposium on Frontiers in Offshore Geotechnics, Austin, TX, USA* (pp. 16-19).

[4] Timoshenko, S. P., and Woinowsky-Krieger, S. (1959). Theory of plates and shells. McGraw-hill.

[5] de Oliveira Barbosa, J. M., Park, J., and Kausel, E. (2012). Perfectly matched layers in the thin layer method. *Computer methods in applied mechanics and engineering*, **217**, 262-274.