Proceedings of ISFOG 2025
5TH INTERNATIONAL SYMPOSIUM ON
FRONTIERS IN OFFSHORE GEOTECHNICS
Nantes, France | June 9-13 2025

ISBN 978-2-85782-758-0

Effects of installation process on lateral bearing behaviour of monopiles for offshore wind turbines

N. Letizia
KU Leuven, Bruges, Belgium

G. Anoyatis
KU Leuven, Bruges, Belgium

M. Spyridis, S. François
KU Leuven, Leuven, Belgium

L. Simonin, H. Rattez
UC Louvain, Louvain-la-Neuve, Belgium

F. Collin
University of Liege, Liège, Belgium

*george.anoyatis@kuleuven.be

ABSTRACT: Monopile foundations are the predominant solution for Offshore Wind Turbines (OWT's). They are installed using methods that involve jacking, impact hammering and vibratory driving. This study aims to investigate the effects of the installation process on the surrounding soil mass, and its impact on the lateral response and capacity of monopiles in sands. In view of the proposed analyses, a large deformation model using the Coupled Eulerian Lagrangian (CEL) method, and a small-strain Finite Element Method (FEM) model are developed in Abaqus, for the simulation of the jacked pile installation and the monotonic lateral response, respectively. In particular, the nonlinear stress-state response of the sand is simulated using the hypoplastic law with intergranular strain. The proposed models are validated against data obtained from centrifuge experimental tests in dry fine silica sand, available in the literature. The findings from the large deformation model show that the initial soil conditions for lateral monopile response are significantly affected by the jacked installation method. For this purpose, the stress-history and the state of the sand around the pile are tracked, and the lateral behaviour of the jacked pile is compared with the wished in place pile.

Keywords: Offshore wind turbine foundations; Monopile installation; Large deformations; Pile lateral response; Numerical modelling.

1 INTRODUCTION

Offshore wind energy plays a crucial role in the global transition toward green energy, with numerous countries investing in extensive wind farms to generate sustainable, multi-gigawatt electricity supplies. Reducing costs is essential to make offshore wind economically viable, and a significant portion of these costs, approximately 30%, is tied to foundation design and installation (Gavin et al., 2016). Monopiles, large-diameter steel tubes driven into the seabed, are the most common foundation type for offshore wind turbines (OWTs). However, conventional design methods, such as the p-y approach, were developed for slender piles and often lack applicability for the larger-diameter monopiles used in OWTs, especially under lateral loads (Abadie et al., 2019; Achmus et al., 2009, 2005).

Recent projects like PISA and REDWIN have advanced monopile design by developing revised p-y curves and macro-element models for lateral response prediction (Byrne et al., 2019; Skau et al., 2018). However, the majority of numerical simulations (Burd et al., 2020; Taborda et al., 2019) assume a “wished-in-place” installation without accounting for the soil disturbances and stress alterations induced by pile driving, which can significantly affect the pile's response to lateral loads. Experimental studies (Dyson and Randolph 2001; Achmus et al. 2020; Fan et al. 2021a) highlight that installation can notably impact initial stiffness and bearing capacity, pointing out the importance of including installation effects in lateral load prediction models.

Given these challenges, more research is needed to establish robust design guidelines that consider the effects of different installation methods on lateral pile response. Numerical investigations by Heins and Grabe (2017) and Murphy et al. (2018) show the potential of using numerical methods to explore the effect of pile installation on the subsequent lateral response. This paper presents numerical findings on the effect of the jacking installation process on the lateral response of monopiles in sands. For the simulation of the pile installation process, the coupled Eulerian–Lagrangian (CEL) method available in the finite element software ABAQUS is used. Following the installation, the resulting soil state is transferred to a purely Lagrangian model, and the lateral loading of the pile is simulated using the hypoplastic model with intergranular strain (von Wolffersdorff, 1996; Niemunis and Herle, 1997).

2 NUMERICAL MODELS VALIDATION

2.1 Centrifuge tests

Monotonic loading tests were carried out at the Geo-engineering Section of TU Delft on test piles installed in dense Geba sand (Li et al., 2022).

All the tests in this study were performed at 100 g. The instrumented pile named P1 in the reference study was jacked to its final penetration depth at 1g, to reproduce a wished in place condition. The data from such a test were used to validate the numerical model for lateral response. In the experiment named P2, the pile was first jacked at 1g to an initial depth of 2 times the pile diameter. The installation was completed in-flight at 100g, to experimentally replicate jacking installation at the prototype scale. This allowed the validation of the numerical model developed for the installation.

2.2 Soil constitutive model and material parameters

Geba sand is a silica sand with sub-angular grains. It has a specific gravity, G_S, of 2.67. The minimum, e_{min}, and maximum, e_{max}, void ratios have been measured as 0.64 and 1.07, respectively. In the reference case study (Li et al., 2022), test piles were installed in dense dry Geba sand with relative density, D_R = 80%. The initial void ratio in the deposit is assumed to vary with depth according to Equation 1:

$$e = e_0 exp\left[-\left(\frac{3p'}{h_s}\right)^n\right] \quad (1)$$

where: e_0 is the void ratio at p'=0 and it is assumed equal to 0.77, thus resulting in e_0 ranging between 0.77 and 0.72 for depths ranging from 0 to 9m.

The hypoplastic model enhanced by the intergranular strain concept has been selected for the present study. The hypoplastic model requires 8 parameters that are listed in Table 1 along with their description.

Table 1: Parameters of the hypoplastic model (von Wolffersdorff, 1996).

Parameter	Description
$\boldsymbol{\phi_c}$ [°]	Critical state friction angle, from critical state soil mechanics
$\boldsymbol{h_s}$ [GPa] $\boldsymbol{n}$ [-]	Control the shape of the limiting void ratio curves and any other normal compression line (NCL) followed in asymptotic compression
$\boldsymbol{e_{i0}}$ [-]	Sets the position of the theoretical isotropic compression line (ICL) in the p'-e plane
$\boldsymbol{e_{c0}}$ [-]	Sets the position of the critical state line (CSL) in the p'-e plane
$\boldsymbol{e_{d0}}$ [-]	Sets the position of the minimum void ratio line in the p'-e plane
$\boldsymbol{\alpha}$ [-]	Controls the actual value of the peak friction angle, ϕ_p; in particular, an increase of α increases ϕ_p
$\boldsymbol{\beta}$ [-]	Controls both the bulk and shear stiffness; in particular, an increase of β increases the soil stiffness

The implementation of intergranular strain requires five additional parameters, briefly described in Table 2, following Mašin (2019).

Table 2: Parameters of the intergranular strain extension of the hypoplastic model (Niemunis and Herle, 1997).

Parameter	Description
$\boldsymbol{m_R}$ [-]	Controls the magnitude of the small strain shear modulus, G_0, in the initial loading and upon a 180° change in the direction of the strain path
$\boldsymbol{m_T}$ [-]	Controls the magnitude of G_{90}, that is the initial shear stiffness after a 90° change in the strain path direction
$\boldsymbol{R}$ [-] $\boldsymbol{\beta_r}$ [-]	Controls the horizontal position of the stiffness degradation curve within the G-lnε_s diagram
$\boldsymbol{\chi}$ [-]	Controls the rate of stiffness decrease with strain

The material parameters of the hypoplastic model for Geba sand are provided in literature (Mašin, 2017).

In the present study, they were recalibrated to get satisfactory agreement of computed monotonic monopile response with the measured from centrifuge tests (Li et al., 2022). Both parameter sets are summarised in Table 3.

Table 3. Parameters for Geba sand of the hypoplastic model with intergranular strain (von Wolffersdorff, 1996; Niemunis and Herle, 1997).

Parameter	Mašin (2017)	This study
ϕ_c [°]	34	34
h_s [GPa]	2.5	2.5
n [-]	0.3	0.3
e_{i0} [-]	1.28	1.28
e_{c0} [-]	1.07	1.07
e_{d0} [-]	0.64	0.64
α [-]	0.11	0.11
β [-]	2.0	0.75
m_R [-]	5.5	5.5
m_T [-]	3.9	3.9
R [-]	10^{-4}	10^{-4}
β_r [-]	0.3	0.3
χ [-]	0.7	0.7

2.3 Finite element model for lateral pile response

The numerical analyses were conducted using the finite element (FE) software ABAQUS/Standard (Dassault, 2022). Considering the symmetry of the geometric model and of the loading condition, a semicylindrical model was developed. Figure 1 presents the finite-element mesh, which consists of 40848 8-noded reduced integration elements with hourglass control available in ABAQUS element library. The pile foundation was modelled as a thin embedded hollow cylinder by solid elements. The cross-section of the pile is circular, with an external diameter, $D = 1.8$ m, a wall thickness of $t_w = 0.03$ m and an embedded length below seabed of $L = 9$ m ($5D$). The pile extends above the seabed by 14.4 m ($8D$). The material behaviour of the monopile was assumed to be linear elastic, with the Young's modulus $E_p = 210$ GPa and the Poisson's ratio $\nu_p = 0.3$.

The size of the discretized model results from a sensitivity analysis to guarantee the accuracy of the results and the efficiency of the computation. The diameter of the domain, L_m, was assumed equal to $12D$. The bottom boundary of the model was taken $4.5D$ below the monopile base, so that the height of the domain, H_m, is $L + 4.5D$. In this model, the nodes belonging to the base were restrained against vertical and horizontal displacements; displacements in the horizontal plane were restrained on the lateral surface; the symmetric plane was constrained in the normal direction.

The FE analyses were conducted in three calculation steps. The first step of FE analyses was a geostatic step. The coefficient of earth pressure at rest, k_0, has been estimated using Jaky's formula $k_0 = 1 - \sin\phi_c$ (Jaki, 1944).

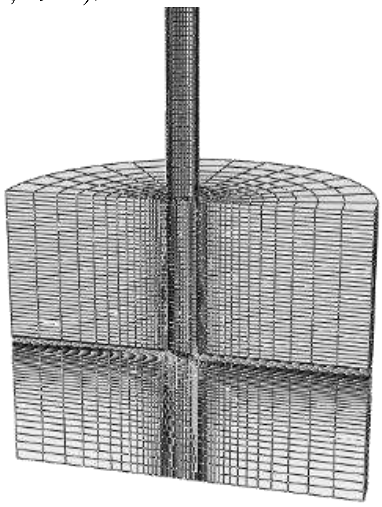

Figure 1: Finite element model for the lateral response of a monopile.

A "wished-in-place" procedure was modelled in the simulation and fully drained conditions have been considered. The dry soil unit weight is $\gamma_d = 15.5$ kN/m^3. In the second loading step, the weight of the pile was applied. In the last step of the analyses, a horizontal displacement, u, was applied at the pile head, at a distance, h, from the ground surface, that represents the eccentricity of the horizontal load, H, that will act at the level of the pile head.

To describe the tangential interaction of contacting surfaces, the friction coefficient, μ, was set equal to 0.3 on the shaft and the tip areas, recommended in literature for the simulation of sand-pile interactions (Lascarro et al., 2024).

2.4 Finite element model for pile installation

The procedure for developing the numerical model used for simulating pile installation is described in this section. For this analysis, the Coupled Eulerian-Lagrangian (CEL) method is adopted. The numerical model is shown in Figure 2. To avoid reflections at the boundaries of the finite soil domain, a relatively large domain is used, specifically with a width of 28 m and a height of 40 m. The Eulerian domain also includes void elements, which are material-free above the red line shown in Figure 2. Below the red line, elements are material-filled to represent the soil domain, allowing soil to be displaced even in initially void spaces. The total number of elements in the soil domain is 286405. The rigid pile penetrates the soil, starting from the depth of $2D$, at a constant rate of 5 m/s, a rate that has been previously adopted for simulating pile installation (Fan et al., 2021; Spyridis & Lopez-Querol, 2024). In the initial condition, the soil inside the monopile is not plugged. The lateral earth pressure and the interface friction coefficient considered equal to the values of the small strain finite element model developed for the lateral response analysis.

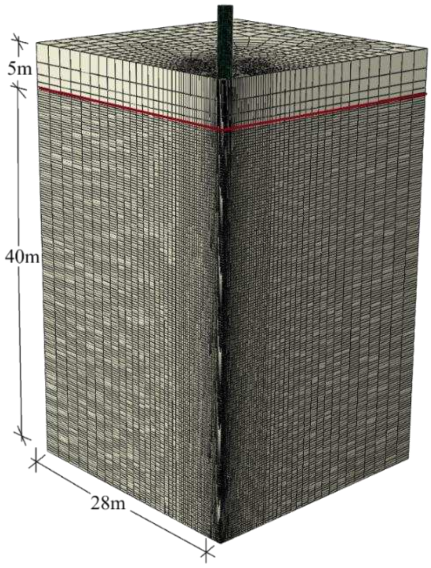

Figure 2: Coupled Eulerian-Lagrangian (CEL) model for the pile installation

3 NUMERICAL RESULTS & DISCUSSION

3.1 Validation of numerical models

The material parameters for Geba sand previously calibrated by Mašin (2017) and reported in Table 3 have been considered in the numerical model used for simulating pile installation.

In view of a rigorous numerical procedure, the initial conditions described by Li et al. (2022) are prescribed in the CEL model, namely, the depth of the pile tip at the beginning of the analysis, relative density etc. It is recalled that the pile tip at the beginning of the procedure is equal to 2D. Hence, from the very first steps of the analysis, a relatively high installation force is computed, which is very well captured from the numerical model in comparison with the experimental data, as shown in Figure 3. Noticeable movement at the pile is observed when the installation force is greater than 5MN. As the pile tip advances at greater depths, the numerical model continues to have an overall excellent agreement against experimental data. The installation force required for the pile to reach at the target depth of 9m is approximately equal to 20MN.

To simulate the monotonic loading test P1 reported by Li et al. (2022), numerical analyses were performed with the same material parameters.

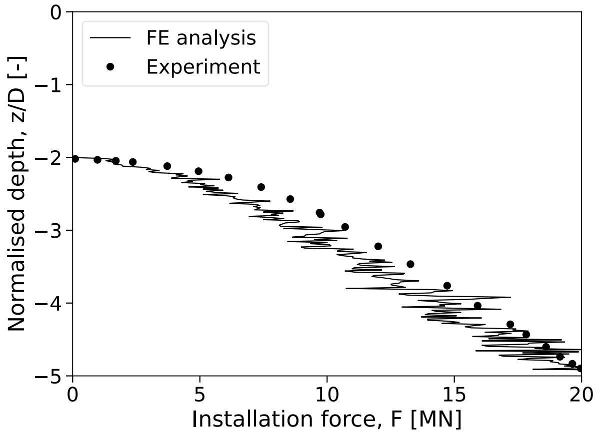

Figure 3: Installation force with depth for a monopile in dense Geba sand, comparison between centrifuge and numerical results.

Figure 4 plots the comparison between the numerical results of this study (FE analysis) and the reference experimental results (Experiment P1).

The results are reported in terms of horizontal load versus the normalised horizontal displacement exhibited by the pile at the mudline.

It can be observed in Figure 4 that the numerical model exhibits significantly larger initial stiffness and lateral resistance than the centrifuge model.

In order to better reproduce the soil-pile interaction observed in the centrifuge test, the set of parameters for the hypoplastic model has been recalibrated as reported in Table 3. The parameters directly related to the sand properties, such as the three void ratios states (minimum, critical and maximum) and ϕ_c, were not changed. The recalibration has focused on β, considering that it controls the soil stiffness.

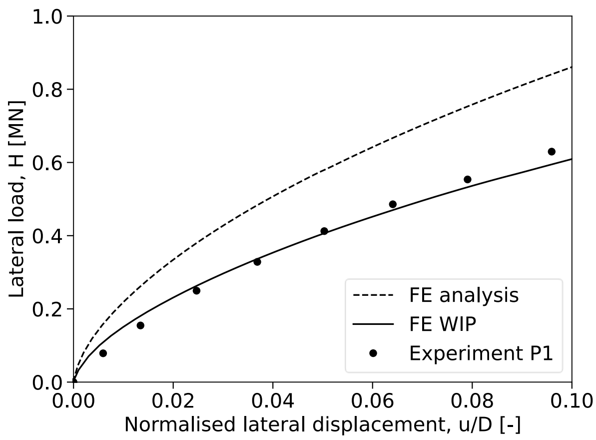

Figure 4: Lateral load-displacement curves for a wished-in-place monopile embedded in dense Geba sand, comparison between centrifuge and numerical results.

Numerical results (FE WIP) are compared with the experimental data in Figure 4. A good agreement between numerical and centrifuge results may be observed.

3.2 Installation effect on the pile lateral response

During the penetration of the pile, the state of the sand changes as expected. This is shown in Figure 5, where radial stresses and the void ratio are plotted at the end of the pile installation. At the conclusion of this analysis, radial stresses reach very high levels, especially beneath the pile tip and within the inner soil region of the pile. In this area, the soil mass densifies, and soil plugging is noticed, while dilation occurs in the surrounding soil mass around the jacked pile. This outcome aligns with findings from previous research on the jacking installation procedure (Fan et al., 2021; Spyridis & Lopez-Querol, 2024).

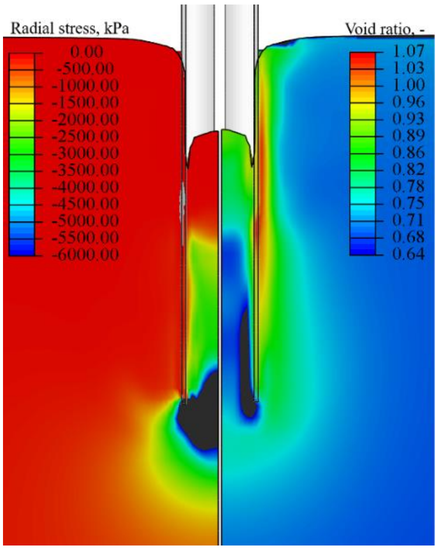

Figure 5: Numerically derived radial stresses and void ratio distribution around the pile at the end of the installation.

To take into account the effect of the installation process on the lateral response of the pile, the state variables of the soil after the installation are transferred to the small-strain FE model. The numerical model for the installation phase is one-quarter of the full model, while for the lateral loading phase half of the full model was considered. Therefore, the installation results were mirrored and subsequently interpolated.

In addition to void ratio, the intergranular strain tensor is considered for the transfer. Figure 6 shows the comparison of the lateral load-displacement curves from the centrifuge tests reported by Li et al. (2022) and the ones derived by simulations with (FE Jacked) and without (FE WIP) incorporation of the installation- induced state variables changes. The key distinction between Experiment P1 and Experiment P2 lies in the installation process, as described in Section 2.1. The pile installed in-flight (P2) exhibits both larger initial stiffness and lateral resistance than that of the pile pre-installed at 1g (P1), as observed by Li et al. (2022), as a result of sand densification and retention of high mean effective stresses caused by the installation process.

In Figure 6, it can be observed a slight increase in the lateral bearing capacity of the pile numerically predicted, as a result of the soil compaction within the inner soil region of the pile and the intergranular strain deformation distribution.

However, it is evident that such an increase is negligible and is not comparable to the strength and stiffness gain of the soil-pile system observed in the experiment P2. Therefore, it results necessary to import from the CEL model also the stress state after the installation process.

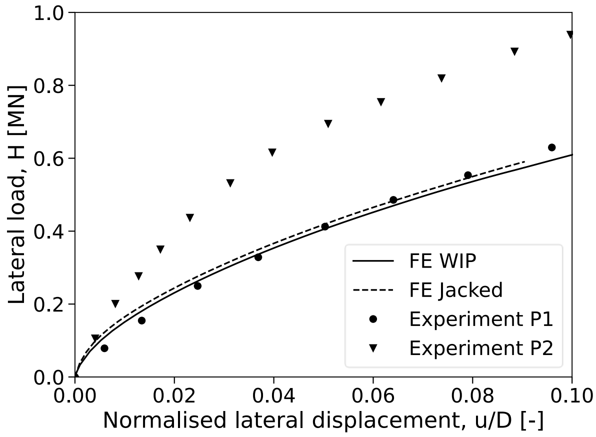

Figure 6: Lateral load-displacement curves for monopile jacked at 1g (P1) and at 100g (P2) in dense Geba sand compared with numerical results with (FE WIP) and without (FE Jacked) the installation effect.

Moreover, it must be recognized that the model pile, consistently with the tested pile, is characterised by a relatively low D/t_w value of 60, whereas typical D/t_w ratios for monopiles in practice are 125÷150. This may explain the significant effect produced by the jacking process to the lateral pile behaviour.

4 CONCLUSIONS

In this study, the impact of a monopile installation method on the lateral response of the offshore wind turbine foundation was investigated using advanced numerical modelling techniques implemented in the finite element software ABAQUS. By employing the Coupled Eulerian-Lagrangian method for jacking installation simulations and small-strain Finite Element modelling for lateral response analysis, the research highlighted the critical role of installation-induced soil state alterations. The FE models were calibrated against available centrifuge test data for model piles jacked in dense sand. The hypoplastic constitutive law with intergranular strain was adopted to simulate the nonlinear behaviour of the soil. The results demonstrated that the studied installation method significantly influences the state of the sand. In detail, the pile installation analysis, illustrates that the initial void ratio of the sand is alternated, with the surrounding soil mass to experience dilation. On the other hand, soil plugging and densification is noticed at the inner part of the pile. As the pile advances, high stresses are induced in the sand. Hence, at the end of the installation, the region where high stresses are recorded is beneath the pile tip.

Subsequent monopile behaviour under lateral loading was studied, after the effects induced by pile installation were imported. Nevertheless, the numerical results highlighted a discrepancy with experimental data, suggesting that further refinements are needed to fully capture experimentally observed soil-pile interactions into the numerical model. Further investigations are also required to extend this study to different installation processes and pile geometries.

AUTHOR CONTRIBUTION STATEMENT

First Author: Numerical modelling, Data analysis, Writing Original draft. **Second Author**: Numerical modelling, Data analysis. **Additional Authors**: Supervision. **Last Author**: Supervision, Funding acquisition, Reviewing.

ACKNOWLEDGEMENTS

The academic consortium KU Leuven – UCLouvain – ULiege is grateful for the financial support provided by the Energy Transition Fund (Energietransitiefonds, ETF2022), via the project SAGE-SAND Soil ageing around OWT foundations – from operational response to decommissioning.

REFERENCES

Abadie, C. N., Byrne, B. W., Houlsby, G. T. (2019). Rigid pile response to cyclic lateral loading: Laboratory tests. *Geotechnique,* 69(11), pp. 863–876. http://doi.org/10.1680/jgeot.16.P.325

Achmus, M., Abdel-Rahman, K., Peralta, P. (2005). On the design of monopile foundations with respect to static and quasi-static cyclic loading. In: *Copenhagen Offshore Wind,* pp. 1–9.

Achmus, M., Kuo, Y.-S., Abdel-Rahman, K. (2009). Behavior of monopile foundations under cyclic lateral load. *Computers and Geotechnics,* 36, pp. 725–735. http://doi.org/10.1016/j.compgeo.2008.12.003

Achmus, M., Schmoor, K. A., Herwig, V., & Matlock, B. (2020). Lateral bearing behaviour of vibro-and impact-driven large-diameter piles in dense sand, *geotechnik*, 43(3), pp. 147-159. https://doi.org/10.1002/gete.202000006

Burd, H. J., Taborda, D. M., Zdravković, L., Abadie, C. N., Byrne, B. W., Houlsby, G. T., Potts, D. M. (2020). PISA design model for monopiles for offshore wind turbines: application to a marine sand. *Géotechnique,* 70(11), pp. 1048–1066. http://doi.org/10.1680/jgeot.18.P.277

Dyson, G. J., Randolph, M. F. (2001). Monotonic lateral loading of piles in calcareous sand. *Journal of Geotechnical and Geoenvironmental Engineering,* 127(4), pp. 346–352. http://doi.org/10.1061/(ASCE)1090-0241(2001)127:4(346)

Fan, S., Bienen, B., Randolph, M. F. (2021a). Centrifuge study on effect of installation method on lateral response of monopiles in sand. *International Journal of Physical Modelling in Geotechnics,* 21(1), pp. 40–52. http://doi.org/10.1680/jphmg.19.00013

Fan, S., Bienen, B., Randolph, M. F. (2021b). Effects of monopile installation on subsequent lateral response in sand. I: Pile installation. *Journal of Geotechnical and Geoenvironmental Engineering,* 147(5), 04021021. http://doi.org/10.1061/(ASCE)GT.1943-5606.0002467

Fan, S., Bienen, B., Randolph, M. F. (2021c). Effects of monopile installation on subsequent lateral response in sand. II: Lateral loading. *Journal of Geotechnical and Geoenvironmental Engineering,* 147(5), 04021022. http://doi.org/10.1061/(ASCE)GT.1943-5606.0002504

Li, Q., Gavin, K., Askarinejad, A., Prendergast, L. J. (2022). Experimental and numerical investigation of the effect of vertical loading on the lateral behaviour of monopiles in sand. *Canadian Geotechnical Journal,* 59(5), pp. 652–666.

Mašin, D. (2017). Calibration of sand hypoplastic model on Geba sand data. *Technical Report.*

Mašín, D. (2019). Modelling of soil behaviour with hypoplasticity. *Springer Series in Geomechanics and Geoengineering,* Ó Springer Nature Switzerland AG. http://doi.org/10.1007/978-3-319-94199-3

Niemunis, A., and Herle, I. (1997). Hypoplastic model for cohesionless soils with elastic strain range, Mechanics of Cohesive-frictional Materials, 2(4), pp. 279–299. http://doi.org/10.1002/(SICI)1099-1484(199710)2:43.0.CO;2-8

Spyridis, M., Lopez-Querol, S. (2024). Installation of open-ended piles: A numerical investigation into the effects on the state of silica sand, *Soils and Foundations*, 64(3), pp. 101458. http://doi.org/10.1016/j.sandf.2024.101458

Wolffersdorff, P.-A. (1996). A hypoplastic relation for granular materials with a predefined limit state surface, Mechanics of Cohesive-frictional Materials, 1(3), pp. 251–271. http://doi.org/10.1002/(SICI)1099-1484(199607)1:33.0.CO;2-3