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Monopile-sand interaction under lateral cyclic loading: simulation of centrifuge test data using a cyclic 1D p-y model

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ABSTRACT: The response of monopiles to lateral loading has attracted considerable research interest in recent years. As monopile foundations are exposed to ever-harsher environmental conditions, the engineering tools used for their simulation should continually update and improve. Recently, the challenge of simulating the behaviour of monopiles under lateral loads has been addressed to a significant extent through a combination of numerical modelling and experimental data. Although monotonic response calculations are still relevant to monopile design, it should be acknowledged that offshore environmental loads are inherently cyclic. To improve the engineering tools for the simulation of cyclic monopile behaviour and our understanding of the relevant geotechnical mechanisms, this study presents and discusses the outcome of advanced 1D cyclic soil reaction modelling of monopile-soil interactions employed to simulate centrifuge data conducted as part of the MIDAS research project. The memory-enhanced p-y model proves capable of simulating cyclic ratcheting behaviour in complex loading histories, which promotes the discussion for the evolution of relevant soil reaction mechanisms during cyclic loads. Finally, preliminary calibration strategies for the employed cyclic soil reaction models are presented.

1 Introduction

In an attempt to limit the impact of humankind on the environment, governments from countries around the globe have ratified the following landmark agreements: (i) Montreal Protocol, 1987; (ii) UN Framework Convention on Climate Change (UNFCCC), 1992; (iii) Kyoto Protocol, 2005, (iv) Paris Agreement, 2015. At the end of 2019, the European Union (EU) complemented these efforts by sanctioning the European Green Deal, aiming to reduce the carbon footprint of its member states and achieve no-net greenhouse gases by 2050. To date, offshore wind energy is expected to contribute substantially to this transition towards carbon neutrality.

Until 2050, the global forecasted capacity is expected to reach or even surpass 2000 GW (Lee et al., 2021), with Asia expected to lead the way in the development of installations of offshore wind turbines, followed by Europe, North America, the Pacific, South America, and Africa. To facilitate such an extraordinary transition towards green energy, considerable research efforts are being devoted to closing knowledge gaps through innovation in all areas of offshore wind science and engineering. Such areas include the advance of installation (and future decommissioning) technologies for ever larger offshore wind turbines (OWTs) and their foundations (Tsetas, et al., 2023; Kementzetzidis et al., 2023b).

Presently, the majority of offshore wind farms have been commissioned in Northern Europe (Lee, Zhao, & Dutton, 2021). The relatively shallow coastline of the northern European countries has promoted the large diameter monopile as the most selected foundation option (i.e., tubular steel piles with a diameter in the range from 5 to 11 m and a low ratio between embedded length and diameter typically between 3 and 6). With 80% of all European offshore wind turbines (more than 4600 in total) supported by monopiles (Ramirez et al., 2021), the foundation concept has matured enough, for the engineering challenges to become apparent to the offshore wind industry. Such concerns primarily relate to the monopile installation procedures but also the long-term behaviour of these enormous foundations.

The design of monopiles against lateral environmental loading (concerning the long-term behaviour of monopiles) is usually conducted by modelling the soil-monopile interactions via the 1D p-y method. Based on the classical Winkler approach, the (mono)pile-soil system is simulated via a set of beam elements (for the pile) supported horizontally by independent, usually non-linear elastic (p-y) springs. Although conceptually simple, the challenge of the method lies in the appropriate selection of those p-y relationships that relate the spring reaction p, with the pile/soil deflection y along the pile length. Established p-y monotonic formulations were originally conceived (and proven in practice) for small-diameter, flexible piles used in the design of oil and gas platforms under monotonic loading (API, 2011; DNVGL (Det Norske Veritas GL), 2016). The method is currently under "revision" as it has been found inaccurate for the design of large-diameter, stubby (non-flexible) monopiles (Byrne, et al., 2019; Pisanò, et al., 2022) due to the disregard of reaction mechanisms considered inconsequential for the design of small-diameter flexible piles (Gerolymos & Gazetas, 2006; Byrne, et al., 2019). Finally, the method is currently under further development, to enable the simulation of complex cyclic loading time histories (Kementzetzidis et al., 2022; Pisanò, et al., 2022; White et al., 2022; Kementzetzidis, 2023a; Kementzetzidis et al. 2023c)

This study examines the applicability of the CPT calibrated cyclic p-y model originally proposed by Kementzetzidis et al., (2022), and later updated in Kementzetzidis, (2023a), and Kementzetzidis et al., (2023c) to simulate the measured response of a monopile to complex lateral loading histories, obtained from centrifuge tests conducted as part of the MIDAS project (Pisanò, et al., 2022). The aim of such endeavours is to improve existing engineering tools for the design of monopile foundations against lifetime environmental loading.

1.1 *Centrifuge tests on monopiles*

Centrifuge tests were carried out at the Geo-engineering section of TU Delft – organized as part the experimental campaign of the MIDAS project (Pisanò, et al., 2022). The beam centrifuge of the faculty (Figure 1) has a nominal diameter of 2.5m and can accelerate samples of maximum 30kg at 300g.

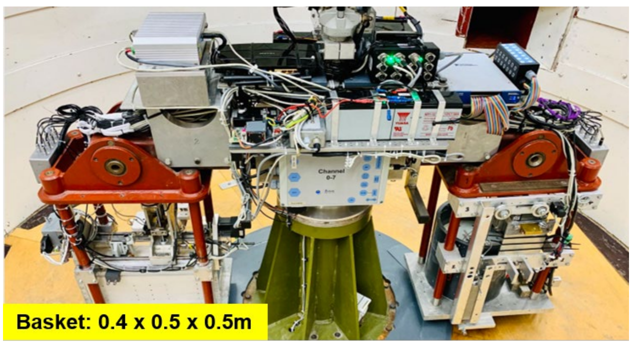

Figure 1. Geo-centrifuge at TU Delft

Particular to the MIDAS project, aluminium pipes of different geometries ($E = 71.7$GPa, $\nu = 0.33$) were first jacked at 1g in clean fine Geba sand (properties are summarised in Table 1) and then were laterally loaded both monotonically and cyclically for thousands of cycles at meaningful eccentricities for offshore wind conditions – monotonic and cyclic loads were applied to different samples with the same test features. More information concerning the centrifuge tests and the general scope of the project can be found in Pisanò, et al., (2022); Wang, et al., (2022).

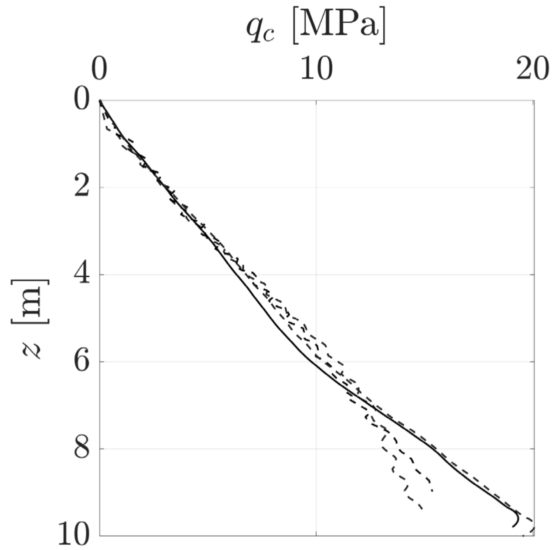

Figure 2. CPT cone resistance profiles (q_c) versus depth (z), from mini-CPT tests performed in clean fine sand of 80% relative density. Solid line denotes the CPT test used for the calibration of the 1D $p-y$ model

Table 1. Geba sand properties

Property	Sand
Median grain size, D_{50} (mm)	0.11
Curvature coefficient, Cc	1.24
Uniformity coefficient, C_U	1.55
Specific gravity, G_s	2.67
Maximum void ratio, e_{max}	1.07
Minimum void ratio, e_{min}	0.64
Critical friction angle, φ (°)	35

This study concerns the cyclic lateral loading tests conducted on a test pipe (scaled down monopile) at 100g, with the following geometrical features: embedded length $L_e = 9$m, diameter $D = 1.8$m, steel thickness $t = 0.1$m, and load eccentricity $e = 9$m ($L/D = 5,\ \ e/L = 1$). The presented test was performed in dry clean sand at relative density of 80%. For modelling and testing purposes, mini-CPT tests were conducted in-flight (Wang, et al., 2022), presented in Figure 2.

For the examined test case, the monopile was loaded laterally for a total of $N = 4000$ cycles of varying load amplitude. The loading programme is presented in Figure 3 with F_f the monotonic load necessary to displace the monopile for $0.1U/D$ -U the monopile displacement at the soil surface as obtained from separate monotonic centrifuge tests. During testing, the motion of the pile was measured at 8.5m and 4.5m above the soil surface, while down the embedded length, the mechanical strain (axial) was measured via 16 pairs of strain gauges installed at each side of the monopile. The test results are presented in Section 3 (Figures 6-8) alongside the 1D FE modelling efforts.

2 1D FE modelling of cyclic soil reactions

The salient features of the cyclic p-y model for sand used to simulate the monopile cyclic test at the TU Delft centrifuge are presented herein. For the sake of simplicity, the additional reaction mechanisms of distributed moment, base shear, and base moment (Gerolymos & Gazetas, 2006; Byrne, et al., 2019) are neglected in this study.

2.1 *1D p-y model*

Elasto-plastic modelling of soil reactions is carried out by combining in series a linear elastic spring and a non-linear hysteretic element as demonstrated by Kementzetzidis, (2023a), and Kementzetzidis et al., (2023c) . These p-y spring elements associate the local lateral deflection of the monopile ($y \rightarrow y = y_e + y_p$) with the soil reaction (p).

2.1.1 *Elastic component*

The mentioned linear elastic component is fully characterised by the corresponding value of the elastic stiffness K_e since:

$$p = K_e \cdot y_e \tag{1}$$

2.1.2 *Plastic component with cyclic ratcheting control*

The hysteretic and ratcheting features of cyclic monopile soil interaction, are introduced in the 1D simulations via the non-linear hysteretic, spring element -set in series with the elastic component, originally presented in Kementzetzidis et al., (2022). The model enables the accurate simulation of cyclic (drained) monopile-soil interaction in either dry or water-saturated sand. Under monotonic loading conditions, the plastic component of the 1D model exactly replicates the empirical relationship by Suryasentana & Lehane, (2014) between soil reaction (p) and the irreversible/plastic displacement, y_p:

$$p = p_u \left[1 - e^{-a\left(\frac{y_p}{D}\right)^m}\right] \tag{2}$$

where p_u represents the ultimate soil reaction force (per unit length), D is the pile diameter, while α and m are dimensionless shape parameters.

2.1.3 *Extension to cyclic loading*

The irreversible response to unloading-reloading cycles (hysteretic behaviour) is reproduced via a standard kinematic hardening mechanism, resulting in the following form of the plastic modulus, K_p:

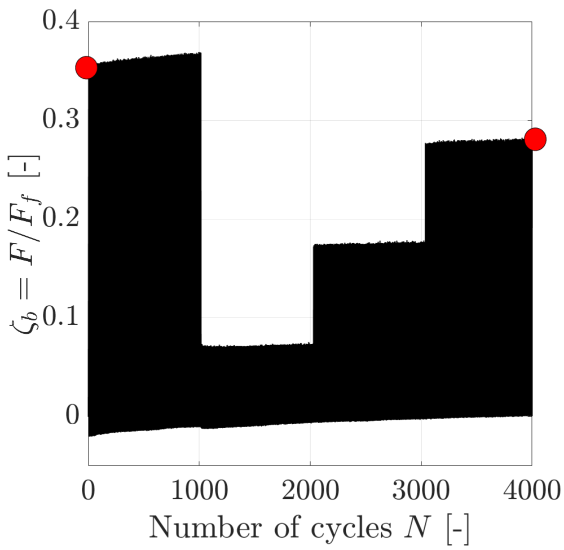

Figure 3. Applied load (normalized) versus number of cycles, for the loading programme on the tested monopile in the TU Delft centrifuge. F_f is the lateral load required to attain $U = 0.1D$ at the soil surface. Red dots denote the instants at which the bending moment profiles in Figure 7 were measured.

$$K_p = \frac{\alpha\, m}{D} \left|\overline{p_u} - p\right| \left|\frac{1}{a} \ln\left(\frac{\overline{p_u} - p}{\overline{p_u} - p_0}\right)\right|^{\frac{m-1}{m}} \tag{3}$$

in which $\overline{p_u} = p_u \, \mathrm{sgn}(\mathrm{d}p)$ with $\mathrm{d}p$ denoting the soil reaction increment within the current calculation step; p_0 represents a projection centre that takes the current p value whenever a soil reaction reversal occurs (i.e., whenever $\mathrm{sgn}(\mathrm{d}p)$ changes). Equation (3) produces a mechanical response that, under monotonic loading, reduces exactly to that established by Equation (2) in the case of monotonic loading.

2.1.4 *Ratcheting control mechanism*

Excessive ratcheting in the elasto-plastic p-y response under (asymmetric) cyclic loading is prevented by introducing a memory-enhancing mechanism. To this end, the model is endowed with an additional memory locus, whose size and location evolve depending on the cyclic loading history. The main role of the memory locus is to introduce an additional metric associated with the distance b_M between the current soil reaction and its projection onto the memory locus along the loading direction. b_M is exploited to enhance the definition of the plastic modulus in Equation (3) as follows:

$$K_{p,M} = K_p \, e^{\mu_0 \left(\frac{b_M}{b_{ref}}\right)^2} \quad (4)$$

where μ_0 is a scalar ratcheting-control parameter, and $b_{ref} = 2\, p_u$ is introduced for normalisation purposes. Equation (4) returns either $K_{p.M} = K_p$ when $b_M = 0$ (`virgin' loading conditions, i.e., when the soil reaction point lies on the memory locus) or $K_{p.M} > K_p$ when $b_M > 0$ due to an expansion of the memory locus induced by the previous loading history. In the latter case, the evolution of the tangent stiffness, and therefore the cyclic accumulation of lateral deflection, is controlled by the value of μ_0.

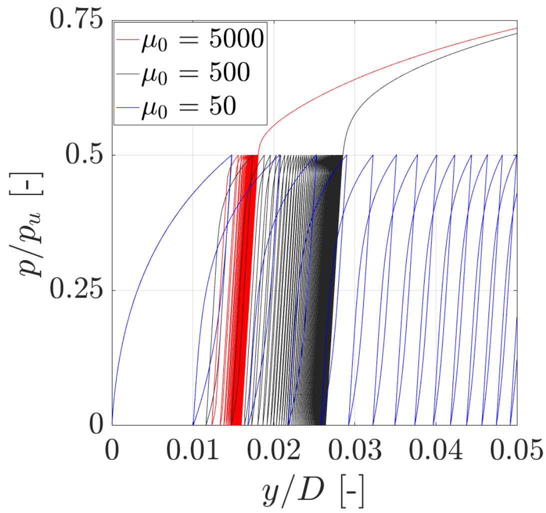

Figure 4a. Response of the elasto-plastic cyclic p-y model to one-way cyclic load for different values of the ratcheting parameter μ_0

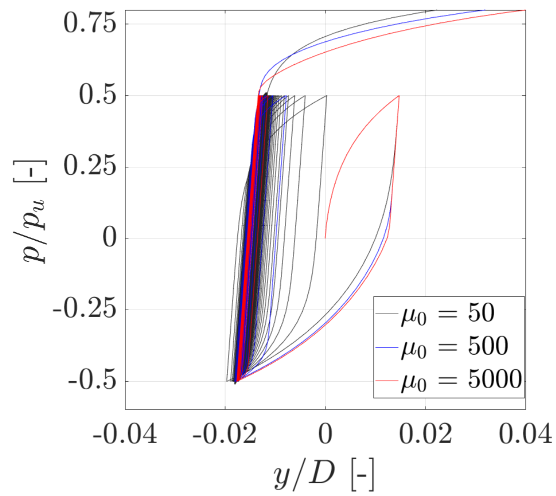

Figure 4b. Response of the elasto-plastic cyclic p-y model to two-way cyclic loads for different values of the ratcheting parameter μ_0

2.2 *Parameter calibration*

The behaviour of the above constitutive equations depends on the calibration of K_e, p_u, α, m and μ_0.

2.2.1 *Elastic component*

The calibration of K_e can be obtained following recent studies (Wan et al., 2021; Delavinia et al., 2023) which examine the elastic lateral behaviour of monopiles under static and dynamic (seismic) loading conditions. With the aid of 3D FE analyses, these studies have reported the equivalent elastic p-y relationships for monopile soil modelling at 1D which in turn can reproduce the behaviour calculated by the 3D models. Specifically, for p-y modelling of quasi-static soil-monopile interactions, Wan et al. (2021) identified an expression for uniform K_e (down the monopile embedded lenght), which relates the elastic spring stiffness K_e to the monopile aspect ratio (L/D) and the elastic shear modulus of the soil (G_0) and reads:

$$\frac{K_e}{G_0} = C_e = 33.73 - 12.56\frac{L}{D} + 1.98\left(\frac{L}{D}\right)^2 - 0.105\left(\frac{L}{D}\right)^3 \quad (5)$$

For the monopile examined in this study $(L/D = 5)$ the above expression yields $C_e = 7.22$. To infer the G_0 profile in this study, the methodology recommended by (Robertson, 2009) is employed. This methodology establishes a correlation between the q_c profile (illustrated in Figure 2) and G_0 in the subsequent manner. In elastic solids shear waves propagate at a velocity (V_s) proportional to their shear modulus G_0 and the material density (ρ):

$$G_0 = \rho V_s^2 \quad (6)$$

In Robertson (2009), V_s is estimated via the empirical correlation with the CPT cone resistance q_c:

$$V_s = \left(\alpha_{vs}\frac{q_c-\sigma_v}{p_a}\right)^{0.5} \quad (7)$$

where p_a is the atmospheric pressure used for normalization purposes, σ_v the total vertical stress (the correlation concerns drained CPT tests – obtained from CPTs in dry sand), and α_{vs} a dimensionless parameter depending on the soil type estimated from:

$$\alpha_{vs} = 10^{0.55 I_c + 1.68} \quad (8)$$

with $I_c = 1.31$ (values suggested for clean sands).

2.2.2 *Plastic component*

The constitutive parameters that relate to the monotonic monopile behaviour (p_u, α, m) are currently calibrated with the CPT-based calibration procedure for dry sand presented in Suryasentana & Lehane,

(2014) and Suryasentana & Lehane, (2016), and later modified in Kementzetzidis, et al. (2022; 2023c), Kementzetzidis, (2023a) namely:

$$\begin{cases} p_u = C_{pu}\,\sigma'_{v0} D \left(\frac{q_c}{\sigma'_{v0}}\right)^{0.67} \left(\frac{z}{D}\right)^{0.75} \leq q_c D \\ \alpha = C_a \left(\frac{z}{D}\right)^{-1.25} \\ m = 1 \end{cases} \tag{9}$$

In the originally studies (Suryasentana & Lehane, 2014; Suryasentana & Lehane, 2016) $C_{pu} = 2.4$, and $C_a = 8.9$ were recommended by the authors while in Kementzetzidis et al., (2022) and also in this study (Section 3) certain values of C_{pu}, C_a, and m were adapted to better fit the corresponding monotonic pile behaviour measured in the experiments.

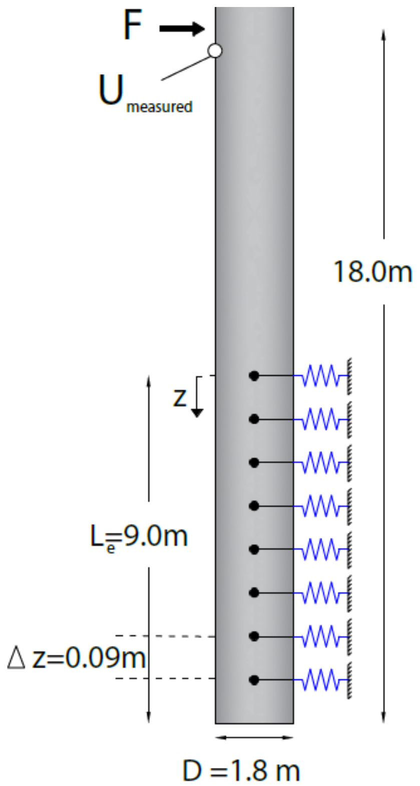

Figure 5. Reference pile subjected to the lateral cyclic loading in Figure 3

For the calibration of the cyclic ratcheting parameter μ_0, a similar CPT-based calibration strategy has been selected. Presently, the available procedures for the calibration of μ_0 are presented in Kementzetzidis et al., (2022; 2023c), and Kementzetzidis, (2023a) and are based on 1D FE simulations of field measurements from four identical piles installed employing various installation methods as part of the Gentle Driving of Piles (GDP) project (Metrikine, et al., 2020). In this study a similar procedure to Kementzetzidis, (2023a), Kementzetzidis et al., (2023c) is selected which associates μ_0 with the CPT cone resistance q_c and geotechnical features of the test as follows:

$$\mu_0 = C_{\mu 0} \left(\frac{q_c}{\sigma'_{v0}}\right)^{0.1} \left(\frac{\sigma'_{v0}}{\sigma'_{ref}}\right)^{0.75} \tag{10}$$

with σ'_{ref} the effective unit soil weight at $z = 1$m. In Kementzetzidis. (2023a), Kementzetzidis et al., (2023c), the dependance of $C_{\mu 0}$ on the geometric monopile features was not examined i.e., diameter, L/D, etc., since the tested piles were geometrically identical. In that study, $C_{\mu 0}$ was identified to reflect the geotechnical features of the pre-installation soil profile.

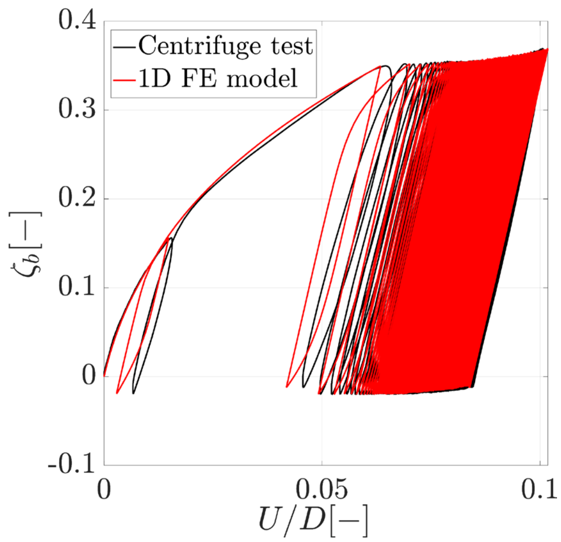

Figure 6a. Normalized load ($\zeta_b = F/F_f$) versus lateral normalized displacement trends form centrifuge measurements and numerical simulations at 8.5m above the soil surface

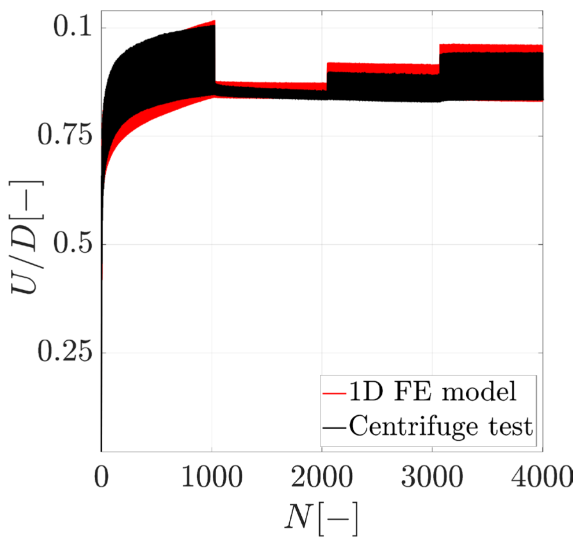

Figure 6b. Normalized displacement trends from centrifuge measurements and numerical simulations at 8.5m above the soil surface

The 1D p-y model presented above is well-suited to simulating the behaviour of cyclic soil reactions at various complex loading conditions. The response of the 1D model to one- and two-way cyclic loading along with the impact of the ratcheting parameter (μ_0) on the model's behavior are presented in Figure 4. The constitutive parameters are calibrated as if the spring elements are located at depth z=D at the examined monopile (Equations 5, 9).

2.3 *1D FE monopile-soil model set-up*

To simulate the reference pile loading tests, 1D FE analyses were set up using the OpenSees simulation platform (McKenna et al., 2010), in which the complete p-y model described above has been implemented. To this end, the tested monopile is simulated via a set of Timoshenko beam elements; to simulate soil-structure interaction effects the beam elements embedded in the soil are set in contact with a sequence of independent $p-y$ springs (Section 2.1) with a vertical spacing of 0.09m, Figure 5.

3 **Simulation results**

The constitutive parameters of the supporting p-y springs were initially selected and later adapted as necessary following the CPT-based procedures set by Equations 9-10 such as to provide a successful simulation of the test results. Specifically:

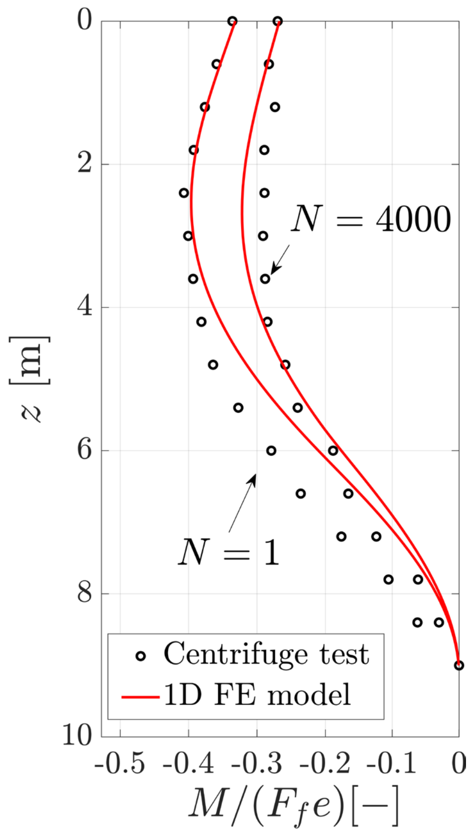

Figure 7. Measured and calculated normalized bending moment profiles (F_f is the load for $U/D = 0.1$ at the mudline and e the load eccentricity) at two instants during the loading programme as highlighted in Figure 3

- C_e (Equations 1, 5) was chosen to fit both the small strain and the unloading reloading stiffness of the monopile – the procedure to infer G_0 was described in Section 2.2.1;
- C_{pu}, C_a , and m (Equation 9) were selected to fit its monotonic behaviour;
- $C_{\mu 0}$ (Equation 10) was tuned to fit the accumulation of cyclic monopile deflection at the measurement locations (4.5m and 8.5m above the soil surface).

The aforementioned procedure led to slightly different values of $C_e, C_{pu}, C_a, m,$ and $C_{\mu 0}$ to the ones presented in Section 2.2.

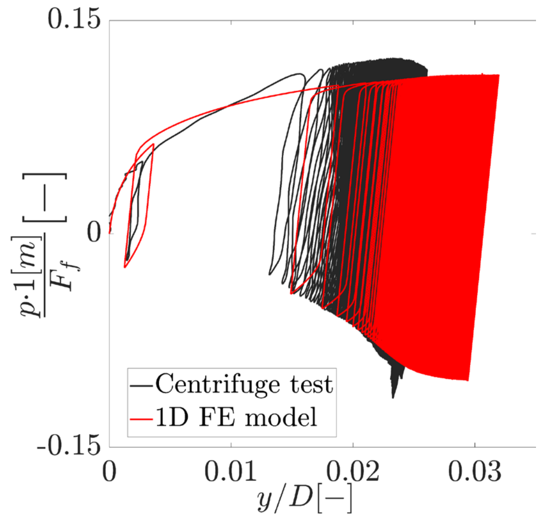

Figure 8a. Back calculated and simulated normalized p-y cyclic soil reactions at $z = 1m$ below the soil surface

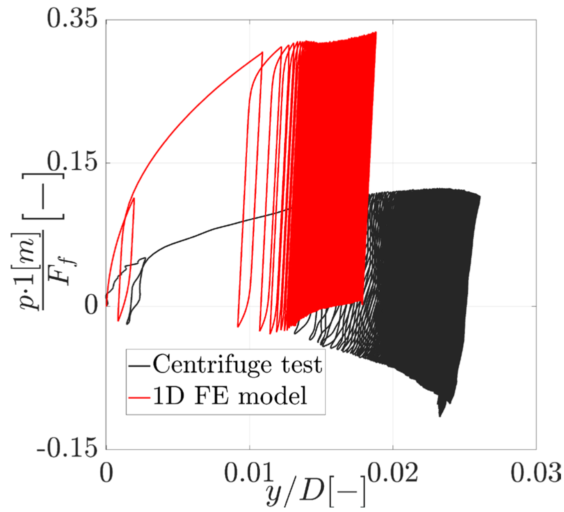

Figure 8b. Back calculated and simulated normalized p-y cyclic soil reactions at $z = 3m$ below the soil surface

The simulated (1D FE analysis) and recorded (TU Delft centrifuge) results of the cyclic tests are presented in Figures 6-8 - sensitive (confidential) information is presented as normalized. Figure 6a presents and compares trends of measured and calculated force-displacement response of the monopile (displacement measured at $z = 8.5$m). Evidently, the model can successfully simulate important features of the cyclic monopile response, namely, the small strain cyclic stiffness, the response to monotonic loading, the stiffness during cyclic loading and the accumulation of the lateral deformations. With the forcing being identical in the centrifuge and the FE analysis, the excellent performance of the model can be re-confirmed by presenting the accumulation of lateral deformations (at $z = 8.5$ m) in Figure 6b.

Measured and calculated bending moment profiles as inferred from the axial strain gauges along the monopile length, are presented at two instants of the cyclic loading programme in Figure 7. The 1D FE model can well capture the inferred bending moment profiles at both peak monotonic loading but also after $N = 4000$ load cycles (please refer to Figure 3). The obtained measurements were further elaborated to back-calculate the local p-y soil reactions following the procedure described in Kementzetzidis et al., (2022). Inferred (centrifuge test results) and calculated p-y reactions at z=1 and z=3 m are presented in Figure 8. Apparently preliminary calibrations of the $p - y$ model (all other soil reactions mechanisms were neglected), can simulate quite reasonably the soil behaviour at shallow depths, which does not hold exactly true further down the monopile length despite the satisfactory simulation of bending moment profiles in Figure 7.

4 Conclusions

This study presents preliminary 1D FE simulation results of monopile-soil interactions as measured in the Geo-centrifuge of TU Delft. A model monopile in dense sand was accelerated at 100 g and then laterally loaded with four cyclic load parcels, each consisting of $N = 1000$ load cycles of varying load amplitude (Figure 3). By employing the 1D FE p-y model presented in Section 2 (Kementzetzidis, 2023a; Kementzetzidis et al. 2023c), the authors were able to simulate with considerable accuracy the measured and inferred cyclic response of the monopile, namely, (i) monotonic behaviour (Figure 6a), (ii) the displacement accumulation and the cyclic monopile stiffness during four thousand load cycles of varying load amplitude (Figure 6b), (iii) bending moment profiles at various instants during the loading programme (Figure 7), and (iv) the local (p-y) cyclic soil behaviour (Figure 8).

By following a similar methodology to the one presented in this study, it is expected that improved calibration procedures will be identified both for the p-y model employed herein, but also for the additional reaction mechanisms neglected in this study i.e., distributed moment (Tott-Buswell & Prendergast, 2022), base moment and base shear.

5 Acknowledgments

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6 References

API . (2011). *API RP 2GEO, Geotechnical and Foundation Design Considerations.*

Byrne, B., McAdam, R., Beuckelaers, W., Harvey J, B., Gavin, K., Houlsby, G., . . . others. (2019). PISA Design Methods for Offshore Wind Turbine Monopiles. *Offshore Technology Conference*, (pp. paper OTC-29373-MS). Houston.

Delavinia, D., Kementzetzidis, E., Panagoulias, S., Tsouvalas , A., & Pisanò, F. (2023). Seismic soil-monopile-structure interaction for offshore wind turbines: from 3D to 1D modelling. *Offshore Site Investigation and Geotechnics*, (pp. --). London.

DNVGL (Det Norske Veritas GL). (2016). *DNVGL-ST-0126: Support structures for wind turbines.* Høvik, Norway: DNV GL Group.

Gerolymos, N., & Gazetas, G. (2006). Development of Winkler model for static and dynamic response of caisson foundations with soil and interface nonlinearities. *Soil Dynamics and Earthquake Engineering, 26*(5), 363-376.

Kementzetzidis, E., Pisanò, F., & Metrikine, A. (2022). A memory-enhanced py model for piles in sand accounting for cyclic ratcheting and gapping effects. *Computers and Geotechnics, 148*, 104810.

Kementzetzidis, E. (2023a). *Cyclic behaviour of laterally loaded (mono) piles in sand: With emphasis on pile driving effects.* Delft: Delft University of Technology. doi:10.4233/uuid:36b8a133-2a5a-49b3-9701-f75f102bbe3d

Kementzetzidis, E., Pisanò, F., Elkadi, A., Tsouvalas, A., & Metrikine, A. (2023b). Gentle Driving of Piles (GDP) at a sandy site combining axial and torsional vibrations: Part II-cyclic/dynamic lateral loading tests. *Ocean Engineering, 270*, 113452.

Kementzetzidis, E., Pisanò, F., Tsetas, A., & Metrikine, A. (2023c). Gentle Driving of Piles (GDP) at a sandy site combining axial and torsional vibrations: quantifying the influence of pile installation method on lateral behaviour. *Accepted for publication at the Journal of Geotechnical and Geoenvironmental Engineering*.

Lee, J., Zhao, F., & Dutton. (2021). *Global Offshore Wind Report 2021.* GWEC (Global Wind Energy Council).

McKenna, F., Scott, M., & Fenves, G. (2010). Nonlinear Finite-Element Analysis Software Architecture Using Object Composition. *Journal of Computing in Civil Engineering, 24*(1), 95-107.

Metrikine, A., Tsouvalas, A., Segeren, M., Elkadi, A., Tehrani, F., Gòmez, S., .De Vries, P. (2020). GDP: a new technology for Gentle Driving of (mono)Piles. In Z. Westgate (Ed.), *Frontiers in Offshore Geotechnics IV: Proceedings of the 4th International Symposium on Frontiers in Offshore Geotechnics (ISFOG 2021)* (pp. 736--745). Austin: CRC Press/Balkema.

Pisanò, F., Askarinejad, F., Wang, H., Magsoodi, S., Gavin, K., Segeren, M., .Konstantinou, M. (2022). MIDAS: Monopile Improved Design through Advanced cyclic Soil modelling. *20th International Conference on Soil Mechanics and Geotechnical Engineering (ICSMGE2022).* Sydney.

Ramirez, L., Fraile, D., & Brindley, G. (2021). *Offshore wind in Europe: Key trends and statistics 2020.* WindEurope.

Robertson, P. K. (2009). Interpretation of cone penetration tests—a unified approach. *Canadian geotechnical journal, 46*(11), 1337-1355.

Suryasentana, S., & Lehane, B. (2014). Numerical derivation of CPT-based p--y curves for piles in sand. *Géotechnique, 64*(3), 186-194.

Suryasentana, S., & Lehane, B. (2016). Updated CPT-based p–y formulation for laterally loaded piles in cohesionless soil under static loading. *Géotechnique, 66*(6), 445-453.

Tott-Buswell, J., & Prendergast, L. (2022). A CPT-based diameter-dependent m-θ spring model for lateral pile analysis. *Cone Penetration Testing 2022* (pp. 1126-1130). Bologna, Italy: CRC Press.

Tsetas, A., Tsouvalas, A., Gómez, S., Pisanò, F., Kementzetzidis, E., Molenkamp, T., . . . Metrikine, A. (2023). Gentle Driving of Piles (GDP) at a sandy site combining axial and torsional vibrations: Part I-installation tests. *Ocean Engineering, 270*, 113453.

Wan, X., Doherty, J., & Randolph, M. (2021). Relationships between lateral and rotational load transfer stiffnesses and soil modulus for the elastic response of monopiles. *Computers and Geotechnics, 137*, 104256.

Wang, H., Veldhuijzen, D. v., de Lange, D., Pisanò, F., Gavin, K., & Askarinejad, A. (2022). Centrifuge study on the CPT based p-y models for monopiles. *Cone Penetration Testing 2022* (pp. 1143--1148). Bologna: CRC Press.

White, D., Doherty, J., Guevara, M., & Watson, P. (2022). A cyclic py model for the whole-life response of piles in soft clay. *Computers and Geotechnics, 141*, 104519.