Proceedings of the 11th ICPMG 2026
11th International Conference on Physical Modelling in Geotechnics
8-12 June 2026, Zurich, Switzerland

Evaluation of the behavior of a monopile in sand subjected to lateral loading using centrifuge modeling

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ABSTRACT: This study investigates the behavior of monopile foundations subjected to lateral loading, with applications in offshore wind turbines. Geotechnical centrifuge tests were conducted at 100g using a 1:100 scale physical model installed in dense sand (DR = 80%). The objective was to generate experimental p-y curves and compare the results with analytical methods commonly used in monopile foundation design. Three monotonic tests were conducted to assess the lateral displacements, the bending moments, and the pile rotation along the embedded length. Based on strain gauge data, fourth-order polynomial equations were fitted to describe the bending moment distribution. Their derivatives enabled the estimation of shear forces and soil lateral reactions. The experimental p-y curves showed good agreement with the model proposed by Klinkvort (2012) but diverged from the API (2021) formulation, which was originally developed for flexible foundations. The results confirm the effectiveness of centrifuge modeling in replicating realistic soil-structure interaction behavior. This research contributes to the enhancement of offshore wind turbine foundation design in Brazil, promoting safer and more efficient solutions aligned with the United Nations 2030 Sustainable Development Goals. The methodology adopted can be extended to future studies involving different soil types and loading conditions.

1 INTRODUCTION

The growing demand for renewable energy sources has encouraged the development of technologies for offshore wind power generation. Monopile foundations are widely used (Panagoulias et al., 2020) due to their simple manufacture, transportation and installation. They are large diameter piles with a low L/D ratio, driven into the seabed, supporting significant aerodynamic (wind) and hydrodynamic (waves and sea currents) lateral loads.

The API (*American Petroleum Institute)* and DNV (*Det Norske Veritas*) have defined limit states that must be met in the design of offshore foundations, but these recommendations are not entirely appropriate for the design of monopiles, as they do not consider the difference between rigid and flexible behavior, and the number of loading cycles over the lifespan of the Offshore Wind Tower (OWT) (LeBlanc et al., 2010; Klinkvort, 2012; Abadie et al., 2019).

The relative stiffness (k_r), defined by the stiffness of the pile divided by the modulus of elasticity of the soil (Poulos & Hull, 1989), determines whether the foundation is considered rigid or flexible, influencing the stress distribution along the monopile. The relative stiffness of monopiles installed in sandy soil typically falls in the intermediate range between rigid and flexible foundations (Abadie et al., 2019).

The p-y curves are essential for analyzing the behavior of foundations subjected to lateral loads. They represent the relationship between lateral soil pressure (p) and lateral displacement (y) along the depth of the foundation. These curves are used to model the non-linear response of the soil, making it possible to predict how the soil reacts under different loading levels.

The concept of p-y curves was initially developed for flexible foundations, but its application has been expanded to include rigid foundations such as monopiles (e.g. Zhang et al., 2005; Spill et al., 2020; Lopes et al., 2023). Classical analytical methods, such as the one proposed by Hansen (1961), introduced the idea of thrust mobilization at different depths. Broms (1964) assumed that the lateral reaction modulus of the soil increases with depth, serving as the basis for obtaining these curves. Reese et al. (1974) developed specific p-y curves for sand, which are widely used in geotechnical engineering.

Furthermore, many authors have used centrifuge modeling to evaluate soil-monopile interaction (e.g.: Klinkvort, 2012; Kirkwood, 2015; Choo & Kim, 2016; Blanc et al., 2019; Truong et al., 2019; Bayton, 2020; Barra, 2020; Chortis et al., 2020; Malakshah et al., 2023; Lemos et al., 2024).

The present study aims to obtain experimental p-y curves through centrifuge tests on monopile foundations subjected to lateral loading, contributing to the development of efficient and safe structures, which is one of the challenges of new power generation projects (Yetginer & Tjelta, 2020).

2 MATERIALS AND METHODS

The physical modeling was carried out in the geotechnical beam centrifuge of the LM²C laboratory under an inertial acceleration of 100g, allowing the simulation of the real conditions of a 1:2 virtual model. On a prototype scale, the monopile foundation simulated has a diameter of 1.94 m and a depth of 10 m.

2.1 Materials

All centrifuge tests were conducted under dry sand conditions. The adopted quartz sand consists of predominantly rounded particles composed of 80.1% SiO_2, 13.1% AlO_{23} and 3.7% K_2O (Gomes, 2020). The other parameters of interest are shown in Table 1. A relative density of 80% was adopted following the standardization of the *"Benchmark Project"* program (Klinkvort et al., 2018), which aims to allow the comparison of the results of prototypes with similar characteristics.

Table 1. Quartz sand parameters

Parameter	**Acronym**	**Unit**	**Value**
Specific weight of grains	G_s	-	2.64
Voids ratio (D_r =80%)	e	-	0.66
Maximum void ratio	e_{max}	-	0.92
Minimum void ratio	e_{min}	-	0.60
Natural specific weight (D_r =80%)	γ_n	kN/m³	15.55
Average grain diameter	D_{50}	mm	0.18
Modulus of elasticity (for σ_c=100kPa)	E_{sec}	MPa	27

2.2 Test set-up

The model consisted of a box with a tube (monopile) embedded in a 0.15 m layer of sand (Figure 1). Table 2 shows the dimensions of the 1:100 scaled monopile model. A controlled load was applied on the top of the pile with a horizontal actuator. The model monopile was fabricated from aluminum, ensuring elastic behavior throughout the test.

Load cells model LC202-50 from OMEGA Engineering, Inc., with a maximum capacity of 1250 N, were used to measure the force applied by the actuator to the monopile during the tests, as shown in Figure 1(a). Laser sensors model OADM 12U6460/S35A from Baumer Electric were used to measure the lateral displacements of the monopile during the tests: one laser close to the load cell level, and another just above the sand surface, as indicated in Figure 1. These two laser sensors were positioned far enough apart to allow the rotation of the pile to be calculated. Strain gauges were diametrically installed at 7 different depths along the buried part of the monopile. The configuration of the strain gauges made it possible to measure both the deformations and the bending moments along the depth of the pile.

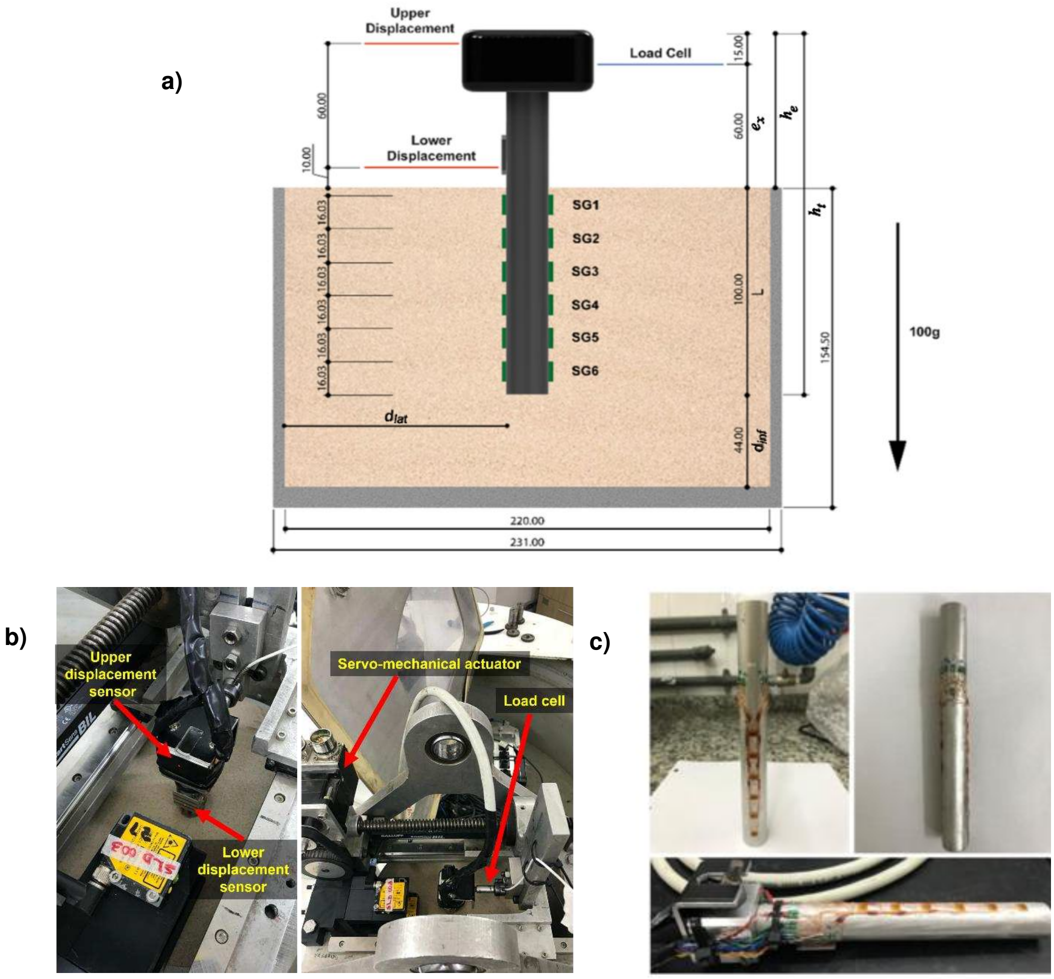

Figure 1. a) *Sketch of the test box and instrumentation layout. All dimensions are given in the model scale (mm);* d_{lat} *is the lateral distance from the pile to the text box;* e_x *is the eccentricity of loading;* h_e *is the monopile height above the ground surface; L is the embedded pile length;-* h_t *is the total monopile height, and* d_{inf} *is the distance from the pile tip to the base of the container. Distances to strain gauges (SG1–SG6) are measured to the centre of each strain gauge.* ***b)*** *Final arrangement for the centrifuge tests, showing the servo-mechanical actuator, load cell, and displacement sensors.* ***c)*** *Monopile instrumented with strain gauges prior to installation*

.Table 2 - Monopile parameters (N=100)

Parameter	Symbol	Model		1:2 Virtual Model	
		Value	**Unit**	**Value**	**Unit**
Total monopile height	h_t	0.175	m	17.5	m
Section buried in the ground	L	0.1	m	10	m
Monopile height above ground surface	h_e	0.075	m	7.5	m
Eccentricity of loading	e_x	0.06	m	6	m
External diameter of the monopile	D	0.0194	m	1.94	m
Internal diameter of the monopile	d	0.0162	m	1.62	m
Modulus of elasticity of the monopile	E_p	70	GPa	70	GPa
Monopile stiffness	E_pI_p	0.25	kN.m^2	25	GN.m^2

2.3 Methodology

Preparation for the test consisted of pouring the sand into the test box (ASTM D2487, 2017) with an automatic pouring device, which ensured repeatability and control around the void's ratio and the relative density that was aimed at D_r = 80%. The monopile model was statically jacked at 1g (Kirkwood, 2015; Futai et al., 2018; Blanc et al., 2019; Bayton, 2020; Almeida et al., 2023) at a constant rate of 0.1 mm/s until 100 mm (Figure 1a) embedment was reached. The centrifuge test was carried out at an inertial acceleration of 100g and a controlled displacement (Table 3) was applied with the horizontal actuator. During the tests, the displacement and the deformation were continuously monitored using, respectively, the laser sensors and the pairs of *strain gauges* fixed to the buried section of the pile.

Table 3. Test data

Test	**D_r (%)**	**Horizontal speed (mm/s)**	**Horizontal displacement (mm)**
MD-1	81	0.32	20
MD-2	81	0.32	20
MD-3	80	0.32	20

3 RESULTS

3.1 Monotonic loading

Three (3) tests, MD-1, MD-2 and MD-3 (table 3) were carried out to analyze the reaction of the monopiles under monotonic loading. Figure 2a shows the normalized lateral displacements calculated by the values measured by the upper laser (UL) and the lower laser (LL) as a function of the lateral force in each of the 3 tests (1:2 virtual model scale). The lateral displacement presented in Figure 2a corresponds to the displacement measured by the upper laser sensor located above the ground surface (d_{lat}). The slightly higher stiffness observed in test MD-1 is attributed to inherent experimental variability associated with dense sand preparation and pile installation, which may influence the initial soil fabric and soil–pile contact conditions without altering the governing soil–structure interaction mechanism.

The bending moment distribution along the foundation was calculated using the measurements obtained from the *strain gauges* (Figure 2b). The highest bending moment values were measured by the SG2 and SG3 sensors, positioned at 1.2D and 2D below the ground surface, respectively. In contrast, the lowest values were observed in the SG5 and SG6 sensors, located at a depth of 3.7D and 4.5D below the ground surface, respectively. The results obtained in the MD-2 and MD-3 tests were very close to each other. A higher stiffness of the monopile was observed in the MD-1 test.

4 ANALYSIS OF THE RESULTS

4.1 Definition of the characteristic equation

Based on the results of the tests, 3rd, 4th and 5th order polynomials were considered, with the best fit achieved in Equation 1.

$$M(z) = C_1.z^4 + C_2.z^3 + C_3.z^2 + C_4.z^1 + C_5 \quad (1)$$

On the ground surface, the bending moment is calculated by the product of the applied force (H) and the eccentricity (e_x), leading to C_5, as follows: $M(0) = H.e_x = C_5$. The shear force equation was obtained from the derivative of the moment equation. Likewise, on the ground surface, the shear force is equal to the applied force (H), thus, $C_4 = H$. Finally, the coefficient $C_3 = 0$ on the ground surface since, at this point, there is no applied force, and the reaction is also zero. Therefore, Equation (1) can be rewritten as:

$$M(z) = C_1.z^4 + C_2.z^3 + H.z^1 + H.e_x \quad (2)$$

C_1 and C_2 coefficients were obtained by numerical fitting using *Origin* software (OriginLab, 2024). Figure 3 shows the data points used to fit the curve for each of the tests. The upper point corresponds to the coefficient C_5, and the lower point is zero, as the bending moment at the base of the monopile is zero (Kirkwood, 2015). The other 6 (six) points were calculated using the *strain gauge* measurements. The lines show the obtained polynomial fitting function. The results show good agreement with the fitting equation (R^2 = 0.99).

Based on the bending moment equation, the shear stress and lateral reaction curves (1:2 virtual model scale) were obtained (Figure 4a and b). The result of the distribution of the lateral reaction of the soil is very similar to that predicted by Prasad & Chari (1999). According to the authors, the maximum positive pressure is at a depth corresponding to 60% of the depth of the rotation point ($0.6z_r$), and the ratio between the maximum negative and positive pressure is 1.7. In the tests, the ratio between the maximum negative and positive pressure was 1.7, and as shown ahead, the maximum positive pressure occurred at $0.54z_r$.

From the bending moment Equation 2 it is possible to obtain the rotation and deflection profiles of the monopile through single and double integration (Equations 3 and 4)

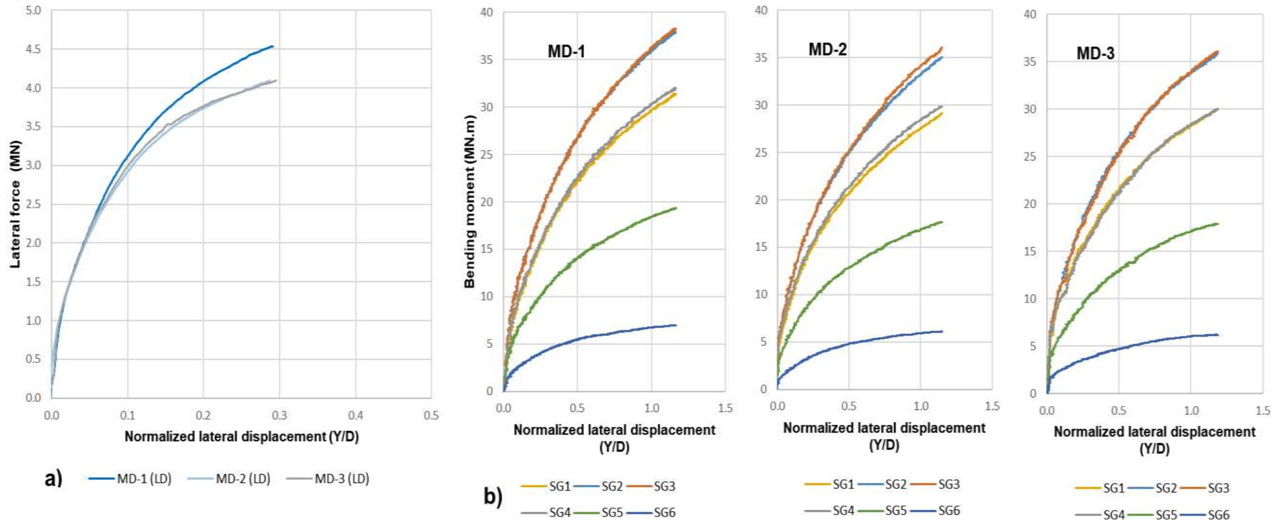

Figure 2. a) Lateral force vs lateral displacement curve; b) Bending moment x displacement curve of tests MD-1, MD-2 and MD3

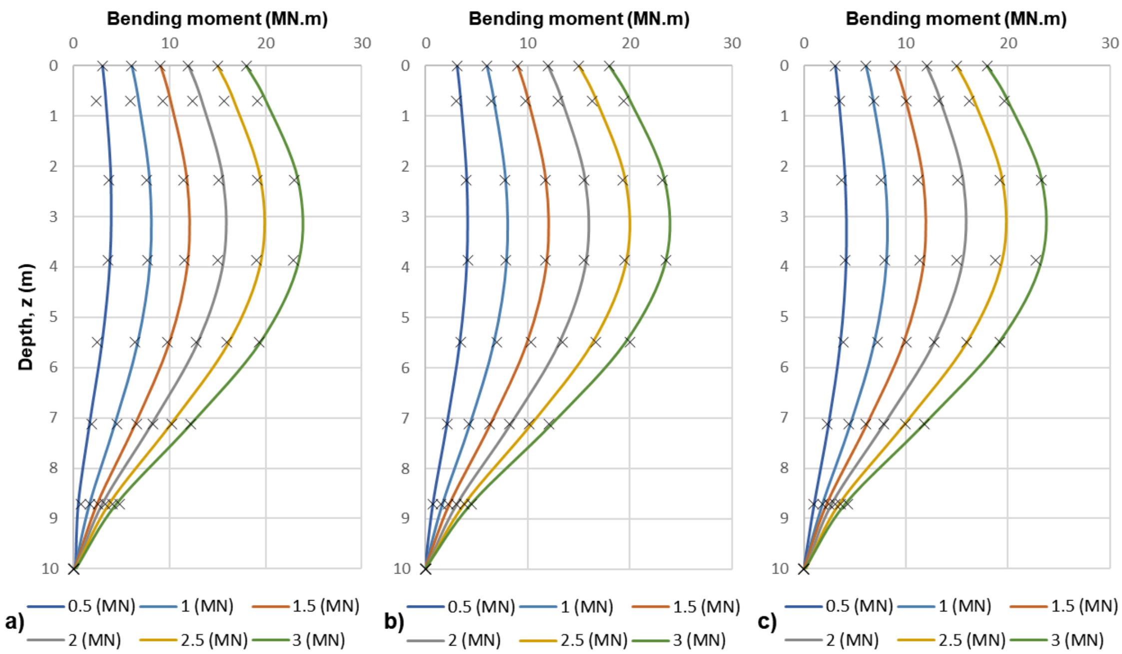

Figure 3. Bending moment correlation curve with 4th order polynomial: a) MD-1, b) MD-2, c) MD-3

$$\theta(z) = \int \frac{M(z)dz}{E_p I_p} = \frac{\frac{C_1.z^5}{5} + \frac{C_2.z^4}{4} + \frac{C_3.z^3}{3} + \frac{C_4.z^2}{2} + \frac{C_5.z^1}{1} + C_6}{E_p I_p} \tag{3}$$

$$y(z) = \iint \frac{M(z)dz}{E_p I_p} = \frac{\frac{C_1.z^6}{30} + \frac{C_2.z^5}{20} + \frac{C_3.z^4}{12} + \frac{C_4.z^3}{6} + \frac{C_5.z^2}{2} + \frac{C_6.z^1}{1} + C_7}{E_p I_p} \tag{4}$$

The rotation of the monopile is given by Equation 5 (Kirkwood, 2015), where the difference between the readings of the upper and lower laser sensors (Figure 1b) corresponds to the sum of the δ_r of the deformation δ_1 and rotation δ_2 (Equation 6). Δh is the difference in elevation between the sensors, H is the applied lateral load. The coefficient C_6 is obtained from the deflection values applied in equation 6.

$$\theta = \frac{\delta_r}{\Delta h} = \frac{H.\Delta h^2}{3E_p I_p} \tag{5}$$

$$\delta_r = \delta_1 + \delta_2 \tag{6}$$

The rotation and deflection profiles along the buried section of the monopile are shown in figures 4c and 4d, respectively. As can be seen in figure 4d, the rotation point occurred at approximately 70% of the buried depth ($z_r \sim 0.7L$). These results correspond to those cited in the literature, which range from 0.6L to 0.8L (Hansen, 1961; Prasad & Chari, 1999; Klinkvort & Hededal, 2011; Kirkwood, 2015; Jose & Mathai, 2016; Li et al., 2023). Christensen (1961) evaluated through tests the model proposed by Hansen (1961), and the value obtained was approximately 0.7L for short columns.

4.2 P-y curves

Figure 5 shows the p-y curves obtained in the three tests for different depths from the ground surface: 1.5D, 2D, 3D, 5D, and for lateral loads of 0.5 MN, 1.0 MN, 1.5 MN, 2.0 MN, 3.0 MN. As predicted in the literature (Klinkvort, 2012), the results show an increase in stiffness with depth owing to the increase in confining stress. The curves obtained using the methods proposed by API (2021) and Klinkvort (2012) are also presented, using the sand properties reported by Gomes (2020), including unit weight, relative density (DR ≈ 80%) and friction angle (ϕ ≈ 40.6°), in accordance with the experimental conditions adopted in the centrifuge tests.

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Test data agreed well with the formulation proposed by Klinkvort (2012), showing that this method is suitable for soil-monopile lateral iteration predictions in sandy material similar to that used in the present research. On the other hand, no good correlation was obtained with the API (2021) method. The reason for this divergence is that these equations were initially formulated for flexible foundation elements (high L/D), resulting in p-y curves with high initial stiffness, compared to the behavior of monopile-type foundations (Reese et al., 1974), which have lower stiffness.

5 CONCLUSION

Centrifuge modeling proved to be effective for evaluating the behavior of monopile foundations under lateral loading. The lateral load capacities obtained experimentally corroborated the theoretical values predicted, demonstrating the feasibility of using centrifuge modeling to study monopile foundations. The experimental p-y curves also showed a good fit with the theoretical model (Klinkvort), validating the employed methodology.

This study provided an important comparison of modeling data with analytical methods used to predict the behavior of monopile foundations in real conditions. The data obtained can be used as a reference for future offshore wind turbine projects in similar conditions, contributing to design optimization, ensuring safety, and operational efficiency. Taking into account the relative stiffness and an accurate set of p-y curves is essential for the reliable and safe design of these structures.

The close agreement observed between repeated tests confirms the robustness and repeatability of the experimental methodology. The limited scatter observed in the global response is consistent with the expected sensitivity of dense granular soils and does not affect the overall interpretation of the soil–structure interaction mechanisms.

In addition, the results of this study highlight the importance of detailed experimental investigations to better understand soil-structure interaction and improve existing theoretical models. The methodology employed can be applied in future studies to explore different soil types and loading conditions, expanding knowledge about the behavior of monopile foundations and contributing to the sustainable development of offshore wind energy in Brazil.

ACKNOWLEDGEMENTS

The authors are grateful for the financial support provided by funding agency FAPERJ, CNPq and Petrobrás S/A

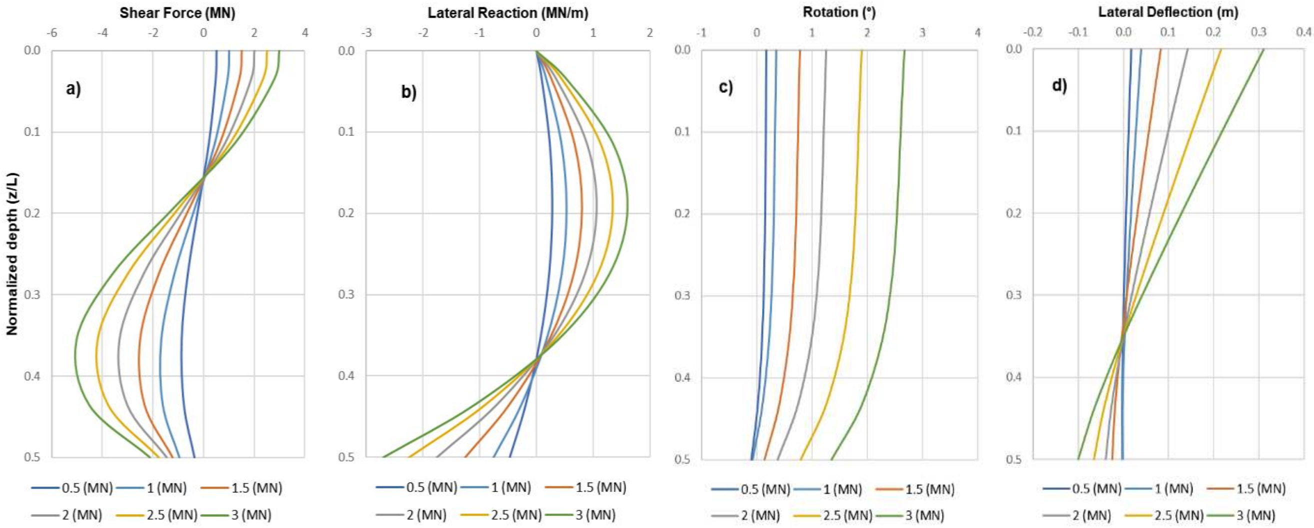

Figure 4. MD-3 test profiles: a) Shear force, b) Pressure, c) Rotation, d) Lateral deflection

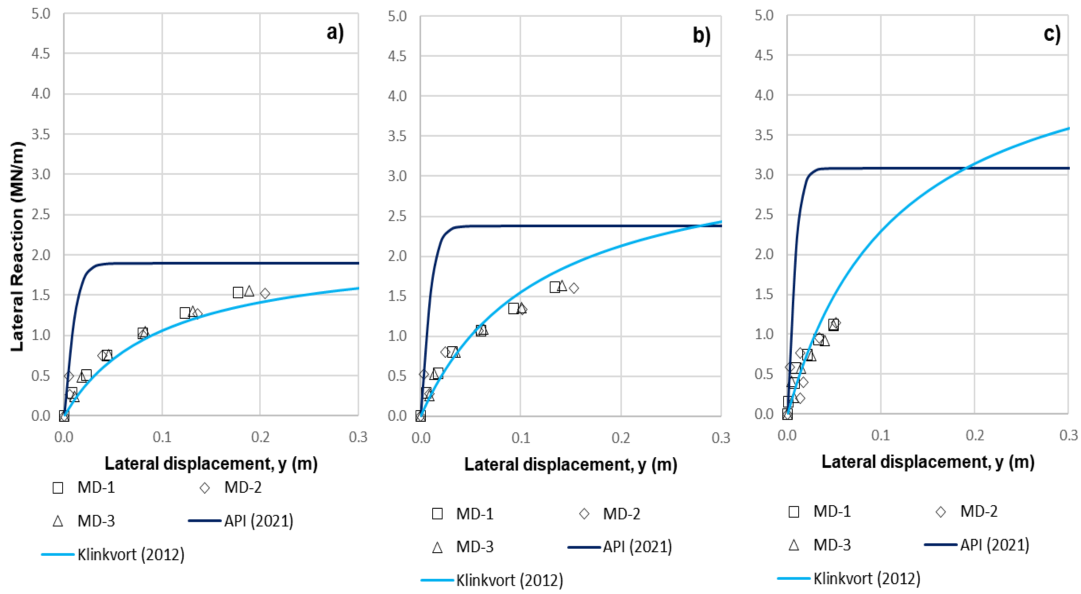

Figure 5. Experimental vs analytical p-y curves for different depths: a) 1.5D; b) 2D; c) 3D; d) 5D

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