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Model Tests on the Displacement Accumulation of Monopiles Subjected to General Cyclic Loading

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Abstract: The design of monopiles for offshore wind turbine structures is dominated by requirements resulting from serviceability and fatigue limit state as this type of foundation is primarily subjected to long-term lateral cyclic loading during its lifetime. The cycling leads to an accumulation of permanent deflections and rotations of the structure, which has to be predicted and limited to fulfil before mentioned criteria. As current design code procedures do not take into account load characteristics and the number of load cycles, they are rather unreliable and further adjustments are required to ensure a more competitive and well suited monopile design for future projects. This paper presents a short overview of current design practice and shortcomings of the calculation methods proposed by current design codes. Then, a new small-scale test setup for the investigation of lateral pile response due to 1-dimensional (one- and two-way) cyclic loading is described. A program of experiments including monotonic and cyclic loading tests to investigate the role of load characteristics, load eccentricity and pile-soil stiffness is presented. The results are evaluated and used to identify the parameters of a correction function for displacement accumulation rate, which accounts for the type of the applied cyclic load.

Keywords: monopile, sand, lateral cyclic loading, displacement accumulation, 1g model tests

1 Introduction

The transition to a low carbon energy supply is a declared aim of different states and governments around the world. To meet the stated targets, there has been a steady increase in the deployment of both on- and offshore wind turbine structures for the generation of electrical energy over the past decade. In this context, especially the offshore wind sector plays a key role and shows high potential as there are several large wind park projects planned for the next years. In 2018 the total installed and grid connected cumulative capacity of all offshore wind turbines in Europe already amounted to approximately 18.5 MW, whereby the most common foundation type for these structures is a large diameter single pile, termed the monopile. In European waters this foundation type has been used for approximately 66% of all newly erected wind turbines in the year 2018. Regarding the total amount of installed offshore wind converters in Europe, the monopile currently represents 81.9% of all installed substructures (Walsh, 2019). The high popularity of the monopile can be attributed to its relatively simple design, robustness in most soil conditions and suitability for mass production.

A challenging task in the economical and reliable design of monopile foundations is the prediction of displacement accumulations induced by long-term lateral cyclic loading. The anticipated lifetime of such structures is nominally 20 to 25 years, during which the monopile is subjected to many different loading conditions arising from varying, repeatedly occurring wind and wave loads. The resulting permanent deflections and rotations of the monopile may not only affect the structural integrity of the complete wind energy converter (ULS) but even more the sound operation of the turbine itself and therefore the serviceability limit state (SLS). While monopile application limitations regarding water depth and turbine size have repeatedly been overcome, mainly by application of increasing pile dimensions, concerns over the applicability of existing design methods for the prediction of the lateral response of large diameter monopiles have been expressed. Further research has pointed out various shortcomings of the current monopile design approaches and numerous proposals for advanced models for the prediction of static and cyclic lateral pile response have been made.

1.1 Current design codes and practice

According to current offshore Guidelines (OGL) such as API (2014) or DNV GL (2018) it is common practice to design monopile foundations using the p-y-method, which assumes the pile to be an elastic beam supported by soil medium represented as a series of uncoupled springs acting normal to the beam element. The non-linear spring characteristics (p-y curves), describing the soil's bedding resistance p dependent on the lateral pile displacement y, are in this respect decisive for an accurate and reliable design. One of the first p-y curve formulations, which is still recommended in API (2014), is largely based on field-test results on small-diameter, slender piles reported by Reese et al. (1974), Murchison & O'Neill (1984) and others. It has been successfully adopted in the oil and gas industry for many years, but as monopile dimensions are permanently increasing, the transferability of this method to the design of today's rigid and large diameter monopiles (often in excess of 5 m) has been questioned and furthermore initiated various research projects and publications dealing with this issue. As an outcome it has been found, that the initial stiffness of large diameter monopiles is underestimated using the static p-y expression stated in API (2014), while at the same time the stiffness due to large loads is overestimated. To address these findings, numerous adjusted static p-y approaches have been proposed. An overview and assessment of current proposals is given in Thieken et al. (2015a), who also developed a new p-y formulation for large diameter monopiles in sand (Thieken et al., 2015b). Recent design codes, such as DNV GL (2018) do not suggest the use of a specific p-y method anymore. Instead, a recommendation is included that any design approach for piles with diameters of more than 1.0 m has to be validated by means of other methods, e.g. finite element calculations.

Regarding SLS proofs, the recommended design code procedure for the prediction of monopile behaviour due to cyclic loading is a simple, depth-dependent degradation of p-y curve stiffness and ultimate soil resistance by application of a single empirical correction factor to the p-y curve expression, resulting in an overall softer foundation behaviour and a reduced capacity (API, 2014). Given the criticality of this proof for the foundation design and the turbine performance, this approach is widely accepted as not being adequate since neither the number of load cycles nor the load characteristics are considered. Further, possible densification processes and therefore increases of foundation stiffness and post cyclic capacity related to the cyclic loading are neglected.

1.2 Developments regarding lateral cyclic pile response

As before mentioned shortcomings of current methodology regarding lateral cyclic pile response may lead to uncertainties in design or on the other hand uneconomical over-dimensioning of monopile foundations, many authors made efforts to investigate the parameters influencing the cyclic pile behaviour and developed more precise predictive models. Therefore, they relate to full scale and model scale cyclic experiments or numerical results. As the numerical research is still at development stage or needs further validation and full scale test data on rigid piles is rare in literature, most reported investigations have been conducted using small scale floor experiments or centrifuge tests. A short overview of some related recent publications can be found in Frick & Achmus (2019). In general, these studies pointed out cyclic load characteristics, i.e. load magnitude and load symmetry, to have a significant influence on pile deflection accumulation, whereby unsymmetrical two-way loading has been found to cause the highest rate of deflection accumulation for rigid piles at a constant load magnitude (e.g. LeBlanc et al., 2010; Arshad & O`Kelly, 2017). Also pile-soil stiffness and load eccentricity were observed to affect cyclic pile response (Albiker et al., 2017). Moreover, cyclic loading has been shown to increase monopile stiffness and capacity (e.g. Klinkvort et al., 2010; Nicolai et al., 2017, Abadie et al., 2018). Despite consensus on these general findings, still uncertainties and divergent results regarding the influence of various parameters on cyclic pile response exist. Further research is required to clarify cyclic monopile behaviour with all its complexity and develop a universally adoptable and more precise design method.

2 Small-scale model tests

2.1 Test design and program

The small-scale 1-g model tests described below are part of a test campaign regarding the influence of load characteristics, load eccentricity and pile-soil stiffness on the pile deflection accumulation rate due to cyclic loading. The test program comprised more than 60 monotonic and cyclic loading tests on two different pile-soil systems in medium dense sand, having embedment length to diameter ratios of L/D = 8 (system 1) and L/D = 6 (system 2). Applying the non-dimensional stiffness ratio suggested by Poulos & Hull (1989), both configurations can be quantified to behave semi-rigid, similar to true scale monopiles. The ratio of load eccentricity e to embedment length L has been varied in the range of e/L = 0.6 to e/L = 0.8 for system 1 and e/L = 0.8 to e/L = 1.2 for system 2. To achieve better comparability between the tests, horizontal loads being applied to the pile have been defined in terms of cyclic load magnitude ζ_b and cyclic load ratio ζ_c as introduced by Leblanc et al. (2010):

$$\zeta_b = \frac{H_{max}}{H_{ult}} = \frac{M_{max}}{M_{ult}} \tag{1}$$

$$\zeta_c = \frac{H_{min}}{H_{max}} = \frac{M_{min}}{M_{max}} \tag{2}$$

where H_{min} and H_{max} are the minimum and maximum horizontal loads within a load cycle corresponding to minimum and maximum overturning moments M_{min} and M_{max} applied to the pile at mudline ($M = H \cdot e$). For two-way loading, H_{min} and H_{max} take negative and positive values, respectively. The ultimate horizontal load H_{ult} and ultimate moment pile capacity M_{ult} are those corresponding to monotonic loading ($\zeta_c = 1$) at pile failure or ultimate capacity defined by reaching a certain displacement or rotation. To systematically evaluate the effects of cyclic load characteristics on the displacement accumulation, different one- and two-way loading conditions with ζ_c–values of -0.75/ -0.50/ -0.25/ 0.00/ 0.25 at a constant load level of $\zeta_b = 0.35$ have been chosen for the cyclic tests, each involving N = 2500 load cycles. Static tests were conducted under displacement control at a velocity of 0.016 mm/s (at the load application point), while cyclic tests were conducted load controlled at a sinusoidal frequency of 0.1 Hz. For redundancy, at least two tests were conducted for each configuration. The test schedule along with the related system parameters and loading characteristics for all 5 test series conducted is provided in Tab. 1.

Tab. 1. Test schedule

Pile-soil system description						Load description		
Test series [#]	System [#]	D [mm]	L/D [-]	e/L [-]	D_r [-]	ζ_b [-]	ζ_c [-]	N [-]
1	1	50	8	0.6	0.40	0.35	-0.75/-0.50/-0.25/0.00/0.25/1.00	2500
2	1	50	8	0.8	0.40	0.35	-0.75/-0.50/-0.25/0.00/0.25/1.00	2500
3	2	50	6	0.8	0.40	0.35	-0.75/-0.50/-0.25/0.00/0.25/1.00	2500
4	2	50	6	1.0	0.40	0.35	-0.75/-0.50/-0.25/0.00/0.25/1.00	2500
5	2	50	6	1.2	0.40	0.35	-0.75/-0.50/-0.25/0.00/0.25/1.00	2500

2.2 Experimental setup and soil properties

The open-ended model monopile was fabricated from aluminium, having an outer diameter D = 50 mm and a wall thickness of 3.2 mm. Two different embedment lengths of $L_1 = 400$ mm (L/D =8) and $L_2 = 300$ mm (L/D = 6) were considered. The tests were conducted in dry, medium grained silica sand, which was pluviated around the pre-fixed pile into a cylindrical sand container with an inner diameter of 600 mm and a depth of 750 mm. Characteristic parameters of the test sand, termed F34 silica sand, are summarized in Tab. 2. Preliminary investigations towards the sand pluviation technique provided reproducible results and a defined k_0 sand state at a relative density of approximately $D_r = 40\%$ corresponding to a soil unit weight of $\gamma \approx 15$ kN/m³.

Tab. 2. Soil properties of F34 silica sand

Description	Parameter	Unit	Value
Mean grain size	d_{50}	[mm]	0.18
Uniformity coefficient	C_u	[-]	1.90
Coefficient of curvature	C_c	[-]	1.02
Minimum void ratio	e_{min}	[-]	0.585
Maximum void ratio	e_{max}	[-]	0.887
Specific density	ρ_s	[g/cm³]	2.65

Horizontal static and cyclic (one and two-way) loading was applied using an electromechanical actuator which was connected to the model pile by a pin-ended stiff rod, allowing free rotation of the pile. Different load eccentricities could be realized as the actuator and also the connection hinge on the pile were adjustable in height. Instrumentation of the experimental setup included a high precision load cell located at the actuator to measure the load being applied and two laser sensors directed perpendicular to the pile at heights of 50 mm and 150 mm above the sand surface, allowing the pile head deflection u (at the embedment point) or the pile rotation θ to be determined. Additionally, a magneto-inductive displacement transducer was arranged within the sand container at height of the pile toe, enabling pile tip movements to be captured. Fig. 1 presents a schematic sketch of the testing arrangement.

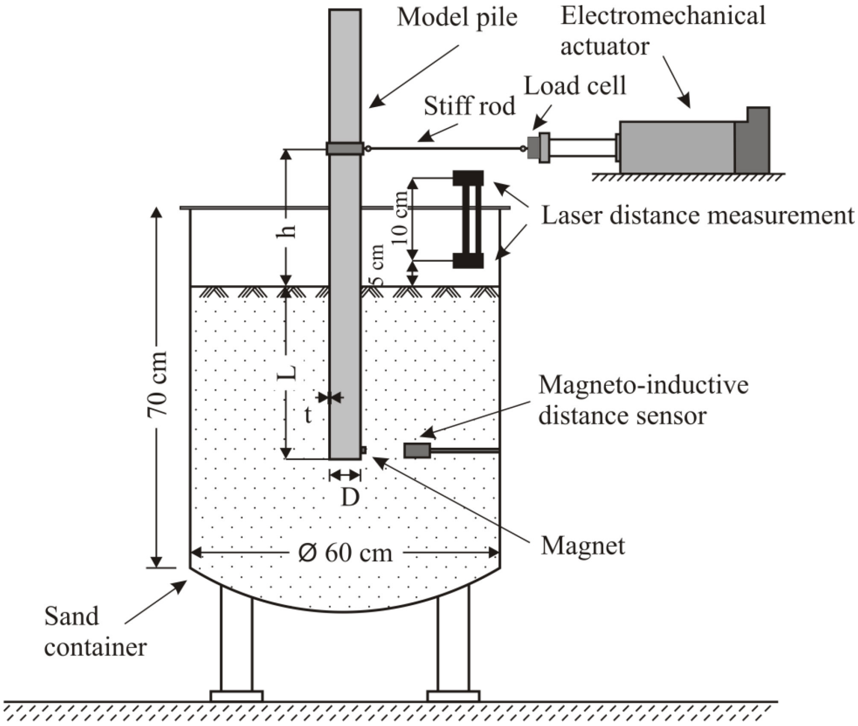

Fig. 1. Experimental setup.

3 Test results

3.1 Monotonic test results: Determination of the lateral ultimate pile capacity

Prior to the cyclic tests, monotonic load tests for the determination of the ultimate pile capacity H_{ult} and respectively M_{ult} have been conducted. The results from the displacement controlled monotonic tests are provided in Fig. 2, which shows normalized load-displacement responses at the pile head (solid lines) calculated from the two laser measurements (cf. Fig. 1) for both investigated pile-soil systems with varying load eccentricities. Each test has been conducted at least twice to ensure repeatability. As there was some scattering in the results for pile-soil system 2 with a load eccentricity of $e/L = 1.2$, this test has been conducted even four times.

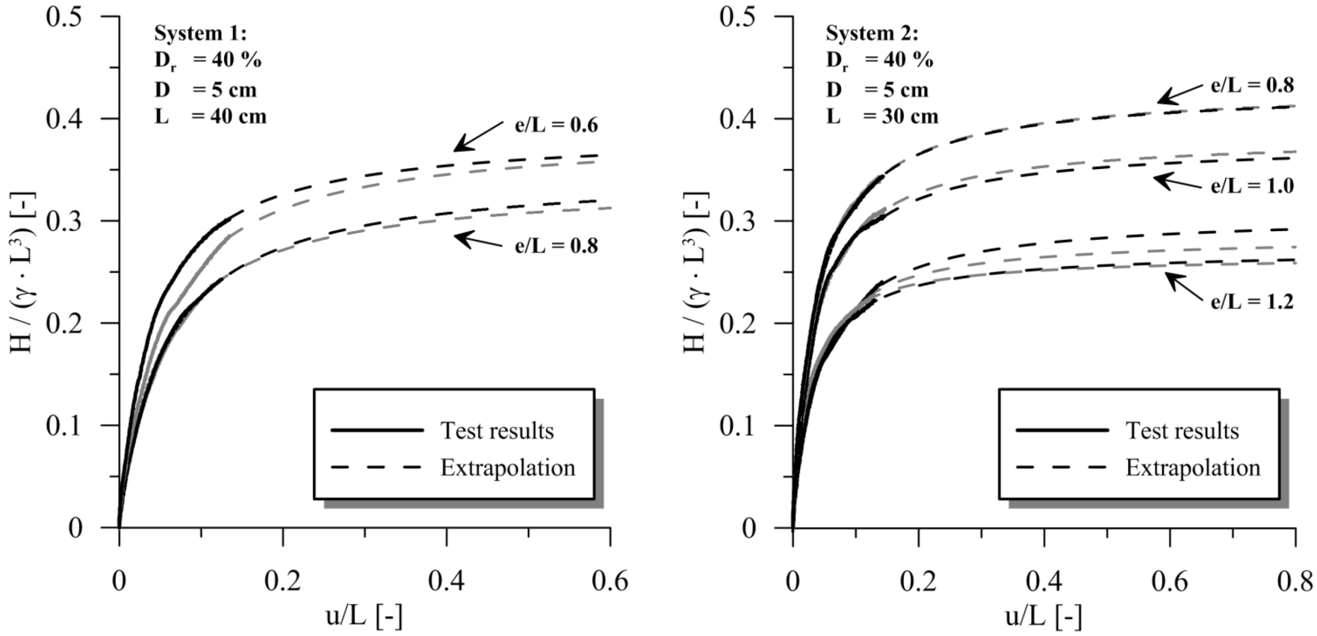

Fig. 2. Normalized monotonic load-displacement response for pile-soil system 1 (left) and pile-soil system 2 (right).

Typically for laterally loaded piles, no distinct point of failure can be determined from the measured load-displacement curves (solid lines) depicted in Fig. 2 as total pile failure is associated with very extensive deformations. Also design standards do not provide guidance on the definition of a failure criterion for ultimate limit state. In literature a large number of different deflection or rotation criteria are proposed. To pick up a few examples, some common criteria are summarized in Tab. 3.

Tab. 3. ULS failure criteria for laterally loaded piles from literature

Author	LeBlanc et al. (2010)	Peralta & Achmus (2010)	Truong & Lehane (2015)	Arshad & O'Kelly (2017)
Failure criterion	4° rotation	Pile head deflection 0.1·L	Pile head deflection 0.1·D	1.5° rotation

As these criteria are more or less arbitrary and do not inevitably represent the true failure load of a laterally loaded pile, the criterion or rather method of Manoliu et al. (1985) has been adopted in this study. It assumes that load-displacement can be described by a hyperbolic function and therefore allows the determination of H_{ult} by extrapolation of test results. Related extrapolation curves to the measured results are depicted in Fig. 2 (dashed lines). The determined mean failure loads for each configuration are presented in Tab. 4. To prove the plausibility of the results, back calculations using the p-y approach proposed by Thieken et al (2015b) have been carried out. The results of these are included in Tab. 4. As the determined failure loads according to both methods are in relatively good agreement, the applied method for the determination of the ultimate pile capacity has found to be reasonable as it allows a clear definition of the true failure load. Further, the derived values for H_{ult} (Tab. 4, column 3 and 4) were used to define the load characteristics in terms of load magnitude ζ_b (Eq. 1) and cyclic load ratio ζ_c (Eq. 2) for the cyclic tests summarized in Tab. 1.

Tab. 4. Failure loads determined by extrapolation of test results according to Manoliu et al. (1985) and p-y method

System	e/L	$H_{ult}/(\Upsilon \cdot L^3)$ acc. to Manoliu et al. (1985)	H_{ult} acc. to Manoliu et al. (1985)	H_{ult} acc. to Thieken et al. (2015b)
[#]	[-]	[-]	[N]	[N]
1	0.6	0.3875	372.0	384.5
1	0.8	0.3438	330.0	336.5
2	0.8	0.4296	174.0	168.0
2	1.0	0.3802	154.0	149.5
2	1.2	0.2825	114.4	134.5

It has to be kept in mind that ζ_b-values reported in literature are not directly comparable among each other and to those defined in this study as different definitions for H_{ult} (or M_{ult}) could have been used. The adoption of the method according to Manoliu et al. (1985) results in significantly higher failure loads compared to other common pile deformation criteria (see. Tab. 3) and therefore leads to relatively high cyclic loads for a given load magnitude ζ_b.

3.2 Cyclic test results: Evaluation of the pile deflection accumulation

Fig. 3 (left) presents the results of cyclic one-way loading tests with complete unloading after each cycle ($\zeta_c = 0$) in terms of calculated pile head deflection accumulation $\Delta u/u_1$ for both pile-soil systems (black and grey) and all applied load eccentricities e/L (different markers).

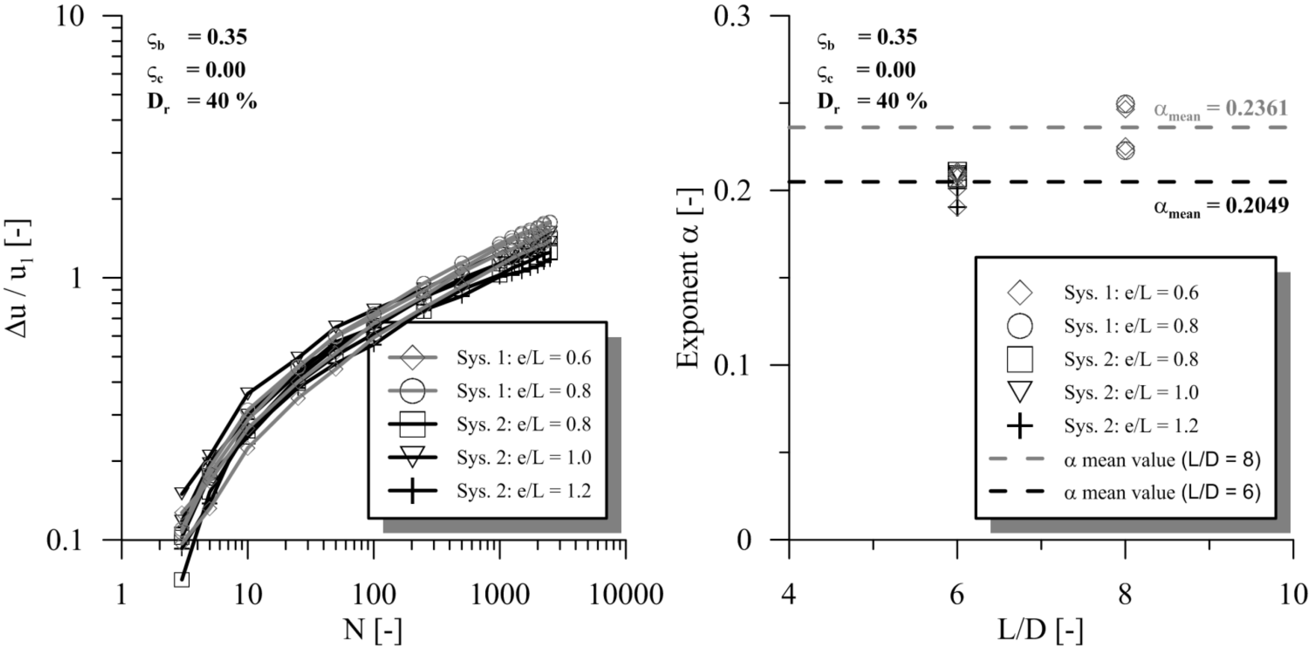

Fig. 3. Pile deflection accumulation due to cyclic loading with $\zeta_c = 0$ (left) and accumulation parameters α (right).

As it can be seen, pile head deflection accumulations exceeding 500 load cycles seem to follow a linear trend when plotted at double logarithmic scale, indicating they can be approximated and extrapolated using a power function as given in Eq. 3:

$$\frac{u_N - u_1}{u_1} = \frac{\Delta u}{u_1} = T \cdot N^{\alpha} \tag{3}$$

here u_1 and u_N are the pile head displacements in the first and the N_{th} load cycle, Δu represents the increase in permanent pile head displacement and α is an accumulation parameter. The factor T represents a system- and load-characteristic dependent value. This is in general consistent with the findings of Leblanc et al. (2010) and other researchers, who also describe pile deflection accumulation of rigid, large diameter piles in sand using a power function. To determine the accumulation parameter α, the tests with loading conditions of $\zeta_c = 0$ have been fitted by Eq. 3. The resulting α values for all test configurations are plotted against L/D ratios in Fig. 3 (right). Even if some scattering exists, a clear dependency of L/D can be observed for the exponent α, which therefore indicates a dependency of α on the pile-soil stiffness. In contrast, a distinct influence of load eccentricity on α could not be identified. Therefore, the exponent α has been assigned to a value of $\alpha_1 = 0.2361$ for pile-soil system 1 and $\alpha_2 = 0.2049$ for system 2, respectively, by taking mean values of the determined parameters for each L/D ratio (see Fig. 3 (right)).
Further, the influence of varying one- and two-way loading conditions expressed in terms of ζ_c (Eq. 2) was investigated. Fig. 4 (left) exemplarily presents the evolution of normalized deflections with number of load cycles derived for pile-soil system 2 with a load eccentricity of e/L = 0.6 subjected to different cyclic loads. Fig. 4 (right) depicts the related pile head deflection accumulations (solid lines).

The dashed lines represent the deflection accumulations approximated by Eq. 3, each fitted to the mean value of two tests with same loading conditions, using the previously determined accumulation parameter $\alpha_2 = 0.2049$ for pile-soil system 2.

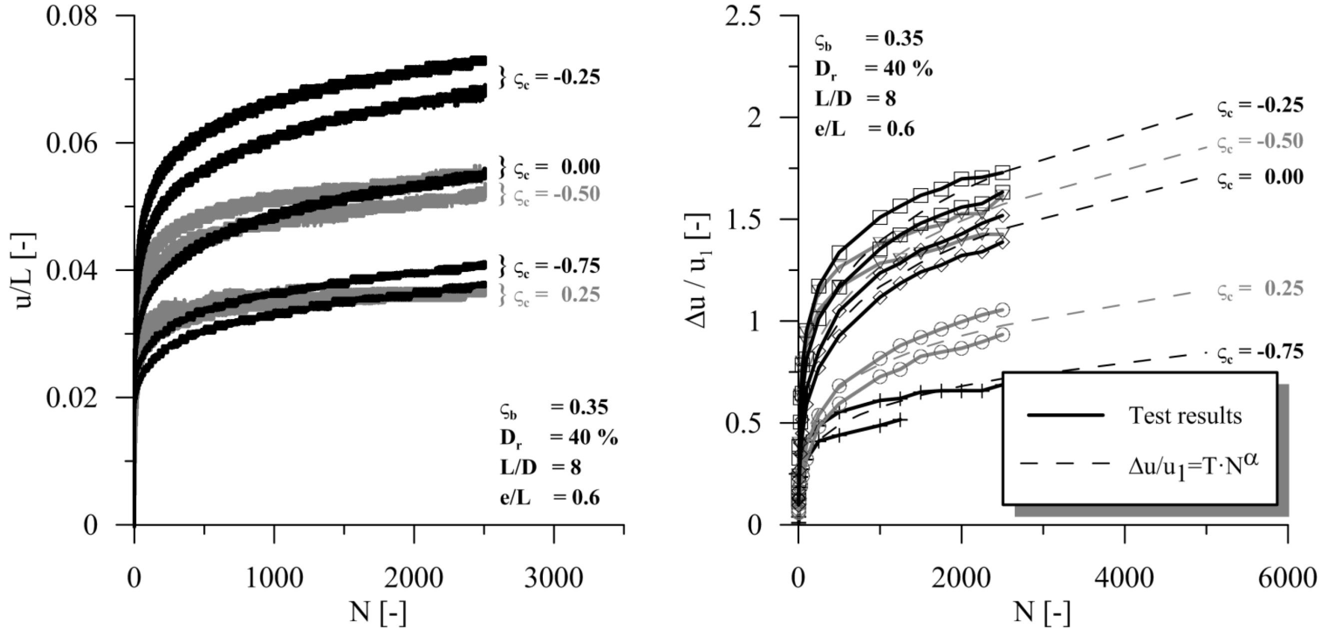

Fig. 4. Example of pile head deflections (left) and accumulations (right) with number of load cycles due to varying ζ_c.

It emerges from Fig 4, that increases in pile head deflections and therefore deflection accumulations for a given load magnitude ζ_b strongly depend on the cyclic load ratio ζ_c. Highest deflection accumulations could be found to result from unsymmetrical two-way loading with $\zeta_c = -0.25$, while lowest accumulations have been measured due to nearly symmetrical two-way ($\zeta_c = -0.75$) or pure one-way ($\zeta_c = 0.25$) loading. Most increases in deflections, i.e. highest accumulation rates, are within the first 100 load cycles, followed by a progressive and steady decrease in accumulation rate with load cycle number. To better quantify the influence of load symmetry and allow comparison between the different test series with varying load eccentricities, the parameter T from Eq. 3, which in conjunction with α describes the deflection accumulation (see Fig. 4, right panel), for each test has been normalized with respect to the related $T(\zeta_c = 0)$ as proposed by LeBlanc et al. (2010). The ratio $T(\zeta_c)/T(\zeta_c = 0)$ for each test series is further termed T_c. Fig. 5 presents the $T_c(\zeta_c)$-functions derived for both pile-soil systems and all 5 test series with varying load eccentricities.

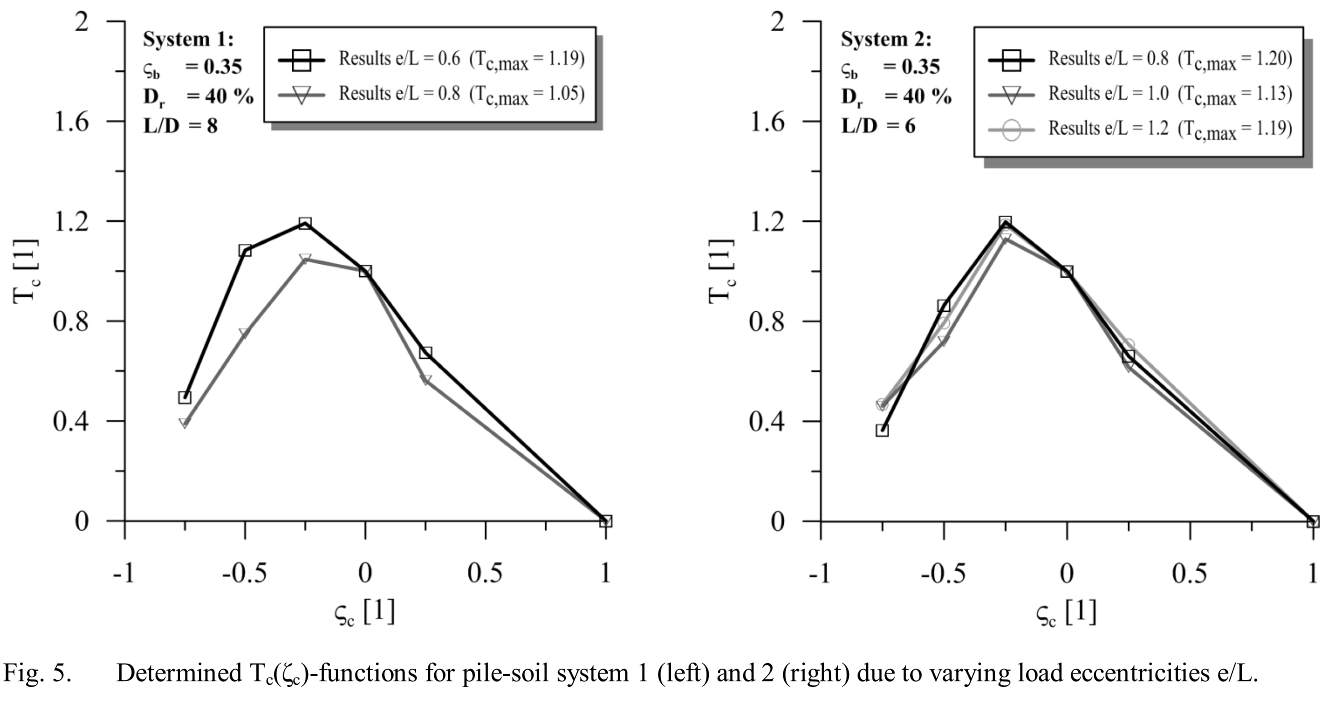

Fig. 5. Determined $T_c(\zeta_c)$-functions for pile-soil system 1 (left) and 2 (right) due to varying load eccentricities e/L.

It can be seen that the $T_c(\zeta_c)$-functions for both pile-soil systems, which are almost rigid, are generally quite similar in shape. The highest amount of deflection accumulation could be observed to arise from asymmetric two-way loading with $\zeta_c = -0.25$ for all test series. Also maximum T_c-values do not differ significantly. Excluding the results for pile-soil system 1 with load eccentricity of $e/L = 0.8$ (test series 2) and a $T_{c,max} = 1.05$ the range of maximum T_c values is 1.13 to 1.20. Regarding load eccentricity, no substantial influence on the shape or maximum of the T_c-function can be found. The slight difference in maximum T_c for test series 2 compared to other values derived may be related to some irregular sand sample preparation for the reference tests with $\zeta_c = 0$ (not presented here). It must be noted that these tests showed quite high deflection accumulations compared to other tests of this series and therefore differ considerably to the trends observed overall. As the T_c-function is based on the results of the reference tests and is very sensitive to them, the deviations of the T_c-functions for system 1 may be explained by that fact. Further tests with $\zeta_c = 0$ have to be conducted to define the T_c-function for test series 2 more reliably.

4 Discussion

The pile deflection accumulation of the nearly rigid pile-soil systems presented in this study can be well described using a power function as given in Eq. 3 having a factor T and an exponent α. The factor T is dependent on load characteristics, pile dimensions and soil conditions. The accumulation parameter α has been found to vary with embedment length or pile-soil stiffness, respectively. An increase in pile embedment length results in an increase in α. For pile-soil system 1 with an embedment length to diameter ratio of 8, the accumulation parameter α was signed to a value of 0.2361. The cyclic test results of pile-soil system 2 ($L/D = 6$) could be approximated well using an α-value of 0.2049. For both pile-soil systems, the α-value was not affected by varying load eccentricities. Compared to literature values, the determined accumulation parameters seem to lie in a plausible bandwidth although they are not directly comparable. LeBlanc et al. (2010) obtained $\alpha = 0.31$ for monopiles ($L/D = 4.5$) in dry sand. Zhu et al. (2013) found a value of $\alpha = 0.39$ for a caisson foundation subjected to horizontal cyclic loading, whereas Foglia (2014) also for a caisson foundation proposed the accumulation parameter α to be 0.18. Albiker et al. (2017) report a value of $\alpha = 0.23$ for a cyclic laterally loaded pile with $L/D = 5.8$.

To further evaluate the influence of loading type on the pile deflection accumulation for the two pile-soil systems with varying load eccentricities investigated here, the factor T of Eq. 3 for each test has been normalized with respect to the related $T(\zeta_c = 0)$ to derive T_c-functions. By comparison of the determined T_c-functions with those found in literature, it emerges that the general shape of the T_c-function for rigid piles as reported by LeBlanc et al. (2010), Albiker et al. (2017) and others - with a maximum value for asymmetric two-way loading - could be confirmed. The presented tests revealed a maximum pile deflection accumulation for cyclic loading with a load parameter of $\zeta_c = -0.25$ leading to maximum T_c-values in the range of 1.05 to 1.20. While the findings regarding critical loading type (ζ_c) are generally consistent with those found in literature, the maximum T_c-values obtained differ significantly from those derived in other studies (see Tab. 5).

Tab. 5. $T_{c,max}$-values and related ζ_c-values reported in literature

Author	D [mm]	L/D [-]	e/L [-]	D_r [%]	$T_{c,max}$ [-]	$\zeta_c(T_{c,max})$ [-]
LeBlanc et al. (2010)	80	4.5	1.19	4/38	≈ 4	≈ -0.6
Klinkvort & Hededal (2013)	28 40	6 6	2.5 2.5	90 90	Slightly higher 1	-0.4 -0.4
Arshad & O'Kelly (2017)	53	6.7	0.25	70-74	Not reported	-0.5
Albiker et al. (2017)	60 60	5.8 5.8	0.36 0.71	44 44	1.35 1.72	-0.33 -0.33

As an example, LeBlanc et al. (2010) found a maximum T_c of approximately 4 for a related ζ_c of -0.6. In contrast, Albiker et al. (2017) determined maximum T_c-values of 1.35 to 1.72 for $\zeta_c = -0.33$ dependent on the load eccentricity, where a higher eccentricity led to an increase in the $T_{c,max}$-value. As the load eccentricity of LeBlanc et al. (2010) was $e/L = 1.19$ and Albiker et al. (2017) applied loads with a lever arm of $e/L = 0.36$ and $e/L = 0.71$, respectively, Albiker et al. (2017) concluded the difference in maximum T_c-values to be a result of varying load eccentricity. The test results presented in this study cannot confirm this hypothesis as no substantial influence of load eccentricity on the maximum T_c-value could be identified. Also maximum T_c-values derived are considerably smaller. Nevertheless, it has to be kept in mind that cyclic loads being defined in terms of load symmetry ζ_c and load magnitude ζ_b strongly depend on the definition of the reference load H_{ult} (or M_{ult}). As no clear definition for the ultimate pile capacity or reference load exists, a comparison of different results from literature with those reported here may be distorted. Moreover, the response of piles to lateral cyclic loading may differ when load levels exceed a certain limit. According to LeBlanc et al. (2010) the T_c-function should be independent of load magnitude, but as already mentioned, the loads applied in this study are relatively high due to the ultimate pile capacity criterion chosen. Based on the results presented here and those found in literature, an influence of load magnitude on the T_c-function should not be excluded.

5 Conclusions

A series of monotonic and cyclic 1g small scale monopile tests at two different (almost rigid) pile-soil systems has been conducted. The tests involved different load characteristics and varying load eccentricities to examine and evaluate the influence of these parameters on the pile deflection accumulation. From the monotonic and cyclic horizontal pile load tests, the following main conclusions can be drawn:

- Monotonic load deflection curves can be well described by the hyperbolic function proposed by Manoliu et al. (1985). The extrapolation of experimentally measured curves by this approach yields reasonable results. A comparison of the results derived by the Manoliu et al. (1985) approach to ultimate pile capacities calculated using the p-y method proves similarity. Therefore, the method proposed by Manoliu et al. (1985) was used to define H_{ult} as it allows a clear definition of pile failure and ultimate pile capacity.
- In comparison of test results of different authors reported in literature, it has to be kept in mind that different ultimate pile capacity definitions have been used. Hence, a direct comparison of tests with same ζ_b-values is not possible. Regarding the tests presented here, a quite high cyclic load magnitude has been applied due to the chosen ultimate pile capacity criterion.
- The cyclic pile test results reported here confirm the suitability of a power function (Eq. 3) to describe cyclic pile deflection accumulation for load cycle numbers $N > 500$. The factor T of this equation varies with pile dimensions, load characteristics and soil conditions. The accumulation parameter α has been found to increase with L/D-ratio and seems therefore to be dependent on the pile-soil stiffness. In contrast no influence of load eccentricity e/L on α could be identified.
- The cyclic test results expressed in term of T_c-functions as introduced by LeBlanc et al. (2010) confirm the general shape of this function for rigid piles having a maximum for unsymmetrical two-way loading. This is consistent with the findings of various authors indicating this type of loading to result in highest deflection accumulations. However, reported maximum T_c-values differ significantly ranging from approximately 4 (LeBlanc et al., 2010) to values slightly higher 1 (e.g. Klinkvort & Hededal, 2013). The maximum T_c-values derived in this study take values between 1.05 and 1.20.

Further testing is necessary to eliminate uncertainties regarding the parameters affecting pile displacement accumulation. Especially the broad spectrum of maximum T_c-values reported in literature needs further explanation. Based on the results presented here, an effect of load eccentricity, i.e. on the combination of horizontal load and the bending moment acting at the pile embedment point, on maximum T_c-value cannot be confirmed.

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