Aalborg Universitet

A Literature Study on the Effects of Cyclic Lateral Loading of Monopiles in Cohesionless Soils

L. Rasmussen, Kristian ; Hansen, Mette ; Kirk Wolf, Torben; Ibsen, Lars Bo; Roesen, Hanne Ravn

Publication date:
2013

Document Version
Publisher's PDF, also known as Version of record

A Literature Study on the Effects of Cyclic Lateral Loading of Monopiles in Cohesionless Soils

Kristian Lange Rasmussen
Mette Hansen
Torben Kirk Wolf
Lars Bo Ibsen
Hanne Ravn Roesen

ISSN 1901-7278
DCE Technical Memorandum No. 025

AALBORG UNIVERSITY
Department of Civil Engineering

Aalborg University
Department of Civil Engineering

DCE Technical Memorandum No. 025

A Literature Study on the Effects of Cyclic Lateral Loading of Monopiles in Cohesionless Soils

by

Kristian Lange Rasmussen
Mette Hansen
Torben Kirk Wolf
Lars Bo Ibsen
Hanne Ravn Roesen

June 2013

Scientific Publications at the Department of Civil Engineering

Technical Reports are published for timely dissemination of research results and scientific work carried out at the Department of Civil Engineering (DCE) at Aalborg University. This medium allows publication of more detailed explanations and results than typically allowed in scientific journals.

Technical Memoranda are produced to enable the preliminary dissemination of scientific work by the personnel of the DCE where such release is deemed to be appropriate. Documents of this kind may be incomplete or temporary versions of papers—or part of continuing work. This should be kept in mind when references are given to publications of this kind.

Contract Reports are produced to report scientific work carried out under contract. Publications of this kind contain confidential matter and are reserved for the sponsors and the DCE. Therefore, Contract Reports are generally not available for public circulation.

Lecture Notes contain material produced by the lecturers at the DCE for educational purposes. This may be scientific notes, lecture books, example problems or manuals for laboratory work, or computer programs developed at the DCE.

Theses are monograms or collections of papers published to report the scientific work carried out at the DCE to obtain a degree as either PhD or Doctor of Technology. The thesis is publicly available after the defence of the degree.

Latest News is published to enable rapid communication of information about scientific work carried out at the DCE. This includes the status of research projects, developments in the laboratories, information about collaborative work and recent research results.

Published 2013 by
Aalborg University
Department of Civil Engineering
Sohngaardsholmsvej 57,
DK-9000 Aalborg, Denmark

Printed in Aalborg at Aalborg University

ISSN 1901-7278
DCE Technical Memorandum No. 025

A Literature Study on the Effects of Cyclic Lateral Loading of Monopiles in Cohesionless Soils

K. L. Rasmussen, M. Hansen, T. K. Wolf, L. B. Ibsen, H. R. Roesen

Department of Civil Engineering, Aalborg University, Denmark

June 13, 2013

Abstract

Today, monopiles are the most typical foundation for offshore wind turbines. During their lifetime large diameter, stiff piles are subjected to millions of small cyclic loads due to environmental forces. The long-term cyclic loading can change the granular structure of the soil surrounding the pile. This may change the stiffness of the soil-pile system and create an accumulated rotation of the pile. The behaviour of the soil-pile system is very complex and the influence of soil parameters, number of load cycles, and size, amplitude and characteristic of the load are examined, as they all contribute to the rotation an the change in stiffness. The scope of this article is to outline current design methods and the state of the art knowledge within the subject of long-term cyclic, lateral loading of piles.

1 Introduction

Today's focus on renewable energy sources as a replacement for fossil fuels and gasses has made the offshore wind industry expand rapidly. Large farms with wind turbines still increasing in size are installed in rough environment and are subjected to lateral loads from wind, waves and current. Monopile foundations are the most common foundation of offshore wind turbines. Currently, these steel cylinders have reached a diameter of 4 - 6 m and have a slenderness ratio, $L/D < 10$, where L denotes the length of the pile and D is the diameter.

A wind turbine will, during its lifetime, be subjected to large loads caused by storms which describe the ultimate limit state (ULS). However, also smaller long-term cyclic loads will affect the serviceability limit state (SLS) and fatigue limit state (FLS). These cyclic loads will rock the pile and restructure the soil grains surrounding the pile. This may change the stiffness of the combined pile-soil system and induce accumulated rotation of the tower due to this change. Change in the stiffness of the pile-soil system changes the frequency of this system which then can interfere with the excitation frequencies. The excitation frequencies are the frequencies of the rotor and the blades, approximately 0.3 Hz and 1.0 Hz, respectively. The natural frequency of the tower is normally designed to be in-between to avoid resonance (LeBlanc et al., 2010a). The design criteria is often very strict due to operating behaviour and often the accumulated permanent rotation of the tower must not exceed 0.5°. As the rotation is an important factor in the design criteria it is important to investigate the effect of long-term cyclic loading on the pile-soil system. In the present standards, i.e. DNV (2010) and API (2007) cyclic loading is not given much attention. These standards use p-y curves based on few full-scale experiments for laterally loaded slender piles and use a simple reduction factor to reduce the ultimate soil resistance for cyclic loading. The effect of long-term cyclic loading of monopiles placed in cohesionless soil is possible to be a critical design factor and the effect of change in load characteristic, soil parameters, number of load cycles have not been properly examined.

A new potentially critical load case, long-term cyclic loading, is possibly the main design criteria and the effect of change in the above mentioned factors should be analysed. Therefore, the concept of degradation due to cyclic loading is of interest. Methods for determining degradation of p-y curves have been presented by Long and Vanneste (1994) and Lin and Liao (1999) based on full-scale tests. Other authors have tried to determine the cyclic load effect by other theories; Testing of soil, small-scale testing and numerical modelling. Niemunis et al. (2005) have suggested a model to predict accumulated deformations based on laboratory tests on sand. Triaxial tests in combination with theoretical and numerical models have been used by Hinz et al. (2006) and Achmus et al. (2009) to determine the relation between cyclic loading and deflection. Small-scale experiments are conducted by Peng et al. (2006), Peralta and Achmus (2010), LeBlanc et al. (2010a) and LeBlanc et al. (2010b) using theories on degradation and concept of superposition to evaluate cyclic loading effect on displacement and change in soil stiffness.

The scope of this article is to outline the current design methods, the state of the art knowledge on the topic and need for further investigations.

2 Behaviour of Cohesionless Soil under Long-Term Cyclic Loading

Subjected to cyclic loading cohesionless soil can experience accumulation of excess pore water pressure. The build-up of this will reduce the effective stresses causing cyclic liquefaction or cyclic mobility, cf. Figure 1.

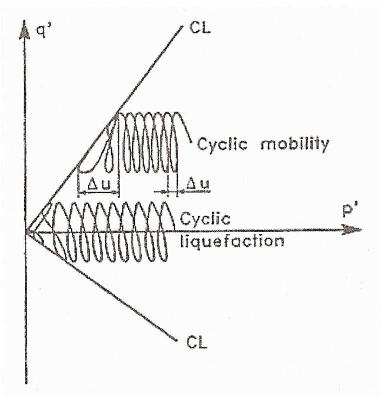

Figure 1: Definition of cyclic liquefaction and cyclic mobility. (Ibsen, 1994)

The build-up of excess pore water pressure is a system behaviour related to drainage conditions and therefore more relevant for shallow foundations. For cohesionless soils of very loose densities a contracting behaviour can be observed. However, the monopile is a deep foundation normally placed in rather dense sands, which makes the concept of cyclic liquefaction less relevant (Lesny, 2010). During the lifetime of an offshore wind turbine waves and wind will cause millions of small cyclic lateral loads. Subjected to those, cohesionless soil will deform both elastic and plastic. Theories on determining the accumulated plastic deformation due to relatively low long-term cyclic loading takes its origin in shakedown theory. Shakedown theory is originally developed for elastic-perfectly plastic materials. However, the theory is used to some extend in soil mechanics, even though behaviour of soils are more complicated. Shakedown has different deformation outcomes related to the type of force applied. For the given problem of long-term cyclic lateral loading elastic and plastic behaviour occurs initially. The shakedown is the development of accumulated plastic strains where the plastic strain increments will decrease with number of cycles and the material will stabilise with eventually only elastic deformation occurring, cf. Figure 2.

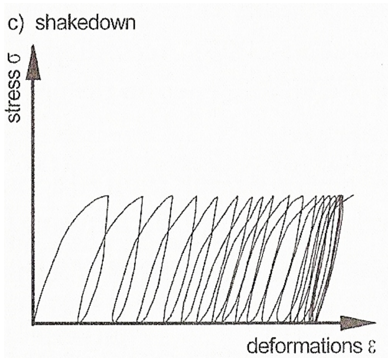

Figure 2: Principle of shakedown due to cyclic loading. (Lesny, 2010)

However, when applying the shakedown theory to soil mechanics in cohesionless soils the theory fits only partially. Cohesionless soil keeps deforming even after long time repetitive loading and does not reach perfect elasticity, but will keep deforming (Goldscheider, 1977). The constant development of strains can increase the accumulated strains of the structure to a point where it becomes unserviceable. Goldscheider (1977) investigated plastic shakedown in sand. After a larger number of cycles the plastic displacement increments will have become almost insignificant. He suggested the allowable total displacement was based on the number of cycles for the lifetime of the wind turbine with an additional small, negligible displacement, Figure 3.

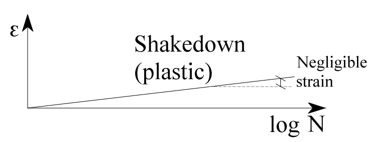

Figure 3: Principle of plastic shakedown. After Peralta (2010)

3 Current Design Regulations

Reese et al. (1974) and O'Neill and Murchison (1983) have formulated the theory on p-y curves for sand to describe the relationship between soil resistance created in the non-uniform stress field surrounding the pile and the lateral displacement of the pile under lateral load, cf. Figure 4. The bending of the pile is described by the fourth-order differential equation for beam bending (DNV, 2010)

$$E_p\, I_p \frac{\mathrm{d}^4 y}{\mathrm{d}z^4} + Q_A \frac{\mathrm{d}^2 y}{\mathrm{d}z^2} - p(y) = 0, \quad z \in [0; L] \quad (1)$$

where E_p and I_p are the elasticity modulus and the second moment of area of the pile, respectively. Q_A is the axial load from the turbine tower. The p-y curves are modelled using the Winkler approach with decoupled springs along the pile, each supporting a pile division. For each spring a non-linear p-y curve is created. These curves are adopted and used in current methods for designing laterally loaded piles in the standard codes DNV (2010) and API (2007). The methods are highly empirical as they are fitted by only a few full-scale experiments described by Cox et al. (1974). The experiments encompass both static and cyclic test with up to 100 load cycles. These experiments are conducted on piles in sand with a diameter of 0.61 m and with slenderness ratio about 30. Other tests have been conducted validating the p-y curves but all tests are conducted using slender piles. The basis for the p-y curves differs significantly from the piles used as monopiles today as the difference in slenderness ratio is pronounced and the amount of load cycles in the tests are limited.

The procedure for creating the p-y curves for cyclic lateral load on monopiles in sand by DNV (2010) is

$$p \;=\; A\, p_u \tanh\left(\frac{k\, z}{A\, p_u}\, y\right) \qquad (2)$$

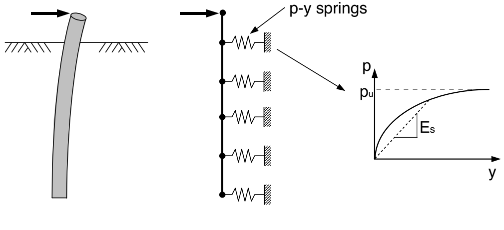

Figure 4: Principle for describing soil behaviour with p-y curves. (API, 2000)

where the p-y relationship is determined from the static ultimate load, p_u. k is the initial modulus of subgrade reaction, z is the distance from soil surface and $A = 0.9$ for cyclic loading. The p-y curves are formulated depending on very few properties of the sand and the pile respectively. For the sand, the angle of internal friction, the relative density, and the specific weight are considered. The dimensions of the pile are considered in terms of length and diameter. However, the general behaviour of the pile is assumed that of slender piles. The monopiles today have a slenderness ratio < 10 and so, this will give the piles a more rigid response which is not accounted for in the current design guidances, i.e. DNV (2010) and API (2007). The difference in behaviour of flexible and rigid piles has great influence on the soil behaviour and the development of a "toe-kick" is significant for rigid piles, cf. Figure 5.

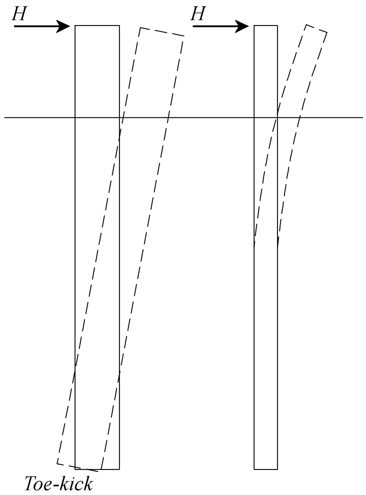

Figure 5: Principle for the behaviour of a rigid and a flexible pile.

Accumulation of displacement and change in stiffness of the soil-pile system are possible over time due to cyclic loading. The relation between the cyclic loading in coherence with number of load cycles and the load amplitude is not considered in the design standards.

4 Methodology for Long-Term Cyclic Loading

In order to incorporate the effect of long-term cyclic loading of a pile, the concept of degradation is adopted by means of different methods. A degradation index is presented by Idriss et al. (1978) as Equation (3) to describe the change in stiffness and shape of the hysteresis loop as a function of the number of cycles.

$$\delta = \frac{E_{sN}}{E_{s1}} = N^{-a} \tag{3}$$

where E_{sN} and E_{s1} are the secant moduli of N and 1 cycles, respectively, and a is the gradient of the regression line for a logarithmic scale, cf. Figure 6 and 7.

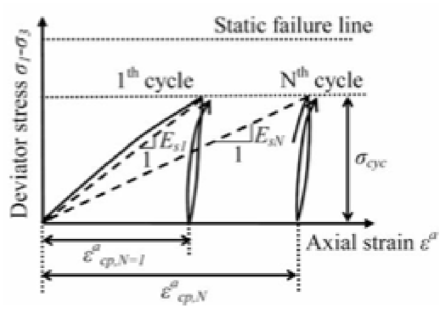

Figure 6: Degradation of stiffness after number of cycles. (Achmus et al., 2009)

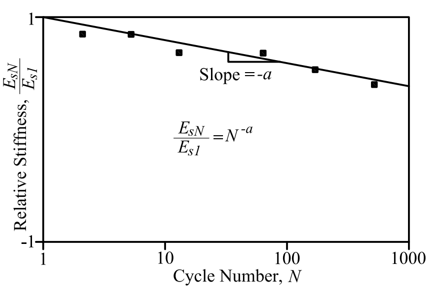

Figure 7: Degradation of stiffness after number of cycles. K is the subgrade modulus. After (Briaud and Little, 1988)

This degradation factor has become a generally adopted concept in determining cyclic load effects, leading to explicit methods for determining the stress-strain relations for cyclic loading. The concept was continued by Briaud and Little (1988) who proposed a power function for degrading the soil resistance as a function of the number of load cycles. With origin in this formulation and the static p-y curves Long and Vanneste (1994) analysed results from 34 full-scale laterally loaded pile tests to investigate which model parameters influenced the behaviour of the pile when repetitively loaded. The 34 tests varied in many aspects from each other: pile type and installation method, length and diameter of the pile, soil density, number of cycles, and load characteristic. The slenderness ratio spanned from 3 to 84 covering both very rigid and flexible piles placed in different cohesionless soils varying from loose to dense compaction. The piles were loaded differently; one- and two-way loaded, subjected from 5 to 500 load cycles. A degradation factor, m, was determined, influenced by the cyclic load ratio, F_L, The installation method, F_I, and the soil density, F_D.

$$m = 0.17\, F_L\, F_I\, F_D \tag{4}$$

Long and Vanneste (1994) specified expressions for calculating soil resistance, p, and displacement, y, as a function of load cycles when using static nonlinear p-y curves. The soil resistance was decreased while pile deflection was increased with increasing number of load cycles, cf Equation (5) and (6).

$$p_N = p_1\, N^{(\alpha-1)m} \tag{5}$$

$$y_N = y_1\, N^{\alpha\, m} \tag{6}$$

where the subnotation $_N$ denoted N cycles and $_1$ denoted the first cycle. The factor α controlled the relative contribution of soil resistance and deflection and was applied so change in p-y relation with depth could be incorporated. The value of the factor varied from 0 to 1. However, changing the α factor provided no improvement in results, so a constant value of $\alpha = 0.6$ was applied, making the method independent of depth.

Lin and Liao (1999) also developed an expression for a degradation parameter, t, to account for different model properties with the purpose of calculating the accumulation of pile displacements. This was derived from analysis of 26 full-scale lateral load tests with pile slenderness ratios from 4 to 84, subjected to a maximum of 100 load cycles. They derived the same factors of influence: Cyclic load ratio, ϕ, installation method, ξ, and soil density, β. In addition, the degradation factor was dependent on pile-soil relative stiffness ratio expressed by a depth coefficient, L/T.

$$t = \eta\, \frac{L}{T}\, \phi\, \xi\, \beta \tag{7}$$

where the coefficient η changes with the model parameters such as soil density, load characteristic and method of installation. To determine the accumulated displacement the relationship between strain, ε, and displacement, y, proposed by Kagawa and Kraft (1980) was used

$$\varepsilon = \frac{y}{2.5\, D} \tag{8}$$

where D is the diameter of the pile. Kagawa and Kraft (1980) investigated displacement due to lateral load and found that a large part of the accumulated strain happened within a radius of 2.5 m diameters of the pile. Lin and Liao (1999) use the strain ratio, R_s, expressed by a logarithmic function, to determine strains as a function of load cycles

$$R_s = \frac{\varepsilon_N}{\varepsilon_1} = 1 + t\ln(N) \tag{9}$$

where ε_N is the strain accumulation after N cycles and ε_1 iss the strain after the first cycle. Additionally, Lin and Liao (1999) investigate the combination of variable load amplitudes. Here, a principle of strain superposition similar to Miner's rule is used (Miner, 1945). An adapted version is proposed by Stewart (1986) to superpose strains in triaxial tests. This theory yields that a specific amount of strain can be developed for various numbers of load cycles at different load levels, cf. Figure 8. Thus, for cohesionless soils it is assumed that at some point the maximum strain will have accumulated independently of the size of the cyclic load; the number of cycles will differ instead. With origin in Equation (9) the amount of strain for a number of cycles at a given load level, N_a, can be found and from this, an equivalent number of cycles for a smaller load level, N_b^*, is determined.

$$N_b^* = \exp\left(\frac{1}{t_b}\left(\frac{\varepsilon_{1a}}{\varepsilon_{1b}}\left(1 + t_a\ln(N_a)\right) - 1\right)\right) \tag{10}$$

where t and ε_1 are the degradation factor and strain for the first load cycles for the respective load cases. a and b denote two different load levels. For varying load amplitudes the total amount of strain can be determined.

$$\varepsilon_{N(a+b)} = \varepsilon_{1b}\left[1 + t_b\ln(N_b^* + N_b)\right] \tag{11}$$

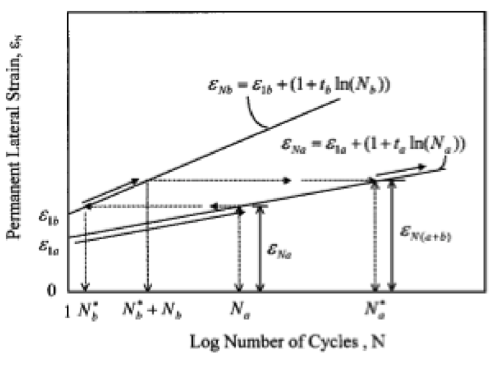

Figure 8: Method used in pile permanent displacement calculations for mixed loads. (Stewart, 1986)

Lin and Liao (1999) used 20 tests to develop the degradation factor, t. Measured and calculated displacements were then found for six additional tests with change in load levels and load characteristics for each ten cycles. In Figure 9 results from Lin and Liao (1999) are presented. As comparison, results from using the method by Long and Vanneste (1994) are presented for one load level along with the measured result by Briaud and Little (1988). For the first three load levels (up to 30 cycles) the calculated and measured displacements are much alike. However, at the fourth load level the calculations overrate the displacement.

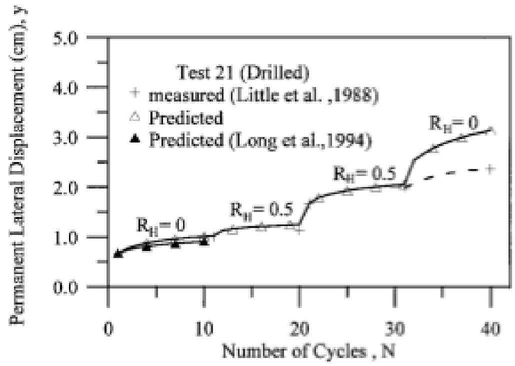

Figure 9: Permanent lateral displacement for number of cycles of test pile. After (Lin and Liao, 1999).

Both Long and Vanneste (1994) and Lin and Liao (1999) have presented simple methods for estimating displacements for piles. The disadvantage of using these explicit methods is their use of an empirical foundation: Their methods are based on experiments conducted on slender piles cyclically loaded to a maximum of 500 cycles. When using these explicit methods for larger numbers of cycles, variation in characteristic and model dimensions should be investigated. Solving implicitly using the finite element method, strains are determined for every load cycle in the load history. This can accumulate computational error when calculating strains for thousands of cycles and the process is time consuming. The studies already done on the effect of cyclic behaviour show that it is a very complex problem. The soil/pile system is affected by material properties of both soil and pile, geometry of the pile and the multifaceted loading. There is a need for experimental work that can validate and improve the theoretical basis so it fits today's problem of cyclic long-term loading of monopiles.

5 Experimental Studies of Cyclic Loading

The formulations by Long and Vanneste (1994) and Lin and Liao (1999) are based on full-scale tests. The formulas are based on empirical data with only a low number of load cycles. Further experiments are needed as a basis for determining the effect of long-term lateral loading. The full-scale test is the primary and best basis to support the theory but it is very expensive and time consuming. A small-scale test is therefore often used in several experiments to obtain data from long-term cyclic loading which then is converted to fit real conditions. Some of the newer research on cyclic loading is presented in the following.

When working with cyclic lateral loading the load characteristics are defined by the ratios ζ_b and ζ_c (LeBlanc et al., 2010a). ζ_b describes the ratio between the maximum cyclic moment, M_{max}, and the maximum static moment capacity, M_S. ζ_c describes the ratio between maximum and minimum moment, M_{min}, of a load cycle.

$$\zeta_b = \frac{M_{max}}{M_S} \,,\; \zeta_c = \frac{M_{min}}{M_{max}} \qquad (12)$$

Peng et al. (2006) investigated different loading devices for small-scale testing and invented a device themselves where the effect of long-term cyclic loading was examined. Most of their focus was on the actual testing device but some test results were presented. They investigated two-way loading of a 44.5 mm wide pile with a slenderness ratio of 9. The pile was placed in dry sand with a relative density of 71.7 %. The applied loading was in the ranges ζ_b = 0.2 to 0.6 and ζ_c = (-1) to (-0.6) creating load amplitude both in and out of balance. 10000 load cycles were conducted for each test and within that range Peng et al. (2006) concluded that the accumulated pile displacement would keep increasing and that displacements were largest for unbalanced loading.

A development in the concept of degradation was made by Achmus et al. (2009) who researched the degradation of stiffness in cohesionless soils as a consequence of cyclic loading. Based on triaxial tests and FEM, design charts for determining deflection along a pile as function of the number of cycles were developed. The degradation was expressed by means of the ratio of the secant elastic modulus, cf. Figure 6. The secant modulus, E_s, is elastic and dependent on the stress conditions along the pile.

$$E_s = k\,\sigma_{at}\left(\frac{\sigma_m}{\sigma_{at}}\right)^{\lambda} \qquad (13)$$

where k and λ are material parameters and σ_{at} and σ_m are atmospheric pressure and mean principal stress. The accumulation of strains and thereby the plastic strain ratio is estimated by the semi-empirical approach presented by Huurman (1996).

$$\frac{E_{sN}}{E_{s1}} \cong \frac{\varepsilon_{cp,1}}{\varepsilon_{cp,N}} = N^{-b_1(X)^{b_2}} \qquad (14)$$

where ε_{cp} is the plastic axial strain. The ratio of secant stiffness and the ratio of the plastic axial strain are determined between the N^{th} and the first cycle. b_1 and b_2 are material parameters and X is the cyclic stress ratio which defines the relation between major principal stresses for cyclic stress state and static failure state. In triaxial tests the initial stress state is isotropic with constant confining pressure during cyclic loading. For real in situ conditions the stresses are anisotropic so to overcome these differences a characteristic cyclic stress ratio, X_c, is defined.

$$X_c = \frac{X^1 - X^0}{1 - X^0} \qquad (15)$$

where indices 1 and 0 define states of loading and unloading. The outcome of the study is design charts recommended by Achmus et al. (2009) for preliminary design giving the deflection as function of number of load cycles, cf. Figure 10. The charts provide deflection curves for up to 10000 cycles. However, the study lacks the support of full- or small-scale tests.

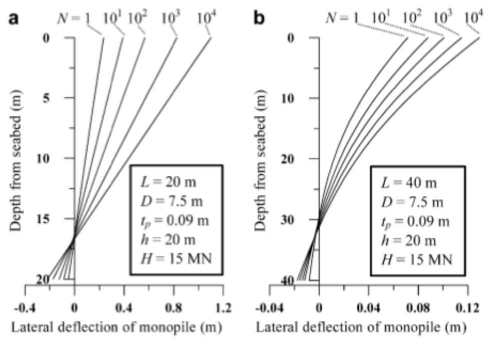

Figure 10: Deflection-Number of cycles curve. (Achmus et al., 2009)

Peralta and Achmus (2010) conducted a series of 13 small-scale tests on rigid and flexible piles with 60 mm diameter and slenderness ratio from 3.2 to 8.3. The piles were tested in medium dense to dense sand with relative densities, D_r, from 0.40 to 0.60. They were subjected to one-way loading of varying load size, ζ_b, for 10000 load cycles and the displacement of the pile was found.

The accumulated displacements obtained from the experiments were compared with results obtained from the power and logarithmic functions by Long and Vanneste (1994) and

Lin and Liao (1999) expressed in Equation (6) and (9), respectively. It was found that the results from flexible piles fitted the logarithmic function best while the power function fitted the results from the rigid piles best.

Small-scale tests were conducted by LeBlanc et al. (2010a) who also put a great amount of work in to the scaling of model and real conditions. They made 21 tests on piles in sand with relative densities, D_r, of 0.04 and 0.38; 6 static and 15 cyclic tests. The pile had a diameter of 80 mm and a slenderness ratio of 4.5. The tests were conducted with variation in ζ_b from 0.2 to 0.53 and ζ_c from -1 to 1 describing both static loading and one- and two-way cyclic loading. The number of load cycles also varied from approximately 8000 to 65000. LeBlanc et al. (2010a) suggest that the best fit of the accumulation of rotation is a power function.

$$\frac{\Delta\theta(N)}{\theta_s} = \frac{\theta_N - \theta_1}{\theta_s} = T_b(\zeta_b, R_d)T_c(\zeta_c)N^{0.31} \quad (16)$$

where θ_N is the rotation at N cycles, θ_1 is the rotation after the first load cycle and θ_s is the rotation in a static test at a load equivalent to the one provided by the maximum cyclic load, cf. Figure 11.

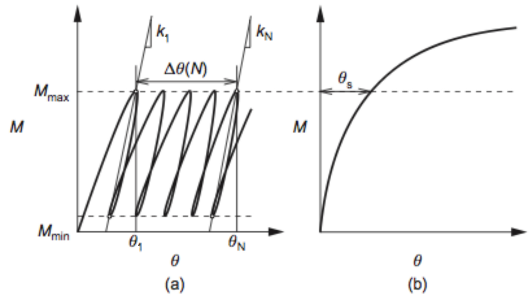

Figure 11: Method for determination of stiffness and accumulated rotation: (a) cyclic test; (b) static test. After (LeBlanc et al., 2010a)

T_b and T_c are dimensionless functions depending on the load characteristics and relative density. For T_b a linear relationship with ζ_b is found depending on D_r, cf. Figure 12. A non-linear relationship between T_c and ζ_c is also found illustrating that the largest accumulation of rotation happens when ζ_c= -0.6 which is a two-way loading.
A study on the change in stiffness of the soil-pile system did not provide as clear results as the rotation accumulation. It cannot be concluded how the stiffness is affected by the relative density. However, similar for all tests is an increase in stiffness with increase in number of load cycles. This increase is contradictory to current methodology which uses degradation of static p-y curves to account for cyclic loading.

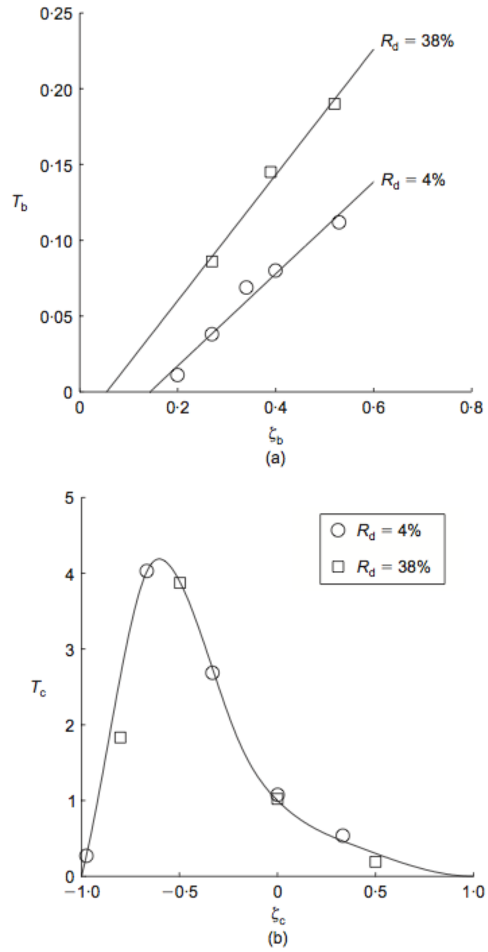

Figure 12: Functions relating (a) T_b and (b) T_c to relative density, D_r, and characteristics of cyclic load in terms of ζ_b and ζ_c. (LeBlanc et al., 2010a)

Achmus et al. (2011) presented a FE-model based on strain degradation to verify the results obtained by LeBlanc et al. (2010a) and found good agreement between the simulations and the test results.

Based on the method by LeBlanc et al. (2010a) and a super positioning concept similar to Miner's rule, LeBlanc et al. (2010b) created design charts for determining the accumulated pile rotation due to random two-way loading. The procedure is based on a limited amount of empirical data from small-scale tests and further research should by carried out to investigate the complicated behaviour of change in parameters.

6 Summary

Currently, the design guidance is limited in knowledge on long-term cyclic loading of laterally loaded piles. They are based on full-scale testing of slender piles subjected to a low number of cycles.

The issue of long-term lateral loading is of complex matters. The physical behaviour of sand subjected to load cycles is a continuous plastic deformation with decreasing deformation increments. This effect of long-term lateral loading has been formulated by Long and Vanneste (1994) and Lin and Liao (1999) as an exponential and a logarithmic expression, respectively, depending on a degradation factor. Both authors find that the degradation factor can be determined based on installation method, soil density and load ratio. In addition Lin and Liao (1999) incorporates a depth coefficient. Still, these theories are based on full-scale testing of no more than 500 load cycles. The small-scale tests on laterally loaded piles focus on a high number of load cycles, i.e. approximately 10000 cycles. Different load scenarios with varying load characteristic and amplitude is tested with the outcome that Peng et al. (2006), Peralta and Achmus (2010) and LeBlanc et al. (2010a) agree that the pile will keep deforming and the exponential expression by Long and Vanneste (1994) fits rigid piles behaviour.

The influence of long-term lateral loading of offshore wind turbines is a multifaceted problem. Though many author have studied the area it is clear that no general approach have been accomplished yet and further studies are needed.

References

Achmus, Kuo, and Abdel-Rahman, **2009**. M. Achmus, Yu-Shu Kuo, and Khalid Abdel-Rahman. *Behaviour of Monopile Foundations under Cyclic Lateral Load*. Computer and Geotechnics, 36(5), 725–735, 2009.

Achmus, Albiker, and Abdel-Rahman, **2011**. M. Achmus, J. Albiker, and Khalid Abdel-Rahman. *Investigations on the Behaviour of Large Diameter Piles under Cyclic Lateral Load*. 2011. ISBN: 978-0-415-58480-7.

API, **2007**. American Petroleum Institute API. *Recommended Practice for Planning, Designing and Constructing Fixed Offshore Plat-forms-Working Stress Design, RP 2A-WSD*, 2007.

API, **2000**. American Petroleum Institute API. *User Manual Program PYGMY.* The University of Western Australia, Department of Civil and Resource Engineering, 2000.

Briaud and Little, **1988**. J. L. Briaud and R. L. Little. *Full Scale Cyclic Lateral Load Tests on six Single Piles in Sand*. Miscellaneous Paper, Geotechnical Division, Texas AandM University, College Station, Texas, USA, GL 88-27, 1988.

Cox, Reese, and Grubbs, **1974**. W. R. Cox, L. Reese, and B. R. Grubbs. *Field Testing of Laterally Loaded Piles in Sand*. Proc. 6th Offshore Technological Conference, Houston, Paper No. 2079, 459–472, 1974.

DNV, **2010**. Det Norske Veritas DNV. *Offshore standard DNV-OS-J101: Design of offshore wind turbine structures. Technical report DNV-OS-J101*, 2010.

Goldscheider, **1977**. M. Goldscheider. *Shakedown and Incremental Collapse of Structures in Dry Sand Bodies*, 1977.

Hinz, Lesny, and Richwien, **2006**. P. Hinz, K. Lesny, and W. Richwien. *Prediction of Monopile Deformation under High Cyclic Lateral Load*. Institute for Soil Mechanics and Foundation Engineering, Germany, 2006.

Huurman, **1996**. M. Huurman. *Development of Traffic Induced Permanent Strain in Concrete Block Pavements*. Heron, 41(1) 2952, 1996.

Ibsen, **1994**. L. B. Ibsen. *The Stable State in Cyclic Loading*. Soil Dynamics and

Earthquake Engineering, Vol. 13, No. 1, 63–72, 1994.

Idriss, Dobry, and Singh, **1978**. I. M. Idriss, R. Dobry, and R. D. Singh. *Nonlinear Behavior of Soft Clays During Cyclic Loading.* Journal of Geotechnical Engineering Division, ASCE, Vol. 104, No. GT12, 1427–1447, 1978.

Kagawa and Kraft, **1980**. T. Kagawa and L. M. Kraft. *Lateral load-deflection relationships of piles subjected to dynamic loadings.* Soils and Foundations, 20(4), 19–34, 1980.

LeBlanc, Houlsby, and Byrne, **2010a**. C. LeBlanc, G. Houlsby, and B. Byrne. *Response of Stiff Piles to Long-term Cyclic Lateral Load.* Géotechnique 60, No. 2, 79–90, 2010a.

LeBlanc, Houlsby, and Byrne, **2010b**. C. LeBlanc, G. Houlsby, and B. Byrne. *Response of Stiff Piles to Long-term Cyclic Lateral Load.* Géotechnique 60, No. 9, 715–721, 2010b.

Lesny, **2010**. Kerstin Lesny. *Foundations of Offshore Wind Turbines - Tools for Planning and Design.* 1. edition, 2010. ISBN:978-3-86797-042-6.

Lin and Liao, **1999**. S. S. Lin and J. C. Liao. *Permanent Strains of Piles in Sand due to Cyclic Lateral Loads.* Journal of Geotechnical and Geoenvironmental Engineering, 125(No. 9), 789–802, 1999.

Long and Vanneste, **1994**. J. Long and G. Vanneste. *Effects of Cyclic Lateral Loads on Piles in Sand.* Journal of Geotechnical and Geoenvironmental Engineering, 120(No. 1), 225–244, 1994.

Miner, **1945**. M. A. Miner. *Cumulative Damage in Fatigue.* Journal of Applied Mechanics, 12, A159–A164, 1945.

Niemunis, Wichtmann, and Triantafyllidis, **2005**. A. Niemunis, T. Wichtmann, and T. Triantafyllidis. *A High-cycle Accumulation Model for Sand.* Computer and Geotechnics, 32(4), 245–263, 2005.

O'Neill and Murchison, **1983**. M. W. O'Neill and J. M. Murchison. *An Evaluation of p-y Relationships in Sands*, 1983.

Peng, Clarke, and Rouainia, **2006**. J. R. Peng, B. G. Clarke, and M. Rouainia. *A Device to Cyclic Lateral Loaded Model Piles.* Geotechnical Testing Journal, 29(4), 1–7, 2006.

Peralta, **2010**. K. P. Peralta. *Investigations on the Behaviour of Large Diameter Piles under Long-term Lateral Cyclic Loading in Cohesionless Soil*, 2010.

Peralta and Achmus, **2010**. K. P. Peralta and M. Achmus. *An Experimental Investigation of Piles in Sand Subjected to Lateral Cyclic Loads*, 2010. ISBN 978-0-415-59288-8.

Reese, Cox, and Koop, **1974**. L.C. Reese, W. R. Cox, and F. D. Koop. *Analysis of Laterally Loaded Piles in Sand.* OTC Huston, (paper no. 2080), 1974.

Stewart, **1986**. H. E. Stewart. *Permanent Strains from Cyclic Variable-Amplitude Loadings.* Journal of Geotechnical Engineering, Vol. 112(No. 6), 646–660, 1986.

Recent publications in the DCE Technical Memorandum Series

ISSN 1901-7278
DCE Technical Memorandum No. 025