Experimental Testing of Monopiles in Sand Subjected to One-Way Long-Term Cyclic Lateral Loading

Étude expérimentale de monopiles dans le sable soumis à un chargement cyclique transversal non alterné

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ABSTRACT: In the offshore wind turbine industry the most widely used foundation type is the monopile. Due to the wave and wind forces the monopile is subjected to a strong cyclic loading with varying amplitude, maximum loading level, and varying loading period. In this paper the soil–pile interaction of a monopile in sand subjected to a long-term cyclic lateral loading is investigated by means of small scale tests. The tests are conducted with a mechanical loading rig capable of applying the cyclic loading as a sine signal with varying amplitude, mean loading level, and loading period for more than 60 000 cycles. The tests are conducted in dense saturated sand. The maximum moment applied in the cyclic tests is varied from 18% to 36% of the ultimate lateral resistance found in a static loading test. The tests reveal that the accumulated rotation can be expressed by use of a power function. Further, static tests conducted post cyclic loading indicate that the static ultimate capacity increases with the magnitude of cyclic loading.

RÉSUMÉ: Dans l'industrie éolienne offshore, le type de fondation le plus largement utilisé est la monopile. En raison de la force des vagues et du vent, la monopile est soumise à une charge cyclique élevée dont l'amplitude, le niveau de charge maximale et la périodicité varient. Dans cet article, l'interaction sol-pieu d'une monopile implantées dans du sable et soumises à un chargement latéral cyclique est étudiée au moyen d'essais à échelle réduite. Les tests sont effectués avec une grue de chargement mécanique capable d'appliquer un chargement cyclique sinusoïdal avec amplitude, niveau moyen et période de chargement variable pendant plus de 60 000 cycles. Les tests sont effectués dans du sable dense saturé. Le moment maximum appliqué durant les essais cycliques varie de 18% à 36% de la résistance latérale ultime obtenue lors d'essais de chargement statique. Les essais montrent que la rotation accumulée peut être exprimée par l'utilisation d'une fonction de puissance. En outre, des essais statiques menés après le chargement cyclique indiquent que la capacité statique ultime augmente avec le niveau du chargement cyclique.

KEYWORDS: Experimental, wind turbine foundation, monopile, long-term cyclic loading, dense sand.

1 INTRODUCTION

In the offshore wind turbine industry, the most widely used foundation type is the monopile, i.e. a large diameter stiff pile. During the lifetime of a wind turbine, the monopile foundation is subjected to few load cycles with large amplitudes, caused by the strong storms, and also to millions of lateral load cycles with low or intermediate amplitudes due to the wave loading. This loading may cause failure in the fatigue or serviceability limit states, FLS and SLS respectively (Wichtmann et al. 2008). The cyclic loading might induce a change in the soil stiffness and a permanent accumulated rocking rotation (tilt) of the turbine. Due to the efficiency of the wind turbine, strict demands for the rotation and the stiffness of the entire structure are normally made and thus, the change in stiffness and rotation becomes key issues in the design. However, the current design guidance, DNV (2011), on this long-term loading is limited and a procedure for designing large diameter piles is yet to be fully expressed and confirmed. The development of a reliable design method requires verification and for that in-situ and large-scale testing is by far the best tool. However, this is also the most expensive and time-consuming tool. Therefore, the recent choice for evaluating the cyclic behaviour has been numerical modelling and small scale testing. Several authors has investigated this e.g. Niemunis et al. (2005), Achmus et al. (2005), Peng et al. (2006), LeBlanc et al. (2010) and Achmus et al. (2011). However, the research has mainly been based on cyclic triaxial tests, FEM-calculations and 1g experimental setups in dry sand.

In this paper, a 1g testing rig for modelling the environmental loading on a stiff monopile foundation in dense saturated sand is described and the results from four one-way cyclic loading tests are presented. The purpose of the cyclic tests is to evaluate the influence of the number of load cycles, N, on the accumulated rocking rotation of the pile at seabed, under long-term cyclic loading with constant frequency but different loading amplitude and mean loading level.

The characteristic of the cyclic loading can be described by the ratios ζ_b and ζ_c as defined by LeBlanc et al (2010). ζ_b expresses the magnitude of the loading as the ratio between the maximum load in a load cycle and the maximum static lateral capacity, $\zeta_b = M_{max}/M_{static}$. ζ_b will take a value between 0 and 1. The cyclic load ratio ζ_c defines the direction of the loading on the basis of the minimum and maximum load in a load cycle, $\zeta_c = M_{min}/M_{max}$. ζ_c will take the value 1 for a static test, 0 for one-way loading, and -1 for two-way loading.

2 EXPERIMENTAL MODEL TESTS

The 1g small scale tests are carried out at the geotechnical laboratory at Aalborg University, Denmark. In the tests an open ended aluminium pipe pile is used. The pile is scaled approximately 1:50 in relation to a typical offshore monopile. In Table 1 the dimensions of the model pile are presented.

Table 1. Dimensions of the open ended aluminium pipe pile.

Diameter D (mm)	Embedded length L (mm)	Wall thickness t (mm)	Load eccentricity e (mm)
100	500	5	600

The bending stiffness of the model pile is similar to a scaled prototype steel pile, however, the behaviour of the pile during loading also depends on the stiffness of the surrounding soil. According to Poulus and Hull (1989) a pile behaves flexible if $L > L_c$ and rigidly if $L < L_c/3$, where L_c is a critical length defined by Eq. 1. $E_p I_p$ is the bending stiffness of the pile and E_s is Youngs modulus of elasticity of the soil.

$$L_c = 4.44 \left(\frac{E_p I_p}{E_s}\right)^{0.25} \tag{1}$$

Due to the low stresses in the soil at 1g small scale testing, the stiffness is also low. From previous testing and numerical modelling an estimated soil stiffness of 4 MPa can be used for the sand in the test setup (Roesen et al. 2010). With use of Eq. 1 the model pile is thereby found to behave rigidly during lateral loading. In comparison a prototype steel monopile with $D = 5$ m and $t = 0.07$ m installed in sand with E_s = 70 MPa is found to behave rigidly with a slenderness ratio $L/D = 3$ and behave flexible with $L/D = 9$. Thus, for the examined slenderness ratio ($L/D = 5$) the model pile experiences a more rigid behaviour than the prototype pile. Nevertheless, the results obtained in the small scale model tests can be used as underlying basis for understanding the monopile behaviour during lateral cyclic long-term loading.

The test setup consists of a cylindrical sand container with an inner radius of 2.00 m and a height of 1.20 m surrounded by a loading frame equipped for both static and cyclic loading. The setup is an improvement of the system presented in Roesen et al. (2012) which originally is based on the setup presented by LeBlanc et al. (2010). A cross-sectional sketch and a photo of the system are shown in Figure 1 and 2. The pile is installed in the middle of the container by use of a mechanical motor with installation velocity of 0.02 mm/s. The container holds up to 0.90 m dense saturated sand with 0.30 m highly permeable gravel underneath. In the bottom a drainage system with perforated pipes ensures homogeneous in- and outflow of water.

The cyclic loading system is a simple load controlled system based on a lever arm, weight hangers with applied masses, m_1, m_2, and m_3, wires, and an electric motor controlling the rotation of weight m_1. The rotation causes an oscillating motion on the lever and thereby a cyclic loading on the pile. The system is thereby capable of providing sinusoidal loading to the pile for more than 60 000 load cycles. The rotational frequency of the motor is set to 0.1 Hz to be in agreement with environmental wave loading (Peng et al. 2006).

Initially, when the mass $m_1 = m_2 = 0$, the mass m_3 is chosen to outbalance the system. Depending on the weights chosen for m_1 and m_2 the system is capable of providing both one- and two-way loading with varying ζ_b and ζ_c, i.e. different direction, amplitude, and mean loading level. The loading is applied through steel wires attached to the pile 600 mm above soil surface. Hence, the pile experiences both horizontal and moment loading. In both sides of the pile a HBM U2A 100 kg load cell is attached measuring the actual force applied to the pile throughout the whole test. The displacement of the pile is measured using three WS10-125-R1K-L10 displacement transducers from ASM GmbH. The transducers, $D1$, $D2$, and $D3$ are mounted 600 mm, 375 mm, and 155 mm above soil surface, respectively. The rocking rotation, θ, and displacement of the pile at soil surface is found by use of linear regression of the three measurements assuming rigid pile behaviour. The data sampling rate is 2 Hz.

Before conducting any cyclic tests a static loading test is performed. The static test is conducted displacement controlled by use of a motor with a loading rate of 0.02 mm/s. The displacement is actuated 600 mm above soil surface, i.e. the same height as the loading in the cyclic loading tests. The pile is loaded to a rotation of 2°, unloaded, and reloaded to failure. The static test is used as a reference for the ultimate lateral resistance and the maximum resistance obtained is interpreted as the ULS load on the pile.

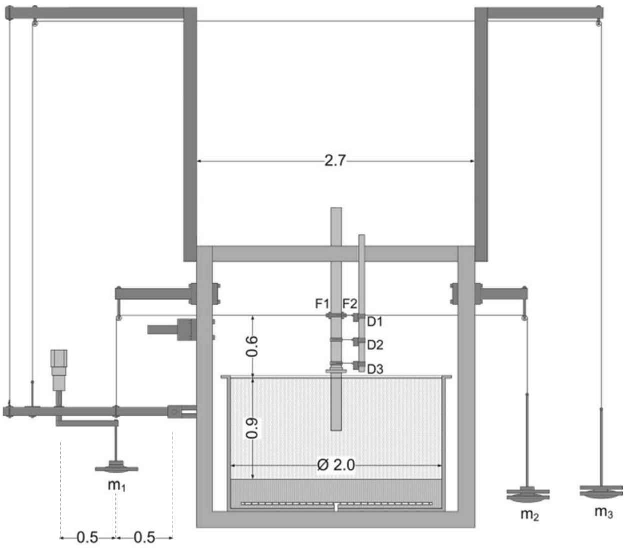

Figure 1. Sketch of the test setup. F1 and F2 refer to the two load cells, D1, D2, and D3 refer to the three displacement transducers and m_1, m_2, and m_3, refer to the weights applied on the load hangers. All measurements are in meters.

Figure 2. Test setup for cyclically long-term loaded monopiles.

Table 2. Test programme with relative soil densities, D_r, loading characteristics, and number of cycles, N.

Test No.	Type	D_r (%)	ζ_b	ζ_c	N	Static test after cyclic loading
1	Static	78.56	-	-	-	-
2	Cyclic	87.76	0.18	0.03	50 894	yes
3	Cyclic	85.38	0.24	0.10	51 732	no
4	Cyclic	87.87	0.25	-0.01	50 960	yes
5	Cyclic	91.70	0.36	0.03	60 224	yes

In total four long-term cyclic loading tests are performed, each with more than 50 000 load cycles. The tests are conducted with $m_1 = m_2$, i.e. one-way loading with the target $\zeta_c = 0$. The magnitudes of the loading in the cyclic tests are chosen to reflect realistic loading conditions for FLS and SLS loading, which according to LeBlanc et al. (2010) is approximately 30% and 40% of the ultimate limit state loading (ULS), respectively. Thus, the target maximum moment applied in the cyclic loading tests are defined as 20%, 25%, 30% and 40% of the maximum static lateral resistance, i.e. ζ_b is chosen in the interval 0.2 to 0.4. In Table 2 a summary of the testing programme with the obtained loading characteristics is presented.

In general the magnitude of the loading is seen to be a little less than expected. This result verifies the importance of measuring the actual force on the pile as some of the applied load is lost in the system due to friction. For three of the tests the cyclic load ratio, ζ_c, is seen to be close to zero which is in agreement with the target loading.

In order to investigate the influence of cyclic loading on the ultimate lateral resistance static loading tests were performed after the cyclic loading.

2.1 *Soil Conditions*

The tests are conducted using saturated Aalborg University Sand No. 1 (Baskarp Sand No.15). In Table 3 the properties of the sand are summarised.

Table 3. Properties of Aalborg University Sand No. 1

Specific grain density	Maximum void ratio	Minimum void ratio	50%-quantile	Uniformity coefficient
d_s	e_{max}	e_{min}	d_{50}	$U = d_{60}/d_{10}$
(-)	(-)	(-)	(mm)	(-)
2.64	0.858	0.549	0.14	1.78

Prior to each test the sand is prepared by use of an initially upward gradient of 0.9 followed by mechanical vibration with a rod vibrator. The obtained homogeneity and compaction of the sand is verified by conducting three cone penetration tests (CPT) with a laboratory cone; one in the middle of the container and two in a distance 400 mm from the centre in the active and passive side of the pile, respectively. The relative densities of the sand, D_r, are derived in accordance to Ibsen et. al (2009) where the laboratory cone is correlated with in-house triaxial tests on the same sand type. The mean values of the relative densities found prior to each experiment are presented in Table 2 together with the characteristic of the tests themselves.

3 TEST RESULTS

Initially, the static loading test is used as a reference test for the ULS moment capacity and thus the choice of maximum moment loading in the cyclic tests. The moment-rotation relationships obtained in both the static and the cyclic tests are presented in Figure 3. The static test clearly defines a maximum moment capacity of 360 Nm which is interpreted as the ULS load. In all the cyclic tests the rotation obtained in the first loading cycle follows the static reference test cf. Figure 3. This verifies the use of the static test as a reference for the loading despite the difference in relative densities of the soil cf. Table 2. Even though the cyclic loading system is an improvement of the system presented in Roesen et al. (2012) the maximum moment loading in the cyclic tests are seen to decrease a little during the test. Therefore, the characteristics of the cyclic loading, $\zeta_b$and ζ_c cf. Table 2, are calculated as mean values over the whole test and $\zeta_b$is seen to be lower than the target value.

In Figure 4 the rotation of the pile, θ, at soil surface as a function of the number of cycles, N, for test no. 2 is presented. The figure shows the cyclic response during loading and the rotation is seen to accumulate throughout the entire test. Similar results are obtained in the three other tests. In the evaluation of the accumulated rotation the maximum values of the rotation are used, i.e. the rotation marked with dark grey in Figure 4. As seen in Figure 3 the rotation in the first loading cycle is equal to the rotation obtained in the static reference test. Thus, in order to evaluate the influence of the cyclic loading only the accumulated rotation, $\Delta\theta(N) = \theta_N - \theta_1$, is investigated. $\theta_N$is the rotation obtained at the N^{th} loading cycle and $\theta_1$is the rotation obtained in the first loading cycle.

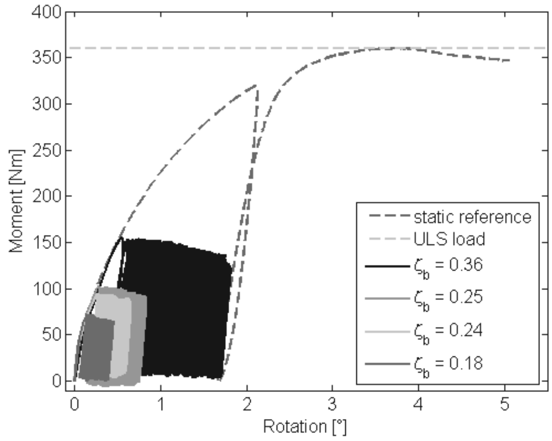

Figure 3. Moment-rotation relationships of the static reference test and the four cyclic loading tests.

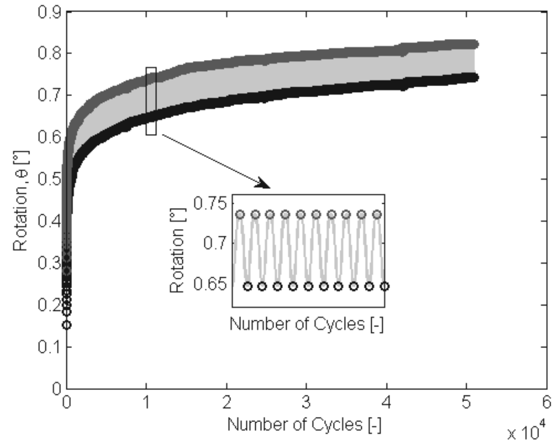

Figure 4. Rotation of the pile at soil surface as a function of the number of cycles in the test with $\zeta_b = 0.25$. Maximum and minimum values of the rotation are indicated by dark grey and black colouring.

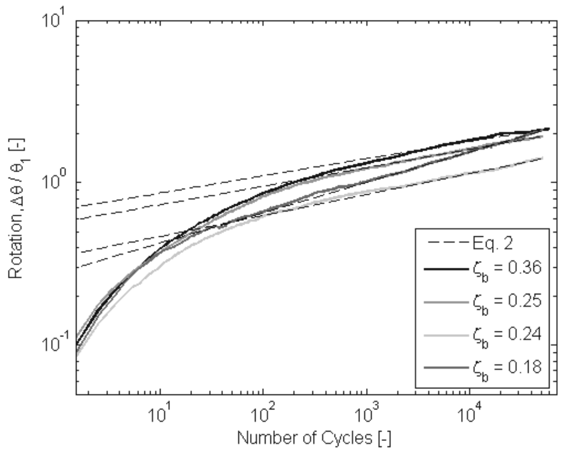

Figure 5. Normalised accumulated rotation as a function of the number of cycles for the four cyclic tests.

In Figure 5 the accumulated rotation obtained in all four cyclic tests are presented. The rotations are normalised with respect to the rotation obtained in the first loading cycle. The accumulated rotations of the stiff pile are fitted with a power function as suggested by several authors, e.g. Long and Vanneste (1994), Peralta and Achmus (2010), and LeBlanc et al. (2010). The fitted expression is given by Eq. 2 and shown as the dotted black lines in Figure 5.

$$\frac{\Delta\theta}{\theta_1} = a\, N^b \tag{2}$$

a and b are dimensionless constants determined empirically from the tests. The results from the long-term one-way loading cf. Figure 5 shows a general good agreement with the power function even though deviations in the first 1000 cycles are observed. The values for the power b are found to be similar for all the tests with values in the range of 0.11 to 0.18. These values are found to be smaller than the value of 0.31 as presented by LeBlanc et al. (2010). The results for the constant a cf. Figure 6 indicates that a depends linearly of the magnitude of the loading ζ_b which is in agreement with the findings in LeBlanc et al. (2010).

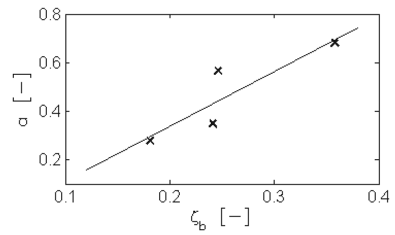

Figure 6. Fitted empirical constant a as a function of the loading magnitude ζ_b in the four cyclic tests.

The influence of the cyclic loading on the static lateral capacity is evaluated by means of the results from the three static tests performed post cyclic loading cf. Figure 7. The maximum moments obtained indicates that the lateral capacity depends on the cyclic loading and increases with increasing load magnitude.

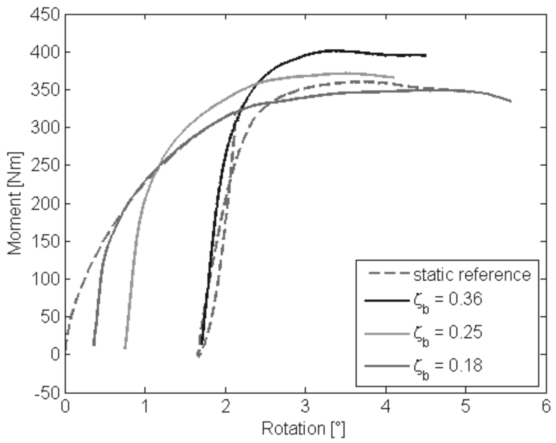

Figure 7. Moment-rotation relationships obtained in the static tests post cyclic loading compared with the reference static test.

4 CONCLUSION

This paper presents a description of a 1g laboratory small scale test setup for modelling laterally long-term cyclic loading of a stiff pile in saturated dense sand. A static loading test and four one-way cyclic loading tests with maximum moment loading equal to 18% to 36% of the maximum static capacity are presented. The purpose of the tests is to evaluate the influence of the number of load cycles on the accumulated rocking rotation of the pile at seabed during long-term cyclic loading. In addition the effect of the cyclic loading on the static lateral capacity is evaluated by means of static loading tests conducted post cyclic loading.

All the tests are carried out with an open ended aluminium pipe pile scaled approximately 1:50 in relation to a typical monopile foundation for an offshore wind turbine. In the four cyclic tests more than 50 000 load cycles are applied to the pile. When evaluating the cyclic tests the accumulated rotation normalised with respect to the rotation obtained in the first loading cycles is used. The results reveal that the accumulation of rotation during long-term cyclic loading can be described by use of a power function. Further, the maximum moments obtained in the static tests conducted post cyclic loading indicates that the lateral capacity depends on the cyclic loading and increases with increasing load magnitude.

The entire test setup is still in the initial phase of testing and can be improved even more. Thus, the findings inhere must be evaluated further and supplemented with additional testing with varied loading characteristics, i.e. varied ζ_b and ζ_c for both one- and two-way loading.

5 ACKNOWLEDGEMENTS

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