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Long-term horizontal cyclic loading model test results of monopile for offshore wind turbines

Résultats de l'essai sur modèle de chargement horizontal cyclique à long terme d'un monopieu pour éoliennes offshore

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ABSTRACT: In this study, a $1g$ model monopile test was conducted under long-term horizontal cyclic loading. The focus of the study is to understand the effect of the number of cycles on the response of the monopile which is mainly used for large $8-9\ MW$ offshore wind turbines OWTs. The monopile was tested in a saturated very dense sand and subjected to a sinusoidal cyclic horizontal load H. The H is approximately 3.5% of the ultimate load capacity H_u. Unidirectional one-way cyclic loading $N = 2{,}000$ with a loading frequency of $f = 0.2\ Hz$ was applied considering the typical frequency range for OWTs. The head of the model pile was equipped with the transducers to obtain the lateral pile head displacement, pile head rotation, and the lateral stiffness evaluation during cyclic loading. The results show that the pile head displacement and rotation accumulation continue to increase with the increase of the number of cycles. In particular, the displacement accumulation during the first few load cycles is clearly larger than the subsequent displacement accumulation. Besides, the lateral secant stiffness k_s decreases with increasing number of loading cycles. The test results indicate that pile head displacement, head rotation, and the lateral stiffness are considerably affected by the number of load cycles.

RÉSUMÉ: Dans cette étude, un essai sur un modèle de monopieu de 1g a été réalisé sous une charge cyclique horizontale à long terme. L'objectif de l'étude est de comprendre l'effet du nombre de cycles sur la réponse du monopieu qui est principalement utilisé pour les grandes éoliennes offshores de $8-9\ MW$. Le monopieu a été testé dans un sable saturé très dense et soumis à une charge horizontale cyclique sinusoïdale H. La H est approximativement 3,5% de la capacité de charge ultime H_u. Une charge cyclique unidirectionnelle $N = 2\ 000$ avec une fréquence de chargement de $f = 0{,}2\ Hz$ a été appliquée en tenant compte de la gamme de fréquence typique des OWT. La tête du pieu modèle a été équipée de transducteurs pour obtenir le déplacement latéral de la tête du pieu, la rotation de la tête du pieu et l'évaluation de la rigidité latérale pendant la charge cyclique. Les résultats montrent que le déplacement de la tête du pieu et l'accumulation de la rotation continuent d'augmenter avec l'augmentation du nombre de cycles. En particulier, l'accumulation de déplacement pendant les premiers cycles de charge est nettement plus importante que l'accumulation de déplacement suivante. En outre, la rigidité latérale sécante k_s diminue avec l'augmentation du nombre de cycles de chargement. Les résultats des essais indiquent que le déplacement de la tête du pieu, la rotation de la tête et la rigidité latérale sont considérablement affectés par le nombre de cycles de charge.

Keywords: Monopile; offshore wind turbines; long-term cyclic loading; 1 g model test.

1 INTRODUCTION

A large number of OWTs with large wind turbines of $8-10\ MW$ rated power are planned to be installed in water depths greater than $40\ m$ over the next few decades (Figure 1). The monopiles, which are the most used foundation type for OWTs, has also been chosen to design OWTs in deeper waters in the current years. The foundations are subjected to large wind and wave loadings with million number of cycles over the duration of OWTs service lifetime in offshore circumstances. It is required to investigate the response of large monopile foundation systems of such OWTs under long-term cyclic loadings.

Several experimental studies have been conducted to understand the behaviour of pile foundation under lateral cyclic loading (Little and Briaud, 1988; Long and Vanneste, 1994; Lin and Liao, 1999). It is stated in almost all investigations that the amplitude and the number of lateral loading cycles have significant influence on the response of pile. The results of 34 cyclic field lateral load tests and 20 full-scale pile lateral cyclic load tests were taken into consideration in the studies of Long and Vanneste (1994) and Lin and Liao (1999), respectively. The researchers indicated that soil-pile stiffness and lateral pile head displacement accumulation are considerably affected by the number of loading cycles. It should be noted that the cycle number of the considered field tests in these studies are less than 100. A series of centrifuge tests were carried out in dry dense sand under one-way lateral cyclic loading ($20 < N < 50$) in the study of Verdure et al. (2003). The authors stated that secant stiffness under cyclic loading increases slightly with the increase of number of cycles and is obtained 1.5 to 3.0 times larger than the stiffness in monotonic loading condition. It was found that the pile head displacement increases with the increase of cycle number. Similar findings were also reported in the study of Rosquoët et al. (2007). However, the study presented from Rosquoët et al. (2007) was also performed under few loading cycles up to $N = 40$.

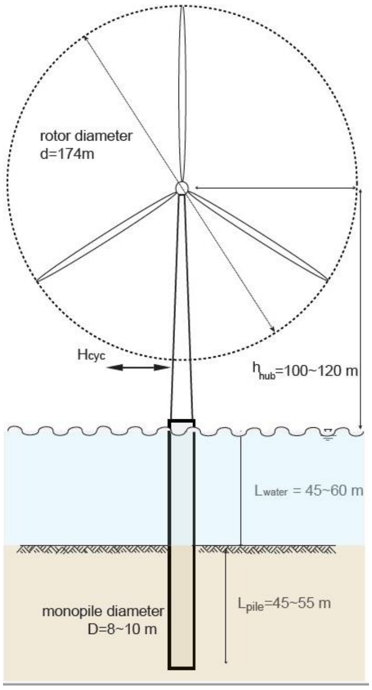

Figure 1. Sketch of a large OWT (8-10 MW).

Model test and field test studies have been implemented on monopiles for OWTs under lateral cyclic loading especially in the last decade. Field test was performed in dense sand with a saturation degree 70% above the ground level under one-way loading up to $N = 5000$ (Li et al., 2015). $1g$ model tests were conducted in saturated loose to dense sand under one-way and two-way cyclic loading between number of cycles $3000 < N < 80{,}000$ (Peralta and Achmus, 2010; Tasan et al., 2011; Nicolai and Ibsen, 2014). The $1g$ tests presented in the study of Nanda et al., (2017) were carried out for open and closed end pile, in dry dense sand under one-way and two-way cyclic loading with $N = 1000$. Centrifuge tests were executed in dry dense sand condition under one-way cyclic loading with $N = 1000$. The results of the above cited investigations on monopile tests in cohesionless soil for OWTs show that the pile head displacement and head rotation accumulation are strongly dependent on the number of cycles, loading type (one-way, two-way), and the amplitude of the cyclic loading.

In this study, the results of the model test are presented. The test was conducted on open-end monopile under unidirectional and one-way lateral loading with N = 2000 number of cycles in saturated very dense sand. The effect of the number of cycles on lateral pile head deformation and rotation accumulation, and lateral stiffness evaluation are investigated and assessed.

2 MODEL TEST

In this investigation, $1g$ model test was conducted to investigate the response of a large OWT with a capacity of $8-9\ MW$ under long-term lateral cyclic loading. The large-scale model monopile test was performed for a large OWT supported by a monopile with a large diameter $D = 9\ m$, a diameter-to-wall thickness ratio $D/t = 75$, and an embedded length $L = 50\ m$, and hence an aspect ratio of 5.55. The utilized scaling approach with implemented relations and equations are stated in detail in the study by Akdag and Rackwitz (2023). The testing system involves test pit, subgrade material, loading mechanism, model pile, pile head instrumentation, and lateral load mechanism. The testing system illustration with dimensions are given in Figure 2 and Figure 3.

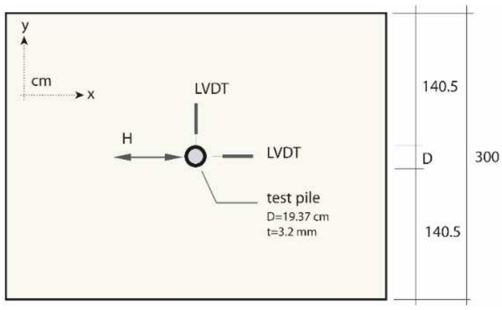

Figure 2. Plan view of 1g model test system.

The large scaled $1g$ model test was conducted on a scaled open-ended steel pile with dimensions of $D = 0.194\ m$, $D/t = 60.53$, and $L = 3.03\ m$.

Poorly graded (SP) "Cottbuser sand" with a grain size among $63 \mu m$ and $2\ mm$ was utilized as the subgrade material for the $1g$ model test. It was obtained from the Cottbus area in Germany and the characteristics of the sand is given in the study by (Akdag et al., 2023). The sand was placed in the test pit at its natural moisture content through a repeatable compaction procedure using a vibration plate. First, the sand was placed and compacted to a height equal to 4 times the pile diameter D to set the soil under the pile. The model monopile was then positioned in the centre of the test pit (Figure 3). Then, sand was located around the pile in layers of 15 cm thickness which are compacted dynamically.

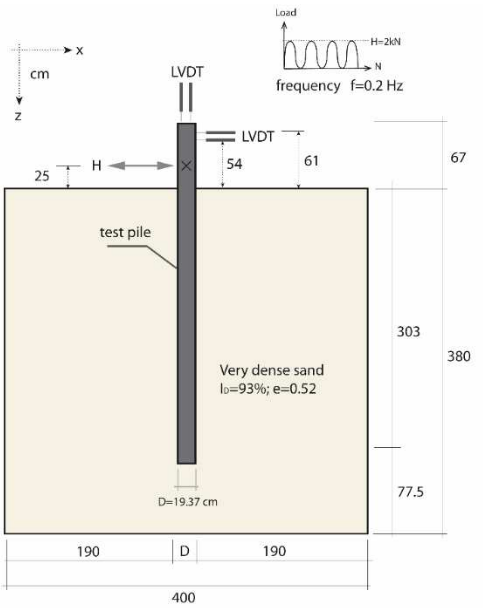

Figure 3. Cross section of model test system.

The average effective unit weight of the sand was found to be $\gamma' = 10.50\ kN/m^3$. The average relative density of the sand was found to be $I_D = 93\%$, which corresponds to very dense sand state. The average void ratio was obtained to be $e = 0.52$. Direct shear test was conducted under normal stresses of $\sigma = 100, 200, and\ 400\ kPa$ to obtain the peak angle of internal friction φ of the sand with a relative density of $I_D = 93$. It was found to be $\varphi = 45.8°$.

During the model test a unidirectional one-way lateral cyclic loading $N = 2000$ was conducted with a constant maximum load value of $H_{max_{cyc}} = 2\ kN$. Applied load amplitude is almost $\xi_b = 3.5\ \%$ of the ultimate load capacity H_{us} of the monopile-soil system in the model test. Two normalised parameters $\xi_b\ and\ \xi_c$ were recommended by LeBlanc et al. (2010) to identify the utilized horizontal cyclic loading characteristics are given in Eq. 1 and Eq. 2.

$$\xi_b = \frac{H_{max}}{H_{us}};\ cyclic\ load\ magnitude \qquad (1)$$

$$\xi_c = \frac{H_{min}}{H_{max}};\ cyclic\ load\ ratio \qquad (2)$$

Because of one-way cyclic loading application cyclic load ratio is $\xi_c = 0$ in this study.The monotonic ultimate lateral load capacity H_{us} of the model pile was estimated according to the three-dimensional finite element model analysis, which was found to be $H_{us} \cong 60\ kN$ corresponding to the pile head rotation $\theta = 2°$ (Akdag and Rackwitz, 2023).

A load-controlled test was performed in this study, and the horizontal loading mechanism was not fixed to the pile head as shown in Figure 4. Sinusoidal cyclic horizontal loading with a loading frequency of $f = 0.2\ Hz$ was performed considering the typical frequency range for OWTs, as reported in the literature (Lesny and Hinz, 2009; Bhattacharya et al., 2013). The horizontal load was carried out to the pile head at a height $h = 1.30D$ above the sand surface (Figure 3).


Figure 4. Lateral cyclic loading mechanism.

The pile head horizontal displacement accumulation u_x was obtained from the displacement transducers which are instrumented at the pile head in the loading direction. The data recorded from the two transducers oriented in the loading direction were used to obtain the pile head rotation θ accumulation during lateral cyclic loading. Pile lateral stiffness k_s evaluation was found using horizontal load (ΔH) - pile head displacement (Δu) relationship.

3 TEST RESULTS EVALUATION

In this section, the pile head lateral displacement accumulation, pile head rotation accumulation, and pile lateral stiffness evolution are assessed based on the test results.

The accumulation of lateral pile head displacements u_x in the loading direction with maximum $u_{x_{max}}$ and minimum $u_{x_{min}}$ values for increasing numbers of loading cycles up to $N = 2000$ is shown in Figure 5. The test results indicate that the lateral displacement accumulation continues to increase as the number of cycles increases. The minimum lateral displacement values show the permanent accumulation occurred and increased with the number of loading cycle. Remarkably, $u_{x_{max}}$ accumulation up to $N = 100$ is almost 25% of the maximum pile head accumulations obtained after $N = 2000$.

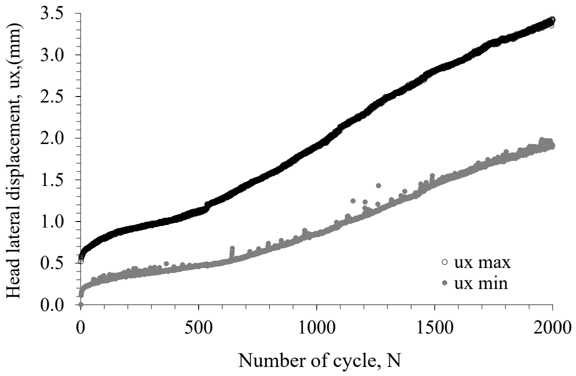

Figure 5. Pile head lateral deformation accumulation.

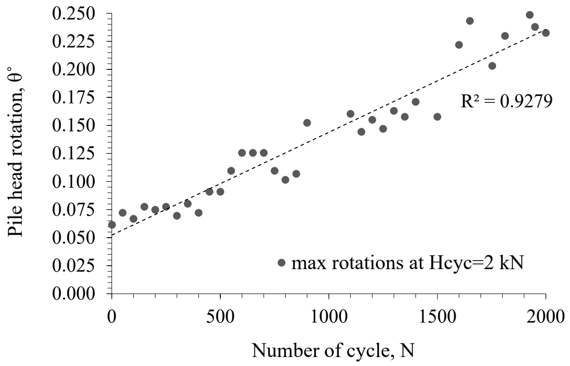

Figure 6. Pile head rotation accumulation.

In Figure 6, the model test results as the pile head rotation accumulation at maximum lateral load level in specific load cycles up to $N = 2000$ is presented. It can be seen from the test results that the accumulation of maximum rotation at $H_{max_{cyc}}$ continues to increase as the number of cycles increases. Notably, the behaviour of the increase in pile head rotation can be evaluated to be linear as shown in the Figure 6. In addition, the maximum rotation reached almost $\theta \cong 0.25°$ after $N = 2000$, which is stated as serviceability limit state SLS according to Det Norske Veritas offshore guideline (DNV, 2018).

The evaluation of pile lateral stiffness during the loading cycles was obtained according to the horizontal load (ΔH) - pile head displacement (Δu) relationship using Eq.3 in Figure 7. The unloading and reloading lateral secant stiffness of the soil-monopile with increasing number of cycles up to $N = 2000$ is given in Figure 8. The test results show that the k_s decreases as the number of load cycles increases. In addition, the rate of decrease in the stiffness alters with increasing N. The rate of reduction in k_s decreased significantly between $N = 1000 - 1400$ with an increasing number of cycles. Subsequently, the change in secant stiffness after the cycles $N = 1400$ is trivial and can be considered almost constant. The stiffness, which reaches an approximately constant value after $N = 1400$, is approximately 3.5 times lower than the stiffness in the initial cycles.

$$k_s = \frac{\Delta H}{\Delta u} \quad (3)$$

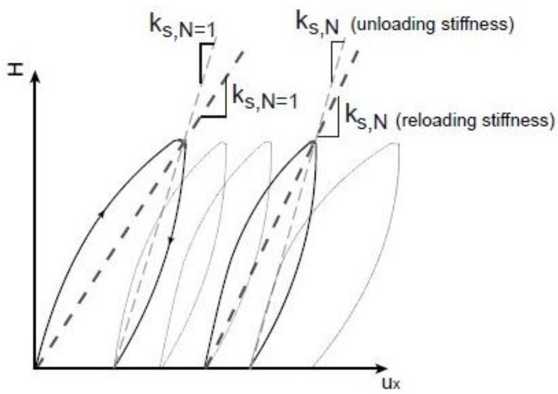

Figure 7. Illustration of secant stiffness determination.

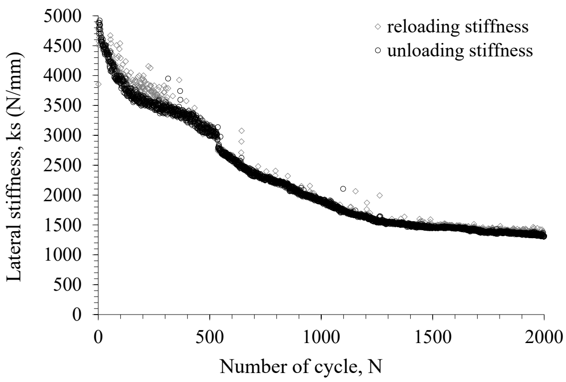

Figure 8. Secant stiffness evaluation.

4 CONCLUSIONS

In this study, the results of the large-scale $1g$ model test is presented. Test was conducted on open-end monopile under unidirectional and one-way lateral loading with N = 2000 number of cycles in saturated very dense sand. The results of the test indicate that the pile head displacement and rotation accumulation continue to increase with the increasing number of cycles. Besides, the lateral secant stiffness k_s decreases with increasing number of loading cycles. Consequently, the test results indicate that pile head displacement, head rotation, and the lateral stiffness are considerably affected by the number of load cycles.

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