Physical Modelling in Geotechnics

Modelling long-term dynamic behavior of offshore wind turbine foundations using a novel hydraulic gradient apparatus

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ABSTRACT: In this study, an innovative geotechnical physical modelling facility - hydraulic gradient apparatus, has been developed and applied to investigate the long-term dynamic behavior of piles for offshore wind turbines. The downward seepage force was employed to create a supergravity field of high g level similar to that in a geotechnical centrifuge. A long-term lateral cyclic loading unit was developed to simulate the cyclic loads under high g level conditions. Two long-term lateral cyclic loading tests on a monopile and a tripod-pile foundation were performed using the facility to investigate the long-term dynamic response of pile foundations for offshore wind turbines. Two critical issues are addressed through the tests: the accumulation of lateral deflection and the variations of the natural frequency and damping ratio of the pile-soil systems. The influences of scale factor, soil type, and foundation type are discussed.

Keywords: Hydraulic gradient modelling, physical modelling, pile foundations, cyclic loading, natural frequency.

1 INTRODUCTION

Pile foundations for offshore wind turbines are exposed to millions of lateral load cycles throughout their service life. Regarding the long-term behavior of offshore piles, two critical issues require particular attention: the accumulation of lateral deflection and the variation of dynamic characteristics. The cumulative deflection of piles under lateral cyclic loading has been studied through soil element tests, soil-pile model tests and numerical simulations (Arshad and O'Kelly 2017; Nikitas et al. 2017; Abadie et al. 2019; Staubach and Wichtmann 2020; Jeong et al. 2021; Liu et al. 2021; Abdullahi et al 2022). The element tests can quantify the dynamic characteristics of soil, but cannot consider the soil-pile interactions, such as soil-pile separation. Most of the soil-pile model tests and numerical simulations are limited to a small number of load cycles, e.g., hundreds to thousands, which are insufficient to represent the long-term accumulation of pile deflection. A series of "real" long-term laterally loading tests with up to six million load cycles was conducted by Cuéllar (2011), which revealed the long-term accumulation pattern of pile displacement. Due to the limitation of 1g model tests, however, 1g test results have to be verified by field monitoring or other advanced physical modelling.

Dynamic characteristics of soil-pile systems are vital to the long-term stability of offshore wind turbines under continuous cyclic loading (Schafhirt et al. 2016). In order to avoid resonance, the target natural frequency of the pile foundation should be designed between the rotor frequency, 1P and the blade shadowing frequency, 3P. To estimate the long-term structural fatigue, an accurate evaluation of the natural frequency and damping ratio of the foundation is indispensable. It has been discovered that long-term cyclic loading results in changes in dynamic characteristics of piles (Grabe 2008; LeBlanc 2010; Yu et al. 2015; Schafhirt et al. 2016), which has a significant influence on the long-term design of offshore wind turbines. Further studies are still required to reveal the evolution mechanisms and quantify the long-term variation patterns of natural frequency and damping ratio.

Research on this topic remains stagnated due to the lack of effective physical modelling tools. Long-period full-scale field tests are costly and difficult to perform, and 1g model tests cannot achieve the prototype stress field in the models. Centrifuge model tests can create a real stress level in a small-scale model but is difficult to operate for a long period, e.g., several months. Zelikson (1969) utilized the top-down seepage force to obtain a super gravity field inside the soil, so that to create the same stress level between the scale-down model and the prototype. Based on this concept, in this study, a novel hydraulic gradient facility was developed and applied to study the long-term behavior of piles foundations.

2 HYDRAULIC GRADIENT PHYSICAL MODELLING APPROACH

The downward seepage due to hydraulic gradient increases the unit weight of the soil. Under a hydraulic gradient ratio, *i*, the scale factor *N* between the soil model and the prototype can be calculated as:

$$N = \frac{\gamma_m}{\gamma'} = \frac{(i\gamma_w + \gamma')}{\gamma'} = i\frac{\gamma_w}{\gamma'} + 1 \quad (1)$$

where γ_w and γ' are the effective unit weights of water and soil, respectively. When the hydraulic gradient ratio remains constant, a uniform supergravity field of *N*g in the soil model can be created. The scaling laws for hydraulic gradient tests are the same as those for centrifuge model tests. Taking advantage of downward hydraulic gradient field, a supergravity model test facility with a long-term cyclic loading capacity was developed.

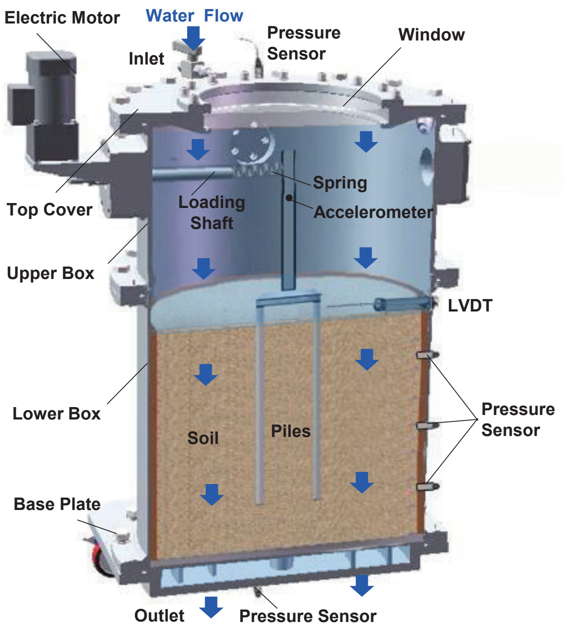

Fig. 1. Cross-section of the hydraulic gradient facility.

As shown in Fig. 1, the main component of the hydraulic gradient facility is a high-pressure stainless steel cylindric model container with an inner diameter of 600 mm and a height of 800 mm. The container is split into four parts: the top cover for observation, the upper box for loading and instrumentation, the lower box to contain the soil, and the base plate. A servo variable-frequency water pump is employed to continuously introduce water from the top valves into the upper box to create a steady water head above the soil surface. The high-pressure water flows through the soil, forming a downward hydraulic gradient field, and finally exits from the valves at the base plate. The lateral cyclic loading unit includes a vertical variable-speed electric motor, a loading shaft, and a compression spring loading device. The running motor drives the loading shaft through eccentric wheels and transmission devices to move in and out of the model container circularly. As a result, a spring connecting the loading shaft and pile mode is cyclically compressed and released, applying cyclic loads onto the pile. Water pressure sensors are installed on the top cover, the vertical wall of the lower box and the base to monitor the pressure distribution inside the soil bed (Fig. 2). A LVDT displacement sensor with a high waterproof capacity is installed 10 mm above the ground. Accelerometers are attached onto the pile head to record the forced and free vibrations of the pile during each loading cycle. A data logger with sampling frequencies of 0.01 - 10 Hz is used for long-term data acquisition. Details of the test device and test procedures refer to Lu and Zhang (2020).

3 LONG-TERM LATERAL CYCLIC LODING TEST SCHEME

Two types of foundations, a monopile and a tripod supported by three piles for offshore wind turbines, were tested in this study (Fig. 2(a-b)). All the model piles were solid aluminum columns with a diameter of 20 mm and a buried depth of 350 mm. The pile spacing in the tripod foundation was 115 mm. Two types of sand with different particle size distributions were employed (Fig. 2(c)). Different hydraulic gradient fields and scaling factors can be realized by adjusting the top water pressure over the soil surface. Different cyclic loads were applied with different springs. After validated by a short-term centrifuge model test (Lu and Zhang 2020), the proposed hydraulic gradient facility was employed in nine different long-term laterally cyclic loading tests (Table 1). In order to make comparison with the 1g long-term model test by Cuéllar (2011), similar load amplitudes were used in this study. Representative results of different tests are discussed in the next.

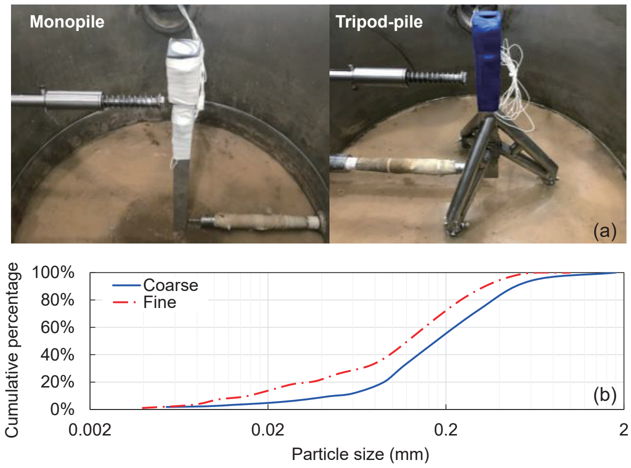

Fig. 2. Test configurations. (a) Photos of monopile and tripod-pile tests; (b) particle size distribution curves of two types of sand.

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Table 1. Summary of long-term hydraulic gradient tests.

Test ID	Sand Type	Foundation Type	Load (N)	Cycles	*N*
FM-20-100g	Fine	Monopile	0-20	2×10^5	100
FM-30-100g	Fine	Monopile	0-30	1×10^5	100
CM-5-100g	Coarse	Monopile	0-5	6×10^5	100
CM-20-80g	Coarse	Monopile	0-20	1×10^6	80
CM-20-1g	Coarse	Monopile	0-20	3×10^6	1
CM-20-100g	Coarse	Monopile	0-20	6×10^5	100
CM-20-120g	Coarse	Monopile	0-20	1×10^6	120
CT-20-50g	Coarse	Tripod-pile	0-20	8×10^5	50
CT-20-100g	Coarse	Tripod-pile	0-20	8×10^5	100

4 LONG-TERM DYNAMIC BEHAVIOR OF PILE FOUNDATIONS

4.1 Long-term accumulation of pile deflection

Fig. 4 presents the lateral displacement in one tripod-pile test and four monopile tests under different supergravity fields or in different soil types. In general, the displacement accumulation pattern could be divided into three stages in all the tests: within 10 cycles, the lateral displacement increases rapidly; from 10 to 5×10^4 cycles the displacement accumulates at a small rate; after 5×10^4 cycles, the pile displacement gradually becomes stable. These results agree well with the 1g long-term model test by Cuéllar (2011).

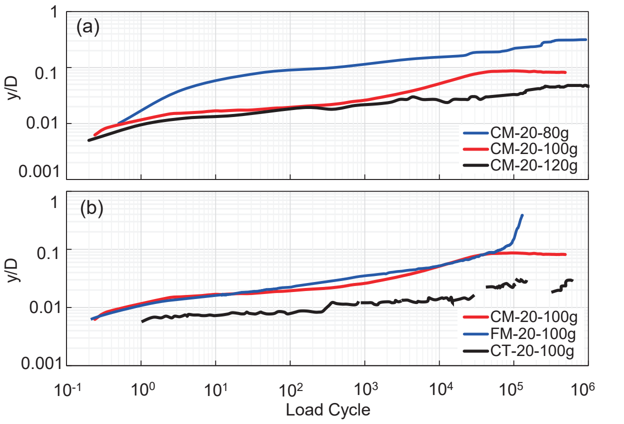

Fig. 4. Lateral displacements in the monopile and tripod-pile tests. *y*, cumulative lateral displacement; *D*, pile diameter.

Different supergravities lead to different scale factors and different dimensions of piles. For example, the embedment depths of piles at 80g, 100g and 120g levels are 28, 35, and 42 m, respectively, at prototype scale. As a result, the lateral displacement at 80g level is about 3 times that at 100g level and 6 times that at 120g level at the final stable stage (Fig. 4(a)). Comparing the pile deflections in fine and coarse sand at 100g level (blue and red curves in Fig. 4(b)), the fine sand exhibits a slightly lower stiffness so that the cumulative rate of pile displacement in Test FM-20-100g is slightly larger than that in Test CM-20-100g within the first and second stages (Fig. 4(b)). But in the third stage, a rapid increment of the pile displacement in Test FM-20-100g is observed, which is due to the rapid development of a separation gap between the pile and the fine, silty sand. The difference between the monopile and tripod-pile foundations under the same loading condition is also presented in Fig. 4(b). The monopile deflects about 5 times that of the tripod-pile foundation after the same loading sequence. The more the load cycles, the larger the difference between these two tests.

4.2 Long-term evolution of dynamic characteristics

The free vibration accelerations of the system were measured at a specific loading interval. Figs. 5(a-c) present the time histories of acceleration at 3×10^5 load cycles in two monopile tests and one tripod-pile tests. The significant decay of vibration amplitude in both tests indicates the damping of the soil-pile systems. The vibration decay of the monopile at 80g is faster than that at 100g level because the "softer" soil exhibits a larger damping capacity. By the Fast Fourier Transform of the time histories, the dynamic characteristics in a frequency domain are derived in Figs. 5(d-f). The frequency corresponding to the first peak of the transferred curve is the first-order natural frequency of the soil-pile system. The softer soil at 80g level corresponds to a lower natural frequency compared with that at 100g. The tripod-pile foundation possesses the largest damping ratio and natural frequency due to its special structure type.

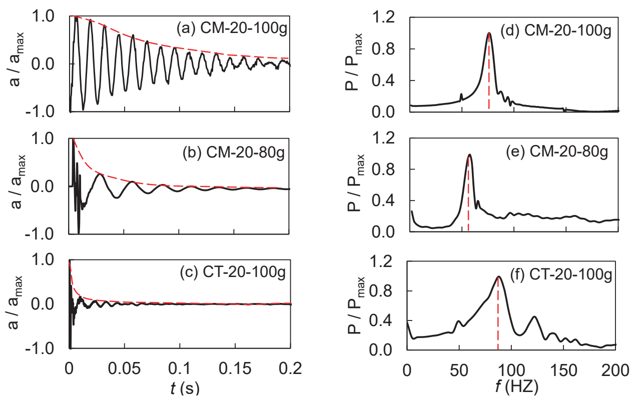

Fig. 5. Dynamic responses in time and frequency domains. *a* and a_{max}, current and maximum acceleration, respectively; *P* and P_{max}, current and maximum power density after Fast Fourier Transfer.

The natural frequencies of the soil-pile system at different load cycles are derived and fitted with a 3-order polynomial to show its evolution (Fig. 6(a)). The natural frequencies of the monopile (CM-20-80g and CT-20-100g) continuously increase due to cyclic loading, which increases by about 10% at 100g and 20% at 80g after 6×10^5 of load cycles. Similar results were also observed in long-term 1 g model tests (Yu et al. 2016), which is attributed to the vibration densification of the soil. The lower supergravity level leads to smaller confining stress of soil at the prototype. The soil densification under this condition may be amplified so that the change of natural frequency becomes more significant. In contrast, the natural frequency in the tripod-pile test (CT-20-100g) exhibits a decreasing trend under the same condition, with a maximum reduction of about 40%. Such a decrease should be attributed to the different foundation types.

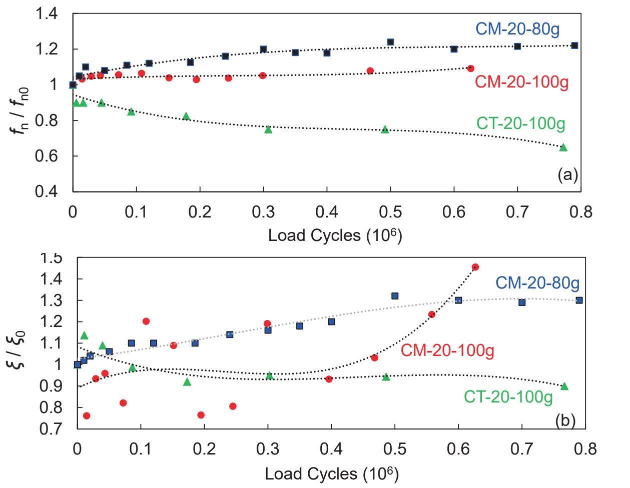

Fig. 6. Evolution of (a) natural frequency and (b) damping ratio of the soil-pile system under long-term cyclic loading. f_n and f_{n0}, current and initial natural frequency, respectively; ξ and ξ_n, current and initial damping ratio, respectively.

The damping ratio of the soil-pile system, ξ, can be derived from the time histories of free-vibration acceleration, using the following equation:

$$\xi = \frac{1}{\omega_n T_d j} \ln \frac{A_1}{A_{1+j}} \approx \frac{1}{2\pi j} \ln \frac{A_1}{A_{1+j}} \qquad (2)$$

where A_1 and A_{1+j} are the acceleration amplitudes at the 1st and (1+j)th load cycles, respectively; ω_n is the natural circular frequency, T_d is the actual vibration period. The evolution of damping ratio during cyclic loading in three tests is shown in Fig. 6(b). The damping ratio of the tripod-pile foundation changes a little after over 7×10^5 load cycles, while the values of the monopile at 100g are more scattered with an overall rising trend. Under the identical supergravity level and loading condition, such difference may also be attributed to the different foundation types. The results in Test CM-20-80g are more convergent, with an obvious increasing trend that is due to the more significant "soil densification" under a lower supergravity field. Further investigation is required to reveal the mechanism of varying evolution patterns of dynamic characteristics of the soil-pile system under long-term cyclic loading.

5 SUMMARY

A novel hydraulic gradient facility was developed and applied into the long-term lateral cyclic loading tests on offshore wind turbine foundations. During the long-term cyclic loading, the accumulation of pile deflection is observed, which is affected by the scale factor, soil type, and foundation type. The natural frequency and damping ratio of soil-pile system also change according to different soil stress states and foundation types.

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REFERENCES

Abadie, C.N., Byrne, B.W. & Houlsby, G.T. 2019. Rigid pile response to cyclic lateral loading: laboratory tests. *Géotechnique* 69(10): 863-876.

Abdullahi, A., Bhattacharya, S., Li, C., Xiao, Y. & Wang, Y. 2022. Long term effect of operating loads on large monopile-supported offshore wind turbines in sand. *Ocean Engineering* 245: 110404.

Arshad, M. & O'Kelly, B.C. 2017. Model studies on monopile behavior under long-term repeated lateral loading. *International Journal of Geomechanics* 17(1): 04016040.

Cuéllar, P. 2011. *Pile foundations for offshore wind turbines: Numerical and experimental investigations on the behavior under short-term and long-term cyclic loading*. PhD thesis, Berlin: Technical Univ. of Berlin.

Grabe, J. 2008. Pile foundations for nearshore and offshore structures. Geotechnics in Maritime Engineering. *11th Baltic Sea Geotechnical Conference*, Gdansk, Poland, 445-462.

Jeong, Y.H., Lee, S.W. & Kim, J.H. 2021. Centrifuge modeling for the evaluation of the cyclic behavior of offshore wind turbine with tripod foundation. *Applied Sciences* 11(4): 1718.

LeBlanc, C., Houlsby, G. & Byrne, B. 2010. Response of stiff piles in sand to long-term cyclic lateral loading. *Géotechnique* 60(2): 79-90.

Lu, W.J. & Zhang, G. 2020. Long-term cyclic loading tests for offshore pile foundations based on hydraulic gradient modelling. *Geotechnical Testing Journal* 44(3): 686-704.

Liu, H., Kementzetzidis, E., Abell, J.A. & Pisanò, F. 2021. From cyclic sand ratcheting to tilt accumulation of offshore monopiles: 3D FE modelling using SANISAND-MS. *Géotechnique*, https://doi.org/10.1680/jgeot.20.P.029.

Nikitas, G., Arany, L., Aingaran, S., Vimalan, J. & Bhattacharya, S. 2017. Predicting long term performance of offshore wind turbines using cyclic simple shear apparatus. *Soil Dynamics and Earthquake Engineering* 92: 678-683.

Schafhirt, S., Page, A., Eiksund, G.R. & Muskulus, M. 2016. Influence of soil parameters on the fatigue lifetime of offshore wind turbines with monopile support structure. E*nergy Procedia* 94: 347-356.

Staubach, P. & Wichtmann, T. 2020. Long-term deformations of monopile foundations for offshore wind turbines studied with a high-cycle accumulation model. *Computers and Geotechnics* 124: 103553.

Yu, L.Q., Wang, L.Z., Guo, Z., Bhattacharya, S., Nikita, G. & Li L.L. 2015. Long-term dynamic behavior of monopile supported offshore wind turbines in sand. *Theoretical and Applied Mechanics Letters* 5(2): 80-84.

Zelikson, A. 1969. Geotechnical models hydraulic gradient using the similarity method. *Geotechnique* 19(4): 495–505.