Behavior of Wind-turbine Pile Foundations in Dry Sand Due to Cyclic Lateral Loading

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1. INTRODUCTION

Wind power currently offers a very competitive source of renewable energy, and therefore the market for onshore and offshore wind farms is projected to expand rapidly within the next decades. For example, coastal zones in Egypt particularly in the Red Sea coast at the Gulf of Suez is one of the highest windy areas of the world, with average wind speeds of around 12m/s. Recently, large-scale onshore wind farms at Zafarana (200 km south east of Cairo) in co-operation with Japan, Germany, Spain, and Denmark have been constructed.

The current theories of analysis of wind turbine foundations under lateral cyclic loading are still approximate, empirical, and they have ignored some key parameters (i.e., L/B, N, and f). Accordingly, it is essential to investigate the influence of those parameters on the performance of wind turbines pile foundations. In order to examine the behavior of pile-soil interaction due to cyclic two-way loading, an extensive experimental program was carried out on a small-scale pile model. Furthermore, evaluation of lateral soil stiffness and bending moment of single pile foundations with loading time was investigated.

2. EXPERIMENTAL SETUP

2.1. Physical modelling and scaling laws

Fig. 1 shows the laboratory test setup and the apparatuses which are used for testing and measuring pile response. Three slenderness values (L/B) for model pile are selected, including 10, 20 and 30 as shown in **Fig. 2**. The pile models are manufactured from closed-end aluminium tube of outer diameter of 15mm and wall thickness of 1.5mm. Scaling law was used adhered to when designing the model pile material, dimensions, and the applied speed and displacement using the following scaling formula:

$$\frac{E_m I_m}{E_p I_p} = \frac{1}{n^5} \qquad (1)$$

Where: $E_m I_m$ is flexural rigidity of model pile; $E_p I_p$ is flexural rigidity of prototype pile; and n is scale factor for length.

2.2. Preparation of testing ground (soil)

Sub-angular, fine Toyoura sand was used as a ground material, and its index properties are given in **Table 1**. Multiple sieving pluviation (MSP) method was used for preparation of sand ground (D_r=45%). Cone penetration test was carried out according to JGS 1431 at different locations after soil placement so that physical soil characteristics can be obtained. **Fig. 3** shows the results of Mini-cone penetration resistance tests (q_c) with depth which gives the following average physical soil properties: Young's modulus (E_s), shear modulus (G), and internal friction angle of 10.40 MPa, 3.92 MPa, and 36.5°, respectively.

Although the geostatic stress does not match the prototype scale, the stiffness of the pile is reduced too. Therefore, the modeling discussed is valid for the interaction of soil and pile. Then it can be modeled as the soil response with some approximation. Besides, pile/soil relative stiffness (E_p/E_s) has been kept constant almost equal to 7000 during the course of the test.

3. ANALYSIS OF THE RESULTS

3.1. Secant modulus of subgrade reaction $(K_h)_s$

To investigate the causes of increase in lateral resistance of pile due to lateral cyclic loading, secant modulus values were estimated from lateral load-displacement tests at lateral deformation of 10%B (i. e., 50% of strain level) for numbers of loading cycles (N= 0, 10, 30, 50 cycle), as given in Eq.2.

$$(K_h)_s = \frac{H}{y * B} \qquad (2)$$

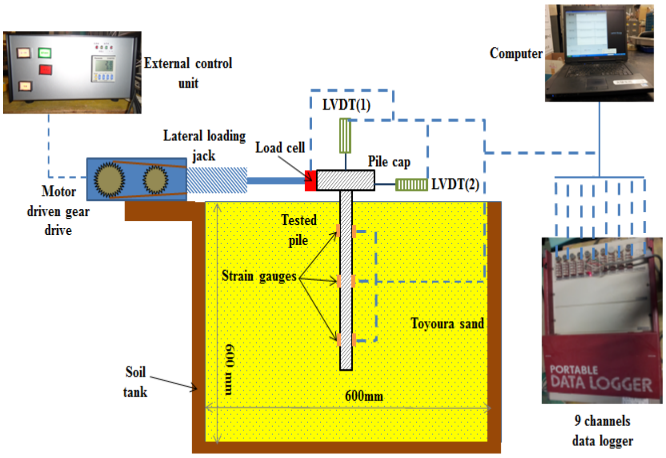

Figure 1 Schematic of single pile model test setup.

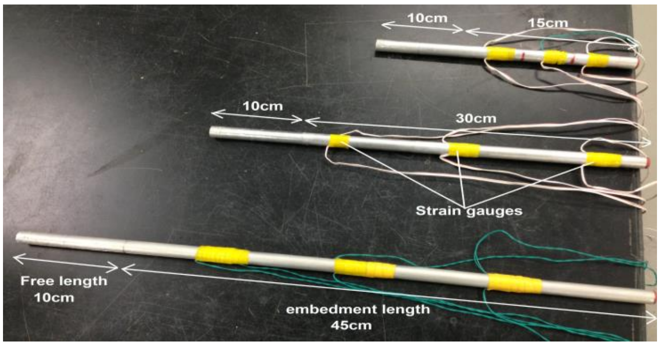

Figure 2 Three slenderness ratios of aluminium pile models attached with strain gauges.

Table 1 Geotechnical properties of Toyoura sand

Property	Value
Specific gravity (G_s)	2.65
Maximum dry density (γ_{max})	16.0 kN/m^3
Minimum dry density (γ_{dry})	13.1 kN/m^3
Maximum void ratio (e_{max})	0.98
Minimum void ratio (e_{min})	0.62
Uniformity coefficient (U)	1.40
Coefficient of curvature (C)	0.86
Effective diameter (D_{50})	0.18mm

Keywords: Cyclic loading, experimental work, lateral deflection, sand, single pile, foundation.
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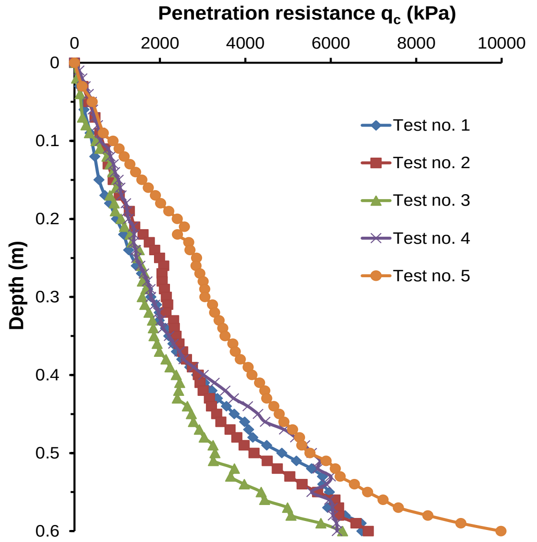

Figure 3 Results of Mini-CPT for the soil inside the testing box.

Where: H is lateral measured load; y is lateral displacement at pile head; and B is pile diameter.

Fig. 4 depicts the change of $(K_h)_s$ with number of cycles, frequency, and slenderness ratio of pile for rigid and flexible piles. It is noticed that, initial loading cycles (monotonic tests, N= 0) generate the lowest values of $(K_h)_s$ than the succeeding cycles. For example, the values of $(K_h)_s$ for long flexible piles (L/B=30) obtained from monotonic test were equal to 0.88 and 0.75 MPa at frequency of 0.05 and 0.017Hz, respectively. However, after 50 cycles of loading $(K_h)_s$ reached to the highest values, which were equal to 1.45 and 1.25 MPa, at frequency of 0.05 and 0.017 Hz, respectively.

3.2. Maximum bending moment

Bending moments created due to applied lateral cyclic displacement were measured periodically at every loading cycle, and they were calculated using Eq. 3. The maximum measured value (M_m) was normalized against the yielding moment (M_y).

$$M_m = \frac{E_m I_m \varepsilon}{r} \qquad (5)$$

Where: ε= measured bending strain; and r = horizontal distance between strain gauge position (outer surface of the pile) and neutral axis.

Yielding moment (M_y) of the pile model is calculated using the following expression (σ_y= yield stress of aluminium of the used pile material= 48.3MPa):

$$M_y = \frac{\sigma_y I_m}{r} \qquad (6)$$

Fig. 5 illustrates the relationships between normalized bending moments (M_m/M_y) and number of cycles (N) for single piles constructed into medium dense sand (D_r=45%). It is noticed that the larger the slenderness (L/B) value of pile, the loading frequency (f), and the applied number of cycles (N) are, the higher the normalized bending moment (M_m/M_y) generated (i.e., converging to 1).

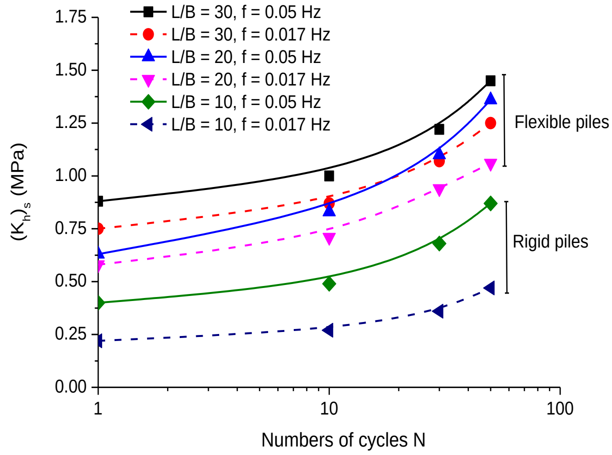

Figure 4 Change of lateral pile capacity with number of cycles at different frequencies and slenderness ratios.

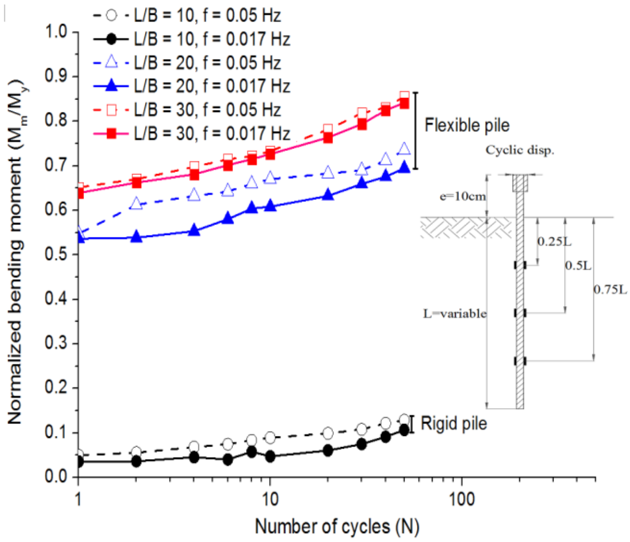

Figure 5 Normalized bending moment versus number of cycles for single piles in medium dense sand.

4. CONCLUSION

Single piles constructed into dry sandy soil and subjected to lateral cyclic push-pull (two-way) loading revealed time-dependent behaviour. Accumulated lateral pile capacity and bending moment have been increased with increasing the frequency of loading (f=1/t), number of loading cycles (N), and slenderness of pile due to change of pile lateral stiffness $(K_h)_s$ with loading time.

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