Experimental Study on the Behaviour of Pile Group under Cyclic Lateral Loading

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1. INTRODUCTION

Pile foundations are widely used to support various types of structures such as offshore platforms, jetties, wharfs, docks, bridges, etc. These structures are subjected to cyclic lateral loading due to wave and wind actions. All cyclic loading sequences are characterized by four parameters, including: (1) the maximum applied lateral load H_{max}, (2) the number of cycles N, (3) the frequency (rate of loading) f, and (4) maximum lateral displacement y_{max}. Two-way cyclic loading can be considered as a simplified representation of dynamic loading without inertia nor damping.

P-y reaction curves represent soil-pile interactions on the assumptions that the soil reaction, P, at all points of the pile is a nonlinear function of the lateral pile displacement. Different methods to determine the P-y curves can be found in the codes of practice such as API code (1993), P. H. R. I. (1980), and D. N. V. (1977). However, only the American and Norwegian technical specifications consider existence of the cyclic effects for designing piles subjected to lateral cyclic loads by introducing a reduction factor A on the ultimate soil reaction P_u, as given by Eq. 1.

$$P = AP_u \tan\left(\frac{K_h}{AP_u} y\right) \qquad (1)$$

Where: A is a reduction factor to be considered for both monotonic loading (A=0.9) and cyclic loading ($A=3-0.8zd^{-1}$); P_u is ultimate soil reaction; and d is pile diameter.

In this paper, to invistigate the effects of soil properties, slow loading rate, and number of cycles on the pile foundations behaviour, 18 experimental cyclic loading tests have been performed. This study is conducted to examine the effects of lateral cyclic loading on, P-y curves, P-multipliers, and group efficiency. In order to examine the behavior of piles under lateral cyclic loads, a new series of two-way cyclic tests is carried out.

2. Experimental Setup

2.1. Testing apparatus

Fig. 1 shows the laboratory test setup and the apparatuses which are used for testing in the current experimental work. The model test facility consists of a container of wall thickness of 5 cm made of rigid fiberglass plates. The housing container has the following dimensions: 30 cm width by 95 cm length and 60 cm depth, resting on steel foundation.

2.2. Pile model material

The pile models are manufactured from closed-end aluminum alloy 6061 tube of outer diameter of 15mm and wall thickness of 1.5mm (Fig. 2). The Young’s Modulus of the used aluminum alloy is 70×10^9 KN/m^2. Equivalence law is used adhered to when designing the model pile material, dimensions, and the applied speed and displacement using the following scaling formula:

$$\frac{E_m I_m}{E_p I_p} = \frac{1}{n^5} \qquad (2)$$

Where: E_m is modulus of elasticity of model pile; E_p is modulus of elasticity of prototype pile; I_m is moment of inertia of model pile; I_p is moment of inertia of prototype pile; and n is scale factor for length.

Figure 1 Horizontal cyclic loading system and measuring apparatus, data logger, and external control unit

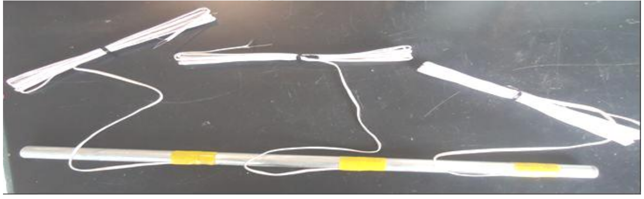

Figure 2 Single pile model and the attached strain gauges

2.3. Preparation of testing soil

The testing soil, used in this laboratory work, is sub-angular, fine Toyoura sand, and its index properties are given in Table 1. Relative density of sandy soil is achieved using especial compaction tool known as multiple sieving pluviation (MSP) method (Miura and Toki, 1982).

Table 1 Geotechnical properties of Toyoura sand

Description	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, pile group, foundation.

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3. ANALYSIS OF THE RESULTS

3.1. Cyclic P-y curve

The bending moment along the length of the pile at discrete points is analyzed using curve fitting involving a fifth order polynomial. The soil reaction (P) is determined by double differentiation, and pile deflection (y) is obtained by double integration of moment curves. The boundary conditions adopted to solve the equations are the measured pile head deflection and zero deflection at pile tip.

Fig. 3 indicates that at shallow depths (z<6d), load cycles and frequencies cause a raise of soil reaction (P), since by increasing the rate of loading and number of cycles, an obvious increase in both of soil reaction and lateral displacement are observed. Therefore, from geotechnical point of view, the top layers (i.e. within z<6d) governs the design and analysis of piles under applied lateral loads since the soil reactions mobilized in these layers control the behavior. But, due to the flexible piles used in the present study, the contribution of deep layers in the pile equilibrium is not significant.

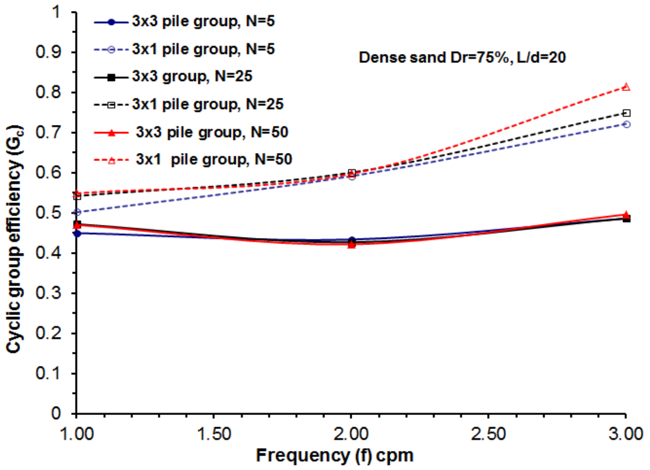

Figure 3 Cyclic P-y curves at depth 6d for piles in dense sand

3.2. Cyclic P-multiplier (r)

Cyclic P-multipliers (r) are evaluated by comparing the ultimate soil resistance at different loading cycle numbers (i.e. N=10, 30, and 50) with that of the single pile under static loading (N=0). The cyclic P-multipliers are evaluated for single piles subjected to frequencies of 1cpm to 3cpm, and the number of cycles is maintained to 50 cycles. Cyclic P-multipliers are calculated using Eq. 3:

$$r = \frac{P_c - P_m}{P_m} \tag{3}$$

Where: P_m= soil reaction mobilized during monotonic test, and P_c= soil reaction mobilized during cyclic test.

Cyclic P-multipliers (r) are markedly affected by the loading frequency and the number of cycles. For the layers at depths between 3d to 6d from ground level, P-multipliers (r) increase with increasing the number of cycles and loading frequencies.

3.3. Cyclic group efficiency (G_c)

Group efficiency is calculated depending on the number of piles in a group and the layout of the group, as given in Eq. 4:

$$G_c = \frac{H_g}{n * H_s} \tag{4}$$

Where: H_g = total horizontal load applied to the group; H_s = horizontal load carried by a single pile at the same horizontal displacement; and n = number of piles in the group.

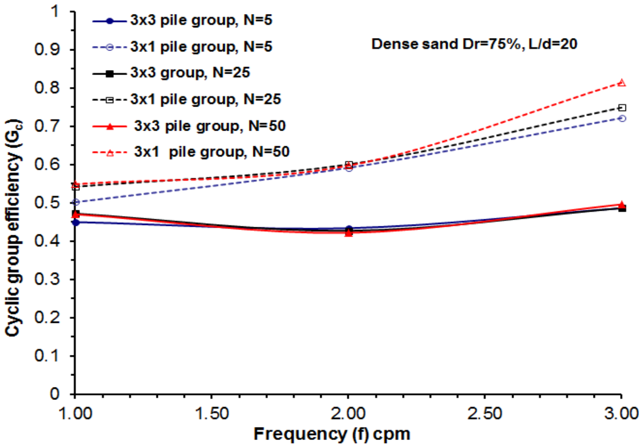

Figure 4 Relationship between G_c and f at different number of cycles N for grouped piles of L/d=20 in dense sand

Fig. 4 depicts the relationship between the cyclic group efficiency (G_c) and loading frequencies (f) at wide range of number of cycles (N) for grouped piles of 3x1 and 3x3 embedded in dense sandy soil. It has been noticed that those relationships are nonlinear. Furthermore, the efficiency of a pile grope reduced with the increase in number of piles in the group. This can be due to the increased number of overlapping zones of passive and active wedges.

4. CONCLUSION

The experimental results are used to develop the cyclic P-multipliers. The conclusion of this study can be summarized as follows:

1) Evolution of cyclic P-y curves does not only based on soil properties, as given in the codes of practice but also the rate of loading (f) and number of cycles (N).
2) Cyclic P-multipliers (r) are obviously influenced by the loading frequency and the number of cycles.
3) Likewise, cyclic group efficiency (G_c) is noticeable affected by increase in loading frequencies and number of piles in the group and to lesser extend on the number of cycles.

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