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CYCLIC LATERAL RESPONSE OF MODEL PILE GROUPS FOR WIND TURBINES IN CLAY SOIL

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ABSTRACT: Due to the large diameter and the cyclic loading, it is necessary to investigate the lateral response of pile groups for wind turbines in clay soil. This paper presents an experimental research on 2x2 model pile groups embedded in different types of clay soil, relatively density of 90% and 10%, subjected to one-way lateral cyclic loading. Analysis on the experimental results, such as load–deflection curves and bending moment profiles, were processed. It is found that the magnitude of the head level deflections and the maximum bending moment increased with the number of loading cycles. The group interaction effect under cyclic lateral loading is more significant in loose soil.

Keywords: Pile groups, Cyclic Lateral Loading, Relatively Density, Wind Turbines, Model Test

1. INTRODUCTION

Wind energy is now the popular energy resource all over the world due to its clean and renewable advantages. Also in Thailand, the government has planned to install the wind energy capacity to 800 MW by the year 2022 [1]. The pile group foundation consisting of a number of smaller piles connected by a platform plate is one of the suitable solutions for supporting wind turbine. The pile groups supporting these structures are subjected to cyclic lateral loading generated by wind, which is quite large and will governs the design of pile groups. Pile group behavior under cyclic lateral loading is nonlinear and involves complicated group interaction [2],[3]. Inevitably, group interaction has significant effect on the behavior of pile groups also.

Fig. 1 The Danish offshore wind farm in the North Sea [1]

Limit research experiences of pile group foundations under cyclic lateral loading could be reviewed. Rollins et al. [4] tested series of full scale pile groups with various spacing to study the effect of pile spacing under cyclic lateral loading on the behavior of pile groups. It was concluded that the group interaction effect decreases considerably with increase of spacing from 3.3 to 5.65 times the diameter of pile. Peng et al. [5] summarized various devices used for applying cyclic lateral load to model piles. Chandrasekaran et al. [6] reported experimental investigation on 1×2, 2×2 and 3×3 model pile groups, having different length or spacing and embedded in soft marine clay under lateral cyclic loading. From the test results it could be seen that, the lateral capacity of the pile group increased with the number of pile. Piles in closely spaced groups carry considerably higher moments at deeper depths. Basak S. and Mastorakis Nikose [7] performed the experiment on 2×2 pile group, each pile being hollow circular stainless steel bar. During cyclic loading in progress, a pair of gaps appeared in front and the back of the pile with the increasing number of loading cycles. The degradation factor decreased with number of cycles and increased with frequency nonlinearly.

Also there are some researches on the lateral behavior of pile groups using numerical analysis. Abbas et al. [8] reported the numerical studies on the lateral behavior of three pile group configurations (i.e. 2×1, 2×2 and 3×2 pile groups) with four values of pile spacing (i.e. 2D, 4D, 6D and 8D). It can be observed that, the group configuration has significant effect on the lateral pile displacement and ultimate soil resistance under the same lateral load. Chore et al. [9] used finite element method to analyze two pile groups subjected to lateral loads by considering the non-linear behavior of soil. It was concluded that due to the non-linear behavior of soil, the top displacement of the pile group was increased 66.4% to 145.6%, while the fixed moments was reduced 2% to 20% and the positive moments 54% to 57%.

There are limited literature presented the experimental results of the pile groups in clay soil with different relative density under cyclic lateral loads. The effects of soil on pile groups under cyclic loading have not previously been studied extensively. Hence, in the present study, four model pile groups embedded in clay soils were tested under one-way cyclic lateral load to study the effects of soil density and number of cycles on load–deflection and bending behavior of pile group.

2. TEST PROGRAM

2.1 Soil Used

Clay used in this study is mined from the area in Pathum Thani province in Thailand. The properties of the clay are: liquid limit = 54.5%, plastic limit= 35.48%, plasticity index= 18.92%. According to the determined value, dense soil with relative density of 90% and loose soil with relative density of 10% were prepared in the test, following the compaction standard method. Clay was put into the test tank and compacted well. The placement density of dense clay soil (relative density of 90%) is 1.425 g/cm^3. The placement density of loose clay soil (relative density of 10%) is 1.253 g/cm^3. The conformed moisture content of both type of soil is 29.5%, according to that in Pathum Thani province of Thailand.

2.2 Pile Groups

The origin of the model pile group is the pile group foundation for wind turbine with the tower of 25 m high and the rotor diameter of 10 m. Four concrete piles, 19 m long and in 50×50 cm solid section, were arranged in the case of 2×2 pile group with the hanging space of 1.9 m. The pile cap is in 2.80×2.80 m square section with the thickness of 45 cm. Similitude laws proposed by Wood DM and Crewe A. [10] are followed to select the material and dimensions of model pile.

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

in which E_m is the modulus of elasticity of model pile, which was recorded as 69 GPa for aluminum in this study; E_p is the modulus of elasticity of prototype pile, corresponding to the reinforced concrete of f_c' = 25 N/mm^2 in this study; I_m is the moment of inertia of model pile; I_p is the moment of inertia of prototype pile; and $1/n$ is the scale factor for length of model pile to prototype pile, which equal to 1/30 in this study.

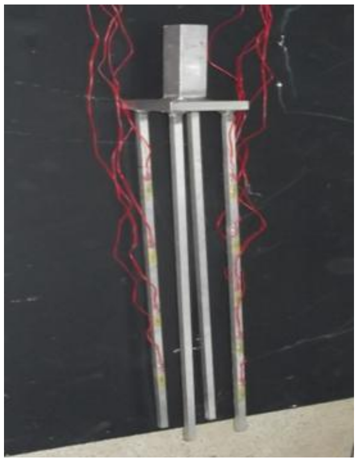


Fig.2 Model pile

750 mm long aluminum stick having square section of 10×10 mm was used as model pile to arrange 2×2 pile group with spacing of 63 mm in this study. Aluminum plate in 93× 93cm square section and in 15 mm thick was used as pile cap. Aluminum stick in size of 30×30 mm and 150 mm long was welded above the pile cap to subject lateral load from hydraulic jack. Four strain gauges at the interval of 150 mm were pasted on selected pile in leading row or rear row to record the bending moment at different depth of pile groups (see in Fig.2).

2.3 Test Loading Pattern

The steel tank used in test is 750 mm high with the section diameter of 650 mm (see in Fig.3). The model pile was then plug into the soil, leaving 120 mm above the soil surface. Then the cyclic lateral load was then applied by pneumatic cylinder attached on the loading frame. The one-way cyclic lateral load was increased from a minimum value of P_{min} = 0 to a maximum of P_{max} =20N, and return to P_{min} = 0 (no reversal of loading direction). The maximum lateral load P_{max} was taken as 80% of the ultimate lateral loading capacity of 25N, which has determined from static test when the corresponding deflection is equal to 20% of pile diameter. The lateral load was repeated for 50 times (cycles) and then increased monotonically until failure.

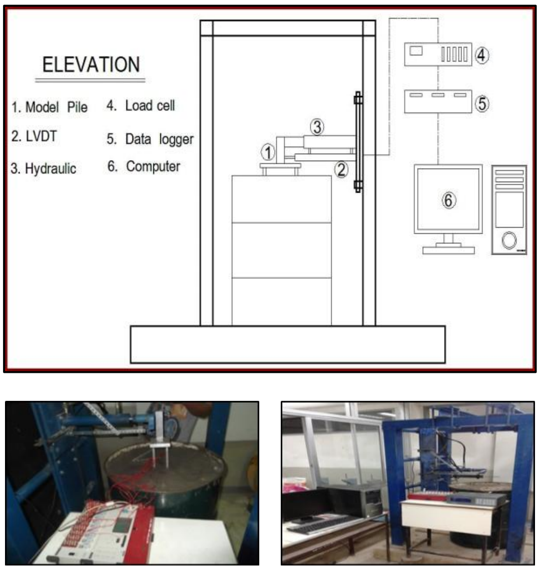


Fig.3 Test set-up

3. DISCUSSION ON TEST RESULTS

3.1 Load-Deflection Curves

The lateral deflection of model pile groups under lateral static or cyclic loading, measured at the level of pile caps, were drawn in Fig. 4. The deflection increased nonlinearly with the number of loading cycles. It shows that, for pile group embedded in dense soil, the load-deflection curves under cyclic or static load behaved similar trend. The deflection of pile group in dense soil after 50 loading cycles was about 4.27 times more than the value for the same static load. However, the deflection of pile group in loose soil after 50 loading cycles was about 65% of the value for the same static load. It can also be seen that the deflection of pile group in dense soil, developed in the first 15 loading cycles, is accounted for 66% of the deflection at 50 cycles. For pile group in loose soil, this value is 50%.

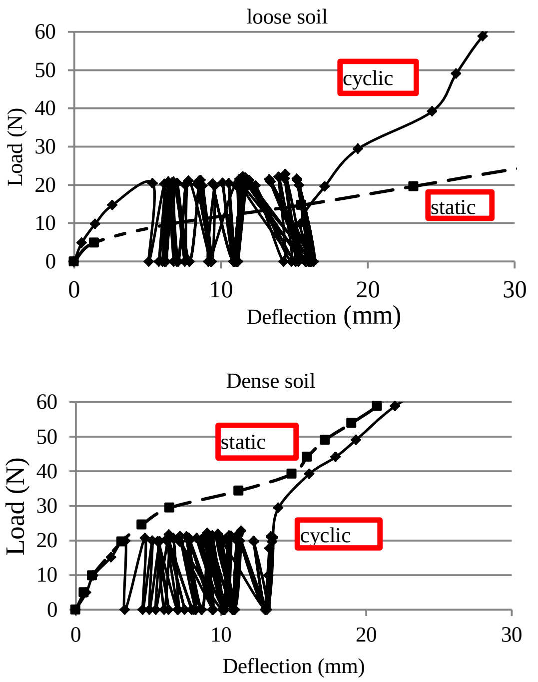


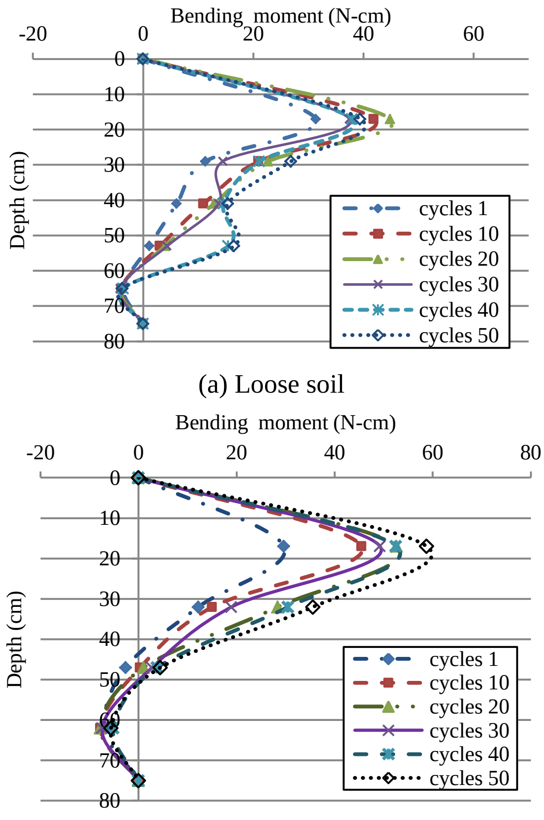
Fig. 4 Load versus head level deflection curves of pile groups in different soil

3.2 Bending Moment Profiles

Based on the strain data measured along the depth of the pile in leading row and rear row of the pile group, the bending moment at various depth can be calculated by the expression: $M = \frac{EI\varepsilon}{r}$, in which E is the young's modulus of the model pile; I is the moment of the inertia of the model pile; $\mathcal{E}$ is the measured strain; and r is the horizontal distance between strain gauge position and neutral axis, equal to half width of the section of pile.

3.2.1 Effect of loading cycles

For the cyclic loading test, Fig.5 presents lateral response of model pile at the same position in pile groups. The bending moments at various depths



(a) Loose soil

(b) Dense soil

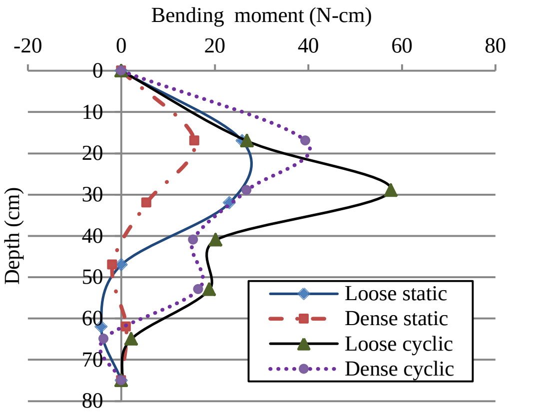
Fig.5 Bending moment of piles in dense or loose soil increased with the number of loading cycles. From 50cm below the soil surface down, the pile in dense soil subjected to bending moment in inverse direction. The maximum bending moment in pile embedded in loose soil after 50 loading cycles was about 1.6 times of that at the first cycle. However, for pile in dense soil, the maximum bending moment for 50 cycles was 2 times of that at the first cycle. The depth corresponding to the maximum bending moment acted on pile group in loose soil at 50 loading cycles were measured at about 5 cm below the corresponding depth at the first cycle. However, marginal increase in the depth corresponding to the maximum bending moment was observed for pile embedded in dense soil.

3.2.2 Effect of loading program

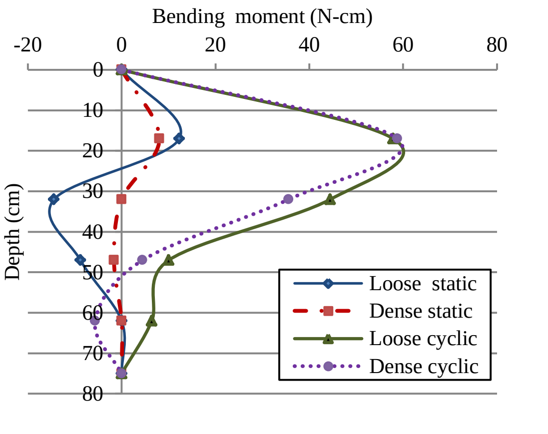
Fig.6 shows the bending moment along the depth of piles under static and cyclic loading at 50 cycles. It is noted that, for pie in leading row of the pile group, the maximum bending moment subjected by pile at 50 loading cycles in either loose or dense soil was more than 2 times of the value for the same static load. Moreover, for pile in loose soil, the maximum bending moment occurred at the deeper depth. For pile in rear row of the pile group, the maximum bending moment subjected by pile at 50 loading cycles in either loose or dense soil was more than 6 times of the value for the same static load. However, depth of the maximum bending moment undergoes little change.

3.2.3 Effect of the position of pile in pile group

The bending moment profiles for piles at different positions in the pile groups embedded in dense or loose soil are shown in Fig.7. More bending moment was carried by pile 2 in rear row under cyclic lateral loading. When embedded in loose soil, the maximum bending moment subjected by pile 2 at 20 loading cycles was 50% more than that of pile 1 in leading row. The magnitude of this difference decreased to 5% at 50 cycles. When embedded in dense soil, the maximum bending moment subjected by pile 2 at

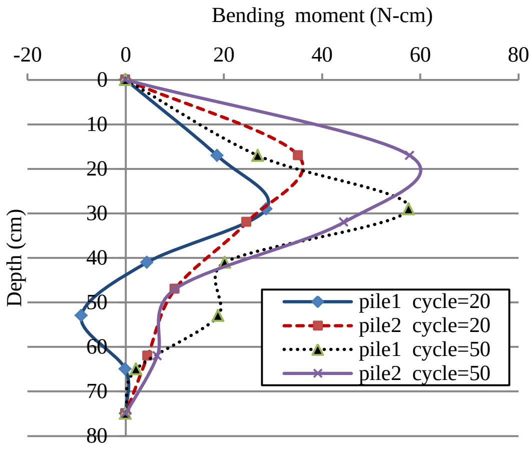


(a) Pile in leading row of the pile group

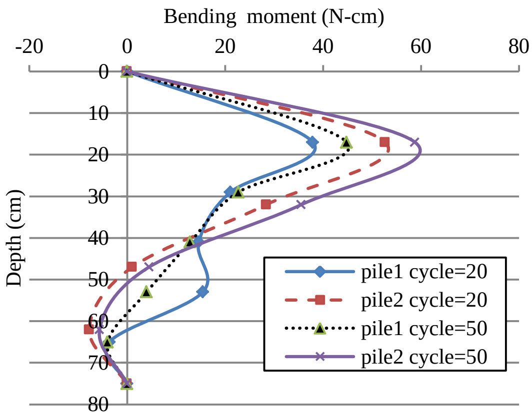


(b) Pile in rear row of the pile group

Fig.6 Bending moment behavior for pile groups under static and cyclic loading (cycles = 50)



Loose soil



Dense soil

Fig.7 Bending moment for piles in leading or rear rows

20 loading cycles was 38% more than that of pile 1 in leading row. The magnitude of this difference changed little at 50 cycles. This indicated that more load was reacted by the rear row piles under cyclic lateral loading. Especially for pile group embedded in dense soil, the design will be governed by the pile in the rear row.

3. 3 Effect of soil

Development of the deflection with the number of loading cycles for pile groups in dense or loose soil is shown in Fig.8. The deflection increased nonlinearly with the number of loading cycles. It can be seen that, with the increasing of loading cycles, deflection of pile groups increased quickly to a certain value. Then after 22 cycles, the increasing became slow. It can also be observed that the soil had a significant effect on the deflections. As the relative density of soil decrease from 90% to 10%, there was approximately 4% to 16% increase in the deflection level. The deflection for pile group in loose soil is 6.16 mm and 15.96 mm for the first and 50th cycles, respectively. The corresponding values for dense soil were 3.42 mm and 13.60 mm, respectively. Plastic soil deformation around the pile was noted (Fig.9). A ‘gap’ occurred under the cyclic loading.

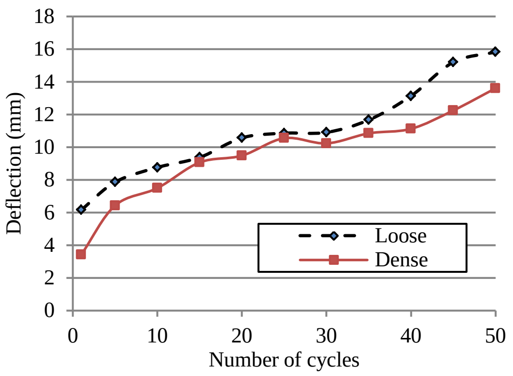


Fig.8 Deflection for pile groups in different soils

Fig.9 Gap occurred under cyclic loading

4. CONCLUSION

Based on the discussion of the test results aforementioned, some conclusions were summarized here.

(1) The deflection of pile group in dense soil after 50 loading cycles was about 4.27 times more than the value for the same static load. However, the deflection of pile group in loose soil after 50 loading cycles was about 65% of the value for the same static load.

(2) With the increasing of loading cycles, the deflection of pile groups increased quickly to a certain value. After 22 cycles, the increasing became slow down. More than 50% of the total deflection at 50 cycles occurred in the first 15 cycles.

(3) More loads were reacted by the rear row piles under cyclic lateral loading. For pile in rear row of the pile group, the maximum bending moment subjected by pile at 50 loading cycles in either loose or dense soil was more than 6 times of the value for the same static load. Especially for pile group embedded in dense soil, the design will be governed by the pile in the rear row.

(4) The depth corresponding to the maximum bending moment acted on pile group in loose soil at 50 loading cycles is deeper than that at the first cycle. However, marginal increase in the depth corresponding to the maximum bending moment was observed for pile embedded in dense soil.

5. ACKNOWLEDGEMENTS

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