Study on the bending moment diagram of straight and inclined pile groups in saturated sands with different thicknesses

Yurun Li\textsuperscript{i)}, Haotian Yang\textsuperscript{ii)}, Dongfeng Qiang\textsuperscript{iii)}, Yan Liang\textsuperscript{iii)}

\textsuperscript{i)} Professor, School of Civil and Transportation Engineering, Hebei University of Technology, Tianjin, China.
\textsuperscript{ii)} Master Student, School of Civil and Transportation Engineering, Hebei University of Technology, Tianjin, China.
\textsuperscript{iii)} Master Student, School of Civil and Transportation Engineering, Hebei University of Technology, Tianjin, China.
\textsuperscript{iiii)} Senior Engineer, Campus Construction and Management, Hebei University of Technology, Tianjin, China.

ABSTRACT

The dynamic response law of a pile foundation in liquefied soil has always been a significant issue in the field of seismic engineering. This paper is based on a shaking table test of 2×2 straight pile groups and 2×2 inclined pile groups in nonliquefied sand and saturated sand with different thicknesses. The bending moment of pile in nonliquefied sand and saturated sand with different thicknesses was studied by applying the Qian'an wave with a certain frequency and acceleration. It shows that the liquefaction of sand will cause the bending moment of pile body to increase. Under the same working condition, the bending moment of inclined pile is smaller than that of straight pile. The difference of bending moment at the bottom of pile is larger, and the difference is more obvious with the increase of the thickness of liquefied sand. Therefore, the inclined pile is more resistant to external load than the straight pile.

Keywords: pile-group structure, shaking table test, bending moment envelope, liquefaction

1 INTRODUCTION

Various types of large-scale engineering construction are currently developing steadily in China. As a type of deep foundation, pile foundations have good bearing capacity, stability and durability, so they are widely used in civil engineering construction. In these projects, pile foundations are often subjected to irregular horizontal dynamic loads, such as vibration loads caused by ground motions (Pecker, 2014). The damage of superstructures is common in many earthquakes. (Kato, 2011; Chen, 2009) Therefore, the dynamic stability of these pile foundations needs to be solved when subjected to lateral loads such as seismic forces. In term of the dynamic analysis of pile group-soil-bridge structure system of high bearing platform under the state of seismic liquefaction, it is found that the bending moment of inclined pile is significantly smaller than that of straight pile and straight pile group, and the different angle of inclined pile also affects the dynamic effect of pile group (Medina, 2015).

It is necessary to further study the dynamic response characteristics of straight group piles and inclined group piles and the distribution law of the bending moment of the pile body. Therefore, this paper designs the similarity ratio of the shaking table model of a pile group structure. Under the input of Qian'an wave, the lateral dynamic response characteristics of a straight inclined pile group - pile cap - superstructure in nonliquefied sand and saturated liquefied sand are focused on.

2 EXPERIMENT INTRODUCTION

2.1 Experiment instrument

The shaking table used in this test is an electromagnetic driven all-numerical control one-dimensional shear vibration simulation table test system. Fig. 1 shows the main equipment of the shaking table. The size of the shear box is 800×600×500mm, and the rubber pad laid at the bottom of the model box is about 50mm. The pile tip is inserted into the rubber pad to simulate the bearing layer of the pile foundation. The covering layer is laid on the surface of saturated sandy soil with a silty clay layer about 50mm thick, so that the entire pile foundation is in the layered soil model.
The diameter of pile is 30mm. The length of the inclined pile is 736.1mm, and the angle of the inclined pile group is 12°. The length of the straight pile is 720mm, and the Young modulus is 2.3GPa. The Fiber Bragg Grating (FBG) sensing system is used to measure the strain of the piles. The grating points are respectively set at positions of 45 mm, 125 mm, 205 mm, 285 mm, 365 mm, 445 mm, and 525 mm from the bottom of the pile. A flexible beam is placed in the sand, and five grating points with the same spacing of 80 mm are arranged thereon for monitoring the soil displacement. The specific layout is shown in Fig. 2 and Fig. 3.

![Fig. 1. Main equipment of the shaking table.](image1)

(a) The 2×2 straight pile group.

(b) The 2×2 straight pile group.

Fig. 3. Schematic diagram of the pile foundation number.

Table 1. Basic properties of the sand.

| Specific gravity $G_s$ | Maximum dry density $\rho_{dmax} (kg/m^3)$ | Minimum dry density $\rho_{dmin} (kg/m^3)$ |
|-----------------------|-----------------------------------------|------------------------------------------|
| 2.644                 | 1.72 x 10³                             | 1.44 x 10³                               |

| Void ratio $e$ | Saturated severity $\gamma_{sat} (kN/m^3)$ | Buoyant severity $\gamma' (kN/m^3)$ |
|----------------|--------------------------------------------|------------------------------------|
| 0.1184         | 24.21                                      | 14.41                              |

2.2 Model soil

The test model pile uses polymathic methacrylate (PMMA) to increase the weight by injecting fine iron sand into the hollow part. The soil sample was prepared by using Fujian standard sand with an obvious liquefaction condition and phenomenon. The basic properties of the sand are listed in Table 1. To reflect the state of the sand in the natural environment as realistically as possible, the experimental model is layered by the sand rain method (Ma, 2014), which is divided into three layers. The thicknesses from the bottom to top are 120mm, 140mm, and 120mm.
3 COMPARATIVE ANALYSIS OF THE BENDING MOMENT

3.1 Comparison of the bending moment in nonliquefied sand

Fig. 4 shows bending moment envelope diagram of straight pile group and inclined pile group in nonliquefied sand. Both the straight and inclined pile group show that the bending moment of the pile bottom and the pile top is large, and the bending moment of the middle part of the pile body is small. They have a relatively similar rule, which is more obvious in straight pile group. According to the distribution law of overall bending moment of pile body, the difference between straight pile group and inclined pile group is not obvious at the minimum bending moment of pile body. The bending moment at other positions of the straight pile group is basically larger than that of the inclined pile group. Especially in No. 2 pile group, the bending moment at each position of straight pile group is all larger than that of inclined pile group.

3.2 Comparison of the bending moment in the saturated sand

Fig. 5 and Fig. 6 respectively show the bending moment envelope of the straight pile group and the inclined pile group in 300mm and 380mm saturated sand. The trend of bending moment in 300mm and 380mm saturated sand is basically the same. It can be seen that the most unfavorable sections of straight pile group and inclined pile group are still the bottom and top of pile, that is to say, the maximum bending moment section is located at the upper and lower part of pile body. And the bending moment of the middle position of pile body is small. According to the distribution law of the overall bending moment of the pile body, the enveloping diagram of the bending moment of the straight pile group is X-shaped, and the enveloping diagram of the bending moment of inclined pile group is “Vase”.

Therefore, the bending moment of the straight pile group is increasing when it is near the bottom of the pile, but the inclined pile group tends to decrease. The bending moment of straight pile group at the bottom of pile is slightly larger than that of inclined pile group. The bending moment of straight pile group and inclined pile group is basically similar in the middle of pile body. The inclined pile group is slightly larger than the straight pile group at the pile head. Compared with nonliquefied sand, the bending moment of straight and inclined pile body increases after liquefaction. The bending moment distribution after liquefaction is more similar, and the bending moment of straight pile group is still larger than that of inclined pile group.
Fig. 6. Comparison of the bending moment envelope diagrams of pile group in the 380 mm saturated sand.

**4 CONCLUSIONS**

Under Qian'an wave input, the maximum bending moment difference at each section position of inclined pile group is relatively small in nonliquefied sand. However, the differences between the sections of the straight piles are obvious. The maximum bending moment of the straight piles at the bottom section of the pile is eight times of that of the inclined piles in No.2 pile. It shows that inclined pile group is more stable than straight pile group under transverse load in nonliquefied sand. Due to liquefaction, the bending moment of straight and inclined pile group in liquefied soil is much larger than that in nonliquefied sand. With the increase of the thickness of saturated sand, the bending moment of the pile increases. And at the same thickness, the bending moment of inclined pile group is larger than that of straight pile group. Through the above arguments, the inclined pile is more resistant to external load than the straight pile.

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