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Experimental study on the horizontal bearing characteristics of pipe pile considering the influence of vertical load

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ABSTRACT: Pile foundations in engineering are often subjected to both vertical and horizontal loads. Most of previous studies focused on the bearing characteristics of pile foundation under a single load, however, the bearing capacity of pile foundation under complex loads is still to be studied, especially for pipe pile. In this paper, the horizontal bearing characteristics of pipe pile are studied by model tests when vertical load applying before horizontal load. The results reveal that the horizontal displacement and rotation angle on pile top decrease as the increase of vertical loading when it is smaller than the vertical ultimate bearing capacity. Therefore, the vertical loading causes the increase of the horizontal bearing capacity of the pipe pile and the reduction of the bending moment of pile shaft. Increasing vertical loading results in the decrease of the horizontal soil resistance at the opposite side of the lateral load along pile as well as at the side of the lateral load near pile tip. The vertical load has little influence on horizontal bearing capacity when it approaches the vertical ultimate bearing capacity.

KEYWORDS: Pipe pile; horizontal bearing capacity; influence of vertical loading; soil resistance; model tests.

1 INTRODUCTION.

Pile foundations are utilized in engineering construction such as highways, railways, ports and bridges, etc. Besides the vertical loads generated by the upper structure, pile foundations are usually subject to horizontal loads caused by water flow, lateral vibration, lateral earth pressure and so on. The bearing behavior of pile foundations under the collective influence of horizontal and vertical loadings is complicated (Abbas et al. 2017; Kanakeswararao & Ganesh., 2017; Lu & Zhang., 2018; Seo et al. 2019).

The bearing behavior of pile foundations under complex loads have been studied to some extent. Gao et al. (2019) investigated the vertical bearing behavior of artificially excavated large-diameter concrete piles. Kong et al. (2019) developed new p-multiplier to quantify group effects in pile groups subjected to eccentric lateral loads. Luan et al. (2019) provided an analysis method for evaluating the dynamic impedance of the pile group. Yang et al. (2019) investigated the lateral behavior of single piles buried in lateral ground and slopes. The work by Zormpa & Comodromos (2018) demonstrated that vertical and horizontal loadings affect the bearing capacity of pile foundations. Designing pile foundations without considering the interaction between vertical and lateral loadings is not safe (Hazzar et al. 2017). Pre-vertical loading significantly affects the lateral bearing behavior of pile foundations. Some scholars (Meyerhof et al. 1993; Sastry et al. 1999) researched the bearing behavior and lateral soil pressure distribution for rigid piles and flexible piles under inclined loading. Karthigeyan et al. (2006, 2007) used GEOFEM3D to establish a numerical model to analyse the influence of vertical load. Researches show that vertical loading can improve the horizontal load-carrying capacity of pile foundations in homogeneous sand and can slightly weaken the horizontal bearing capacity in homogeneous clay. Karasev et al. (1977) hypothesized that vertical loading reduces the influences on the horizontal displacement of single piles. Hazzara et al. (2017) used three-dimensional finite difference analysis to demonstrate that vertical loading does not obviously effects the horizontal load-carrying capacity of pile foundations in sand (especially loose sand), but weakens the load-carrying capacity of pile foundations in clay. The experimental results for flexible piles in soft soil reported by Kesavan & Chandrasekaran (2016) were similar. Some related research show that pre-vertical loading results in the reduction of the horizontal bearing capacity and increase of the lateral displacement of single piles (Meera et al. 2007; Lee et al. 2011; Liang et al. 2012). Clearly, the bearing capacity of single piles under the action of complex loads has not yet reached consistent conclusions.

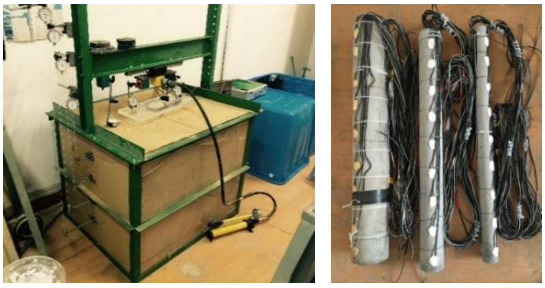
As the rapid development of the infrastructure consturctions in China, the requirement of the pile foundation is increasing (Zheng et al. 2016; Briançon et al. 2011; Wu et al. 2017). Many new piles are used in ground improvement engineering, such as rectangular piles, L-section piles, Y-section piles, I-section piles, barrettes, tapered piles, belled piles, squeezed branch piles, and pipe piles (Seo et al. 2009; Lv et al. 2016). PCC pile (Cast-in-place concrete large-diameter pipe piles) is a new type of pile (Ding et al. 2016). Owing to its larger bearing capacity, high efficiency, and smaller concrete use than common circular-section piles, PCC pile has been successfully applied in embankment engineering as embankment piles and in municipal engineering for soft foundation treatment (Zhou et al. 2016).

Owing to different study conditions, the conclusions from different studies regarding the bearing behavior of piles under complex loadings have not been consistent. The research on the bearing capacity of PCC piles mainly considers vertical or lateral loadings (Liu et al. 2009; Liu et al. 2011). The bearing behavior of PCC pile under complex loading conditions requires further studies. In this paper, the effects of pre-vertical loading on the horizontal bearing capacity of PCC piles are studied by using model tests.

2 MODEL PREPARATION AND TESTING CONDITIONS

2.1 *Development of the model test system*

The model test system for addressing the bearing behavior of pile foundations under complex loading conditions was developed (Zhou et al. 2015). As shown in Fig. 1(a), the model test equipment consists of a sturdy model cistern, a measurement system and a loading system. The dimension of the model container is 1 × 0.8 × 0.8 m (length × width × height). The model tank is made of a 12-mm-thick organic glass and angle steel. It includes some important test processes, such as control-layered fill thickness, model pile, and embedding of measuring components. Four sets of pile lateral measuring parts made of thin steel pipes and pulleys are provided. The development of the lateral displacement of the pile shaft can be effectively evaluated by using the connection line between the pile and the dial gauge. The components of the pile top displacement and rotation measurement are connected to the linear sliding guides by bolts, which allows them to move laterally with the pile top to ensure the reliability of the pile top settlement and angle.



(a) The model test system (b) The model piles

Fig. 1 Photographs of the model test system and the model piles

2.2 *PCC model pile preparation*

The prototype of the model pile was a PCC pile. A PVC pipe was used as the inner and outer formwork. A PVC reducer straight connector was used to ensure that the inner and outer formworks are concentric. Owing to the small cavity of the template, the model pile was made of 1:2 cement mortar, cold drawn steel wires with 2.6mm diameter were used as the reinforcement. The mold was removed after the concrete sets. Three length-diameter ratio model piles were produced, as shown in Fig. 1(b). Table 1 shows the model pile parameters. According to the analysis of the horizontal unidirectional loading test, the #1 pile can be regarded as a rigid pile. The #2 pile can be regarded as a semi-rigid pile. The #3 pile can be regarded as a flexible pile. Nine strain key point and five soil resistance measuring points of the pile side were arranged equidistantly on both sides of the pile. The resistance strain gauge and micro-earth pressure cell data were collected by performing static stress and strain tests.

Table 1 Parameters of model pipe piles

Type	External diameter (mm)	Wall thickness (mm)	Cross-section area (mm^2)	Length (m)	Reinforcement number	*EI* ($kN\cdot m^2$)
#1	105	15	4240	0.7	6	112.46
#2	70	10	1884	0.7	6	22.21
#3	45	10	1100	0.7	4	2.70

2.3 *Test soil preparation*

The sand was collected from the Hexi District in Nanjing, China. After drying, the test soil was sieved using a 2mm pore diameter geotechnical sieve. The soil test showed that the uneven coefficient Cu was 2.08 and the curvature coefficient Cc was 0.99. Other mechanical and physical parameters are shown in Table 2. The test used layered backfills and marked the graduation line at the organic glass lateral in advance. The compaction quality was controlled by the density method, the thickness was 10 cm, and the density of the sand was 1.67g/cm^3 after compaction.

Table 2 Physical and mechanical parameters of sand

ρ_{dmax} (g/cm^3)	ρ_{dmin} (g/cm^3)	Φ (°)	E_s (MPa)
1.73	1.41	39	12.5

2.4 *Test conditions*

Before the test, the vertical unidirectional load testing was carried out using the model test system. With reference to the "Technical Specifications for the Detection of Building Foundation Piles" (JGJ106-2014) (Chen et al. 2003), the vertical ultimate bearing capacities V_{ult} of piles #1, #2, and #3 were 4.5 kN, 4.0 kN, and 3.0 kN, respectively. Afterward, horizontal load testing was carried out when the vertical load applied on the pile top was 0.1V_{ult}, 0.3V_{ult}, 0.5V_{ult}, 0.7V_{ult}, and 0.9V_{ult}, respectively.

3 RESULTS AND ANALYSIS

3.1 *Horizontal displacement of the pile head*

The curves for the horizontal displacement of the pile head are illustrated in Fig. 2. The results show that pre-vertical loading significantly affects the horizontal displacement development of the pile head. In the case of vertical loading in advance, the horizontal displacement development of the pile head for #1, #2, and #3 piles slows down. The larger the vertical load, the gentler the curve. For the vertical load of V = 0 kN, piles #1, #2, and #3 appear inflection points at 1.6 kN, 1.2 kN, and 0.6 kN, respectively, which indicating that the lateral ultimate bearing capacity is reached. However, for positive pre-vertical loads (V > 0 kN), there are no obvious inflection points in the curves for the three piles. The results show that pre-vertical loading is beneficial for improving the horizontal load-carrying capacity of PCC piles. A certain level of pre-vertical loading is beneficial for reducing the horizontal displacement of the pile head. For pre-vertical loadings closer to the vertical ultimate load, the effect on the horizontal load-carrying capacity is smaller.

Referring to the approach of Karthigeyan et al. (2007), the curves of V/V_{ult}-y_V/y are shown in Fig. 3. This figure compares the effect of length-diameter ratio of piles on the horizontal displacement of the pile heads induced by pre-vertical loading. In this figure, y_V is the horizontal displacement of the pile head measured in the pre-vertical loading condition test, and y is the horizontal displacement of the pile head measured for the same horizontal load. During pre-vertical loading, when the horizontal load is the same, the horizontal displacement ratio increases with the length-diameter ratio increases.

3.2 *Rotation on the pile head*

The curves of the rotation on the pile head for piles #1, #2, and #3 are shown in Fig. 4. Pre-vertical loading slows down the development of the rotation on the pile head. The rate of development decreases with increasing pre-vertical loading. Comparing Fig. 2 and Fig. 4, it is evident that the distributions of the curves of the rotation on the pile top and the lateral displacement on the pile head are approximately the same, indicating the consistency of the test measuring device. In addition, since pre-vertical loading is pre-applied to the pile head, the pile head is restrained in action, which limits the displacement and rotation of the pile head. At the same time, compared with the effect of pre-vertical loading on the rotation on the pile head, the effect of the latter is reduced.

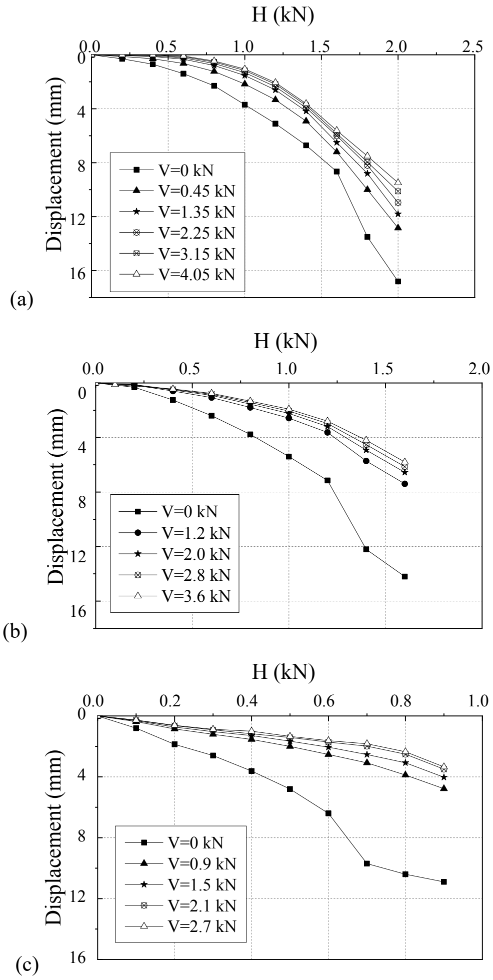


Fig. 2 Horizontal displacements of the pile heads: (a) #1, (b) #2, (c) #3

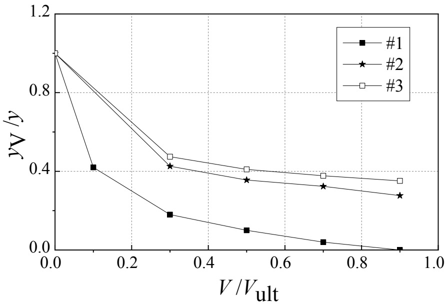


Fig. 3 V/V_{ult}-y_v/y curves when H = 0.4 kN

3.3 *Horizontal displacement of the pile shaft*

Fig. 5 illustrates the horizontal displacement distribution of the shaft of pile #1. Pile #1 presents the largest bending stiffness and the lateral displacement of the pile is linearly distributed along the buried depth of the pile shaft. It accelerates with increasing lateral load. The pile shaft does not show any obvious flexural deformations. Therefore, pre-vertical loading does not influences the horizontal displacement distribution for pile #1. The pile still rotates with the zero displacement point as a fixed point. Over the zero point, the pile moves in the direction of the lateral load. Below the zero point, it moves in the opposite direction. For the pre-vertical loadings of 0 kN and 4.05 kN, the buried depth of zero displacement points are, approximately 0.6 m and 0.68 m, respectively. The zero displacement point gradually moves down with increasing pre-vertical loading. This is because pre-vertical loading significantly increases the stress level of the soil near the pile tip. The development of the displacement of the pile tip is limited, thus the zero point of the lateral displacement shifts down.

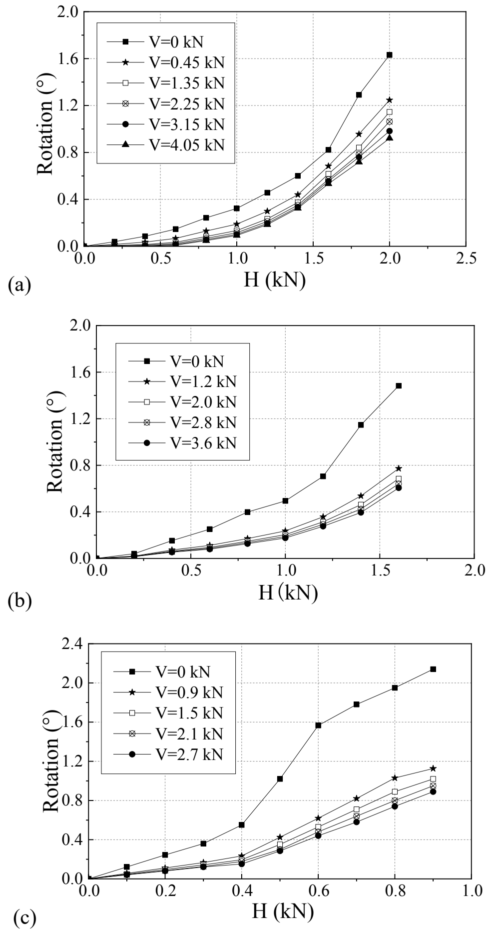
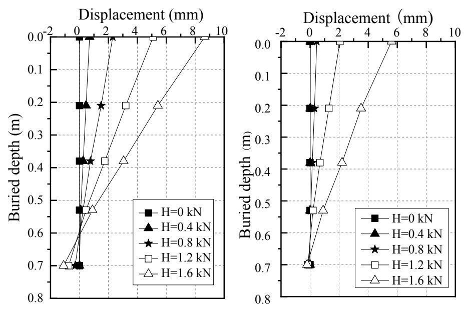


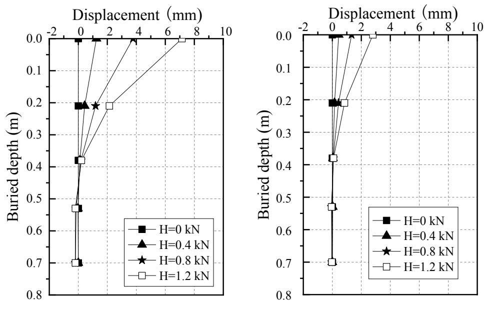
Fig. 4 Curves of rotation on the pile head: (a) #1, (b) #2, (c) #3



(a) V = 0 kN (b) V = 4.05 kN

Fig. 5 Horizontal displacement curves for the body of pile #1

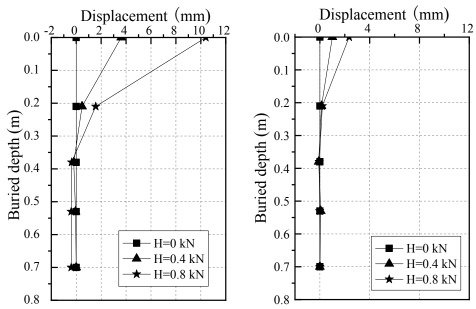
Fig. 6 shows the lateral displacement distribution diagram for the shaft of pile #2. Clearly, the lateral displacement for the shaft of pile #2 decreases nonlinearly along the buried depth, as the rate increases with increasing lateral load. Obvious deflection deformation occurred above the zero displacement point, while the lateral movement of the pile under the zero point was not obvious. It indicates that the distribution and the development of the lateral displacement of the pile shaft are significantly affected by pre-vertical loading. Moreover, the depth of the zero displacement point is approximately 0.42 m when V=0kN, while the zero displacement point is shifted upward to 0.38 m when V=3.6kN. Similar to pile #1, the lateral displacement of pile #2 decreases with increasing pre-vertical loading. For pile #2, pre-vertical loading significantly slows down the development of the flexural deformation of the upper pile part, and improved the horizontal pile bearing capacity.



(a) V = 0 kN (b) V = 3.6 kN

Fig. 6 Horizontal displacement curves for the body of pile #2

Fig. 7 shows the lateral displacement distribution diagram for the shaft of pile #3. Similar to pile #2, the horizontal displacement of the shaft of pile #3 decreases nonlinearly with the increasing buried depth of the pile. At the same time, there is an obvious deflection deformation of the pile above the zero displacement point. When V=0kN, the buried depth of the zero displacement point is 0.35 m. Negative displacement occurs below zero point along the pile. When the lateral load reached 1.4 kN and 0.7 kN, cracks appeared at the buried depth of 0.3 times the pile length. For the pre-vertical loads of 2.7 kN, the buried depth of the zero displacement point was 0.27 m. Moreover, with increasing pre-vertical loading, the reverse displacement of the pile below the zero point gradually decreased. With increasing pre-vertical loading, the zero point of the displacement of pile #3 moved up, similar to pile #2, but different from pile #1. According to the analysis, this occurred because pile #1 had the highest bending stiffness and the smallest length-diameter ratio. The pile exhibited rotation, and deflection was not obvious. Comparing with pile #1, piles #2 and #3 show different properties.



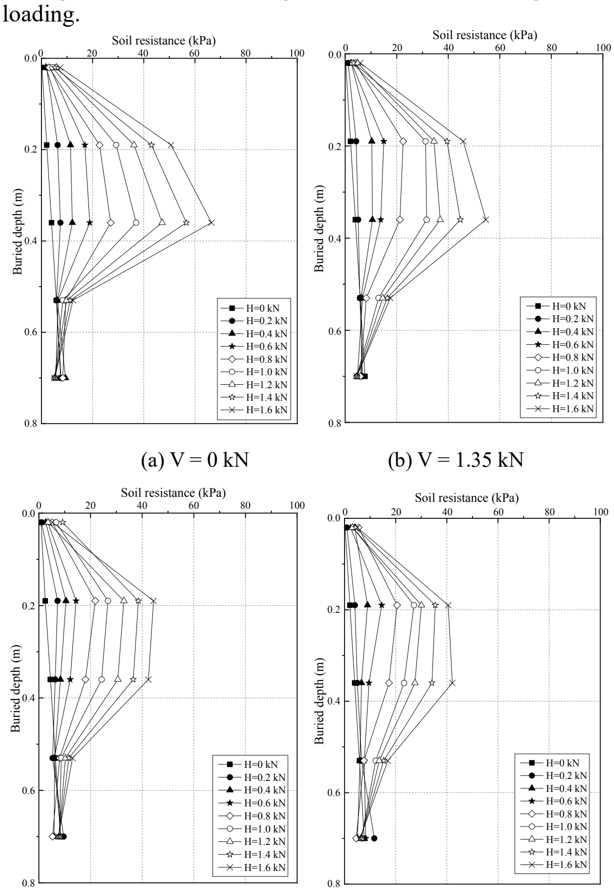
(a) V = 0 kN (b) V = 2.7 kN

Fig. 7 Horizontal displacement curves for the body of pile #3

Based on the above analysis, for piles #1, #2, and #3, pre-vertical loading did not affect the distribution patterns of the horizontal pile displacement and the development patterns associated with lateral loading. However, the development rate of the horizontal displacement of the pile decreased with the increasing horizontal loading, and the horizontal bearing performance of the pile was improved. At the same time, after the vertical load reached a certain level, the effect of the horizontal displacement on the pile body weakened.

3.4 *Lateral soil resistance*

Fig. 8 shows the curves for the lateral soil resistance at the side against the lateral loading for pile #1. Clearly, the lateral soil resistance at the side against the lateral loading primary increases along the depth and then decreases. The maximal value appears at the buried depth of 0.5 times the pile length. The distribution form and the development characteristics of the lateral soil resistance at the side against the lateral loading for pile #1 are not affected by pre-vertical loading. At the same time, for the same lateral loading, the amplitude of the lateral soil resistance at the side against the lateral loading decreases with increasing vertical loading.



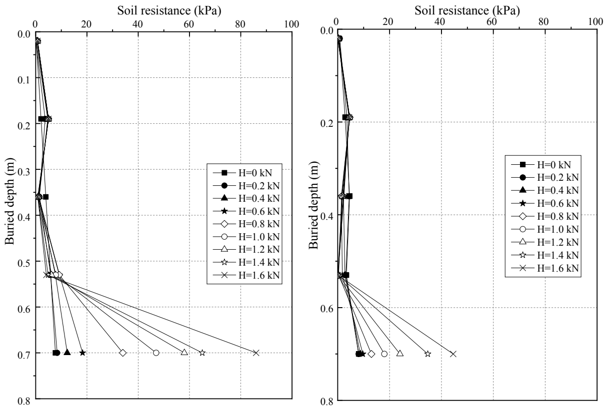
(c) V = 3.15 kN (d) V = 4.05 kN

Fig. 8 Lateral soil resistance curves for the side against the lateral loading, for pile #1

Fig. 9 shows the lateral soil resistance curves for the side along the lateral loading for pile #1. Clearly, pre-vertical loading does not affect the distribution pattern and the development trend of the lateral soil resistance at the side along the lateral loading. Futhermore, pre-vertical loading slows the development of the lateral soil resistance at the side along the lateral loading with lateral loading. Higher pre-vertical loading yields stronger mitigation effect.

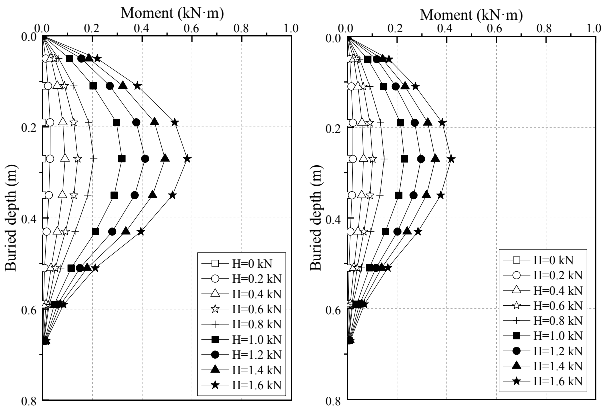
3.5 *Bending moment*

Fig. 10 shows the moment of pile #1. Under pre-vertical loading, the moment increases when the horizontal loading increases. The maximum moment appears at the buried depth of 0.4 times the pile length, which does not change with increasing lateral loading. The vertical loading has less influence on the distribution pattern and the development characteristic of the moment along the shaft of pile #1. However, the moment of the pile shaft decreases with the vertical load increases for the same horizontal loads. When the pre-vertical loading is 4.05 kN(V=4.05kN), the maximum moments corresponding to horizontal loads 0.4kN, 0.8kN, 1.2kN and 1.6kN are 80%, 75%, 72%, and 74% of those when V=0kN. This becauses pre-vertical loading changes the stress state inside the pile.



(a) V = 0 kN (b) V = 3.15 kN

Fig. 9 Lateral soil resistance curves for the side along the lateral loading, for pile #1

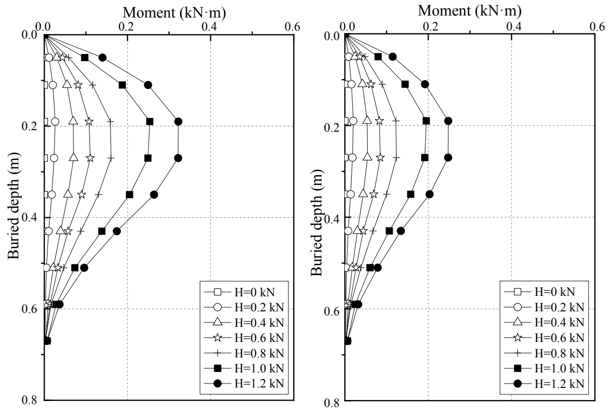


(a) V = 0 kN (b) V = 4.05 kN

Fig. 10 Bending moment curves along the shaft of pile #1

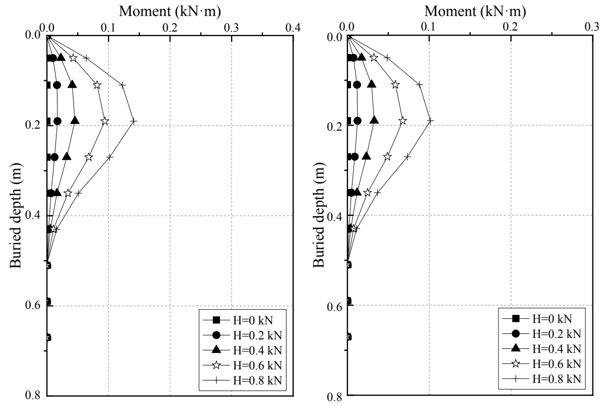
Fig. 11 shows the development and change of the moment along the shaft of pile #2. The pile moment increases with increasing lateral loading. The maximal moment appears at the buried depth of 0.3 times the pile length. For higher lateral loads, the moment is mainly distributed in the pile section above the buried depth of 0.8 times the pile length. Similar to pile #1, the distribution pattern and the development characteristics of the moment for the shaft of pile #2 are less affected by vertical loading. However, for the same horizontal load, the moment decreases with increasing vertical loading. Because the bending rigidity of pile #2 is smaller than that of pile #1, the shaft of pile #2 shows a larger lateral deformation, and the reduction of the tensile-compressive strain difference of the pile is smaller than that for pile #1. The amplitude reduction of the moment also decreases.

The development and change of the moment for the shaft of pile #3 are illustrated in Fig. 12. The moment is mainly distributed in the pile section above the buried depth of 0.8 times the pile length. The maximal moment appears at the buried depth of 0.3 times the pile length. Similar to piles #1 and #2, the distribution pattern and the maximum location for the body of pile #3 are not affected by pre-vertical loading. Similar to pile #2, the amplitude of the moment decreased when vertical load was applied.



(a) V = 0 kN (b) V = 3.6 kN

Fig. 11 Bending moment curves along the shaft of pile #2



(a) V = 0 kN (b) V = 2.7 kN

Fig. 12 Bending moment curves along the shaft of pile #3

4 CONCLUSIONS

By model testing the horizontal bearing capacity of PCC piles subjected to pre-vertical loads, the horizontal displacements and rotations of the pile heads, the lateral soil resistance, the horizontal displacements and the moments of the pile shafts were obtained. The effects of vertical loading on the horizontal bearing behavior of the PCC piles were analyzed. The main conclusions are as follows:

- The horizontal displacement and rotation of the pile head decrease due to the application of the pre-vertical loading when it is smaller than the vertical ultimate bearing capacity. Therefore the bearing capacity of the PCC pile is improved for pre-vertical loading. However, the effect of vertical loading on the horizontal bearing capacity is not obvious when the pre-vertical loading approaches the vertical ultimate bearing capacity.
- Influence of pre-vertical loading on the horizontal displacement of the pile shaft and the moment is significant in the reduction of the development rate with increasing lateral loading, however, the effect on the distribution is not obvious.
- The lateral soil resistance at the side against the lateral loading gradually decreases with increasing pre-vertical loading. The influence of vertical loading on the lateral soil resistance at the side along the lateral loading is obvious near pile end, where the increment of the soil resistance is smaller.

5 ACKNOWLEDGEMENTS

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