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Influence of Axial Loads on the Lateral Capacity of Instrumented Steel Model Piles

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Abstract: Only a few experimental studies have been performed on the response of piles subjected to combined loading, although the load applied on a pile is usually a combination of a vertical and a lateral load in practice. In addition, the experiment results available in the literature are inconsistent with respect to the effects of axial loads on the lateral capacity of piles. The objective of this paper is to assess the influence of axial loads on the lateral response of piles driven in sand through model pile combined load tests. Large-scale sand samples were prepared in a cylindrical steel tank with different relative densities (dense and loose) using a pluviation method, and an instrumented steel model pile was driven using a drop hammer. A series of lateral load tests were performed on the model piles subjected to different axial loads. The combined load test results demonstrated that the presence of an axial load on a driven pile is detrimental to its lateral capacity, for the bending moments and lateral deflection of the pile head increased substantially with increasing axial load.

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***Key words:** Axial load; Combined load test; Lateral capacity; Steel model pile.*

Introduction

Piles are analyzed independently in most cases although loads applied on piles are usually a combination of both axial and lateral loads. In current practice, pile design is carried out separately for axial and lateral loads based on the assumption that the effects of these loads are independent of each other [1, 2]: first, an ultimate axial load capacity is calculated, and then, the pile is analyzed for lateral loads with the geometry resulting from axial load calculations. The main reason for this approach in design is that pile response under combined loading is more complex and difficult to analyze than pile response under either axial or lateral loading.

Extensive research has been performed on pile foundations subjected to either axial loads or lateral loads, even though pile response under combined loads can be significantly different due to the interaction of axial and lateral loads. The influence of axial loads on the lateral response of pile foundations needs to be considered for optimum design; however, only a few experimental studies have been conducted for this purpose [3-9] as shown in the following section. Moreover, the results available in the literature are inconsistent with respect to the effects of axial loads on the lateral response of piles. For example, Pise [4] and Jain et al. [9] reached opposite conclusions although both studies were based on model pile load tests in sand. Therefore, studying the interaction effects between axial and lateral loads is necessary to identify key factors influencing pile response subjected to combined loads. The main objective of this paper is to investigate the influence of axial loads on the lateral response of model piles through experimental study under well controlled conditions.

Reviewing Previous Research

Model pile load tests

Pise [4] conducted combined load tests on a 2x3 model pile group embedded in sand. The model piles were fabricated with an aluminum alloy tubing 19 mm in diameter and 76 mm in length. The center-to-center spacing between the piles was three times the diameter of the pile. The sand was prepared at a relative density of 75% for all the tests. The results of this investigation showed that the presence of a vertical load reduced the lateral deflection of the pile group (i.e., the lateral deflection decreased as the vertical load increased). The restraint imposed on the pile head by the loading device used for the application of the vertical load was suspected to be the main cause of the results.

Jain et al. [9] performed combined load tests on fully and partially embedded long flexible single piles and pile groups. Samples were prepared in a soil tank using a rainfall technique. The relative density of the sand samples was 78%. The model piles were aluminum tubes, with outer and inner diameters equal to 32 mm and 28.8 mm, respectively. The embedded length of the pile was 100cm. The vertical load assembly of the test equipment was fitted with rollers so that the vertical load would not offer any restraint on the pile head at the time of lateral loading. The lateral load tests were performed with a vertical load equal to 0 (pure lateral load), 20%, 40%, and 50% of the ultimate load. The test results for single piles and pile groups clearly suggested that the presence of a vertical load increased the lateral deflection of the pile head. This experimental study indicated that the lateral ultimate capacity of piles subjected to combined vertical and lateral loads decreased due to the presence of a vertical load.

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Full-scale Pile Load Tests

Evans [3] conducted a series of lateral load field tests with and without vertical loads to determine safe vertical and horizontal loads. The tests included vertical and battered piles, embedded 10.3 m to 17.5 m into loam. Various types of piles (steel H and precast piles, Raymond step-taper, and Union Monotube piles) were tested. The test results indicated that the response of both the vertical and battered piles was similar with respect to the effect of the vertical load on the magnitude of the horizontal deflection; namely, the pile lateral deflection decreased in the presence of a vertical load.

Sorochan and Bykov [5] investigated the effect of a vertical load on the bearing capacity of horizontally-loaded pile foundations in a natural deposit of brown clay. Eight pile groups (four piles in each group) were prepared for testing. The piles were reinforced cast-in place concrete piles with shaft diameters of 600 mm and embedment depths of 3 m. The results of the tests conducted on pile groups subjected to combined loads showed that the vertical load exerts a significant effect on the bearing capacity of horizontally-loaded piles (i.e., the vertical load reduces the lateral deflection of piles). They noted that with a vertical load equal to the design load, the ability of pile foundations to resist horizontal loadings increased by a factor of 1.5-1.7, which illustrated that the lateral capacity of piles in clayey soils increased due to the presence of a vertical load.

Bartolomey [6] studied the behavior of single piles and pile groups subjected to lateral loads and the combined action of vertical and lateral loads. The test piles were 30 cm x 30 cm in cross section and 5 to 12 m long prestressed concrete piles embedded in clay. The test results indicated that the resistance of single piles and pile groups to lateral loads in the case of both vertical and lateral loads combined increased by 15 to 30 percent as compared with the lateral resistance of piles to which no vertical load was applied; that is, the lateral deflection of the piles decreased due to the vertical loads. It was noted that cracks were observed in the piles when the piles were subjected to a pure lateral load without a vertical load. It was indicated that the tensile stresses due to bending were reduced by the presence of a vertical load, and the concrete cracking was reduced accordingly.

Karasev et al. [7] investigated the effect of horizontal and vertical loads on the bearing capacity in each direction of full-size single cast-in place concrete short piles, 600 mm in diameter and 3 m in length, at a sandy loam site. The piles were reinforced over the entire length, and a concrete single pile cap (dimensions of 60 cm in diameter and 50 to 60 cm in height) was installed on top of the piles. The test results indicated that the vertical load had a favorable effect on the lateral resistance of the horizontally loaded piles (i.e., the lateral deflection of the piles decreased considerably by increasing the vertical load). The authors concluded that the main cause for a decrease in the horizontal deflection of the piles was the increased frictional forces at the rigid pile base due to the vertical load.

Zhukov and Balov [8] performed full-scale load tests using horizontal static loads with different vertical surcharges on precast concrete piles embedded in homogeneous saturated clay. The total number of test piles was 43, and the cross section of the piles was 30 cm x 30 cm. The driving depth of the piles was 2 to 4 m, and the height above the ground surface was around 2.5 m. The test results indicated that the vertical surcharge decreased somewhat the resistance of the piles to horizontal loads in weak saturated soils.

Table 1 summarizes the limited research on this topic, which has produced conflicting results concerning the effect of axial loads on the lateral response of piles. As shown in this table, the previous experimental investigations are inconsistent. Some studies have shown that the presence of an axial load increases the pile lateral deflection while other investigations report that the presence of an axial load decreases the lateral deflection of the pile head for both single piles and pile groups.

Test Equipment

Soil Tank and Pile Driving System

The soil tank used in this study is a cylindrical steel tank manufactured using 13-mm-thick stiff steel plates. The internal diameter and height of the soil tank are 2,000 mm and 1,600 mm, respectively (volume of 5.03 m^3). The bottom of the soil tank was welded to the sides with a 25-mm-thick rigid steel plate. The tank consists of three main parts: 1) a guide leader for pile driving, 2) two supports for setting up a reaction beam, and 3) two holes for draining the sand after testing. The guide leader rotates and extends as needed so that model piles can be installed at any location in the deposited sand sample in the soil tank. The reaction beam is a 170-mm-wide H-beam, fabricated from 12-mm-thick steel plates. It was designed to be detachable from the soil tank, so it could be mounted and bolted to the supports after model pile installation.

Table 1. Summary of the Effect of Axial Loads on the Lateral Response of Piles.

Method	Literature	Effect of AxialLoad	Soil	Number of Piles	Pile Installation Method
Model Pile Load Tests	Pise [4]	Decreased Deflection	Sand	Group (6)	Driven
	Jain et al. [9]	Increased Deflection	Sand	Single Group (2, 4)	Driven
Full-scale Pile Load Tests	Evans [3]	Decreased Deflection	Loam	Single	Driven
	Sorochan and Bykov [5]	Decreased Deflection	Clay	Group (4)	Nondisplacement
	Bartolomey [6]	Decreased Deflection	Clay	Single Group (4, 6)	Nondisplacement
	Karasev et al. [7]	Decreased Deflection	Sandy Loam	Single	Nondisplacement
	Zhukov and Balov [8]	Increased Deflection	Saturated Soil	Single	Nondisplacement
		Decreased Deflection	Very stiff Clay	Single	Driven

The head of the model pile is connected to the guide rod and hammer so that it can be driven into the sand sample by blows of a hammer released from a certain height. The driving energy can be adjusted by changing the hammer weight and/or drop height. The sand can be removed from the soil tank after finishing each experiment by draining it through two holes on the side of the soil tank.

Large-scale Sand Pluviator

Sample preparation is one of the most important issues in laboratory model pile tests because the behavior of piles is closely related to the relative density of the sand sample. In this study, a large-scale sand pluviator was employed to prepare uniform sand samples in the soil tank. The sand pluviator has a slightly smaller diameter (D = 1,905 mm) than that of the soil tank, and consists of a steel cylinder 152 mm high and a perforated steel plate welded to the bottom of the steel cylinder. The bottom steel plate was covered by another perforated acrylic plate with exactly the same pattern of holes (D = 10 mm); it was designed to work as a shutter plate that can be opened or closed by matching the holes in these two plates. Additionally, two layers of diffuser sieves with different opening sizes [No. 6 (3.35 mm) and No. 16 (1.18 mm)] were installed below the shutter plate. Fig. 1 illustrates the sand pluviation system in detail.

The main idea of this system is to rain the sand into the soil tank from a certain height while maintaining the same flow rate. Once the appropriate amount of sand is placed in the sand supply, it is discharged by aligning the shutter plate holes with those in the steel plate. The falling sand jets are diffused from the first diffuser sieve like funnels; then the sand is deposited uniformly into the soil tank by raining from the second diffuser sieve. These diffuser sieves played an important role in creating the conditions for uniform sand pluviation, ensuring that the sand was always distributed evenly inside of the soil tank. The sand discharge rate was controlled by selecting the opening size of the sieves. The free falling height of the sand also was controlled by adjusting the elevation of the pluviator with the hoist crane.

Instrumented Steel Model Pile.

A smooth stainless steel pipe was used for the model pile in this paper. The model pile outer diameter, wall thickness, and length were 30 mm, 2 mm, and 1,200 mm, respectively. Eighteen strain gauges were attached to the model pile (with the strain gauge axis parallel to the pile axis) directly opposite each other at nine levels along the model pile shaft, as shown in Fig. 2. The main purpose of using strain gauges is to compute the shaft resistances and bending moments directly from the measured data.

The bottom of the model pile was closed by pile base, so this model pile worked as a closed-ended pipe pile. A vertical gap of 3 mm was left between the end of the steel pipe and the pile base to prevent some of the base load from being transferred to the steel pipe and measured erroneously as shaft load. This vertical gap was sealed with silicone to avoid intrusion of soil particles into the gap during pile driving.

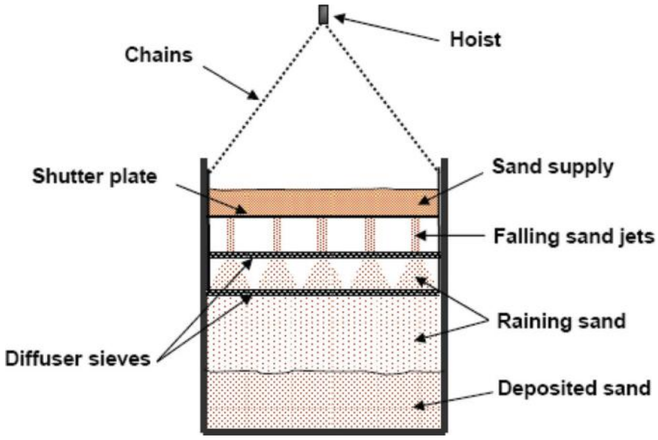


Fig. 1. Schematic View of the Sand Pluviator.

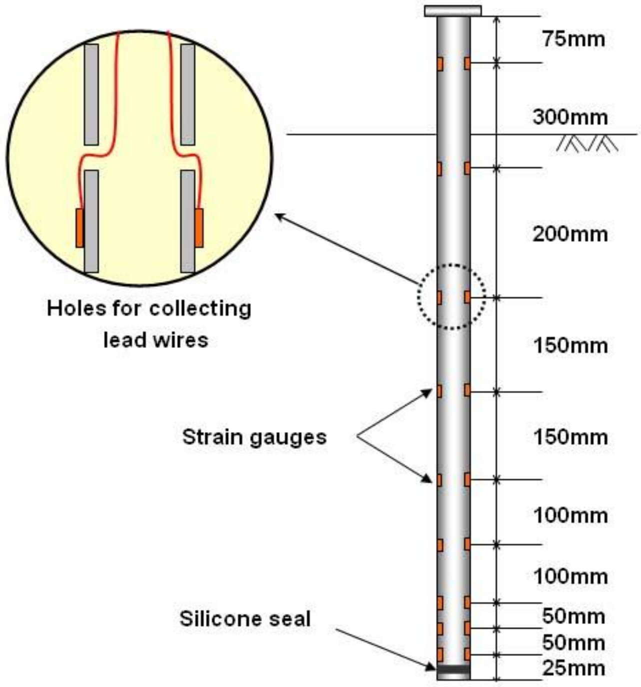


Fig. 2. Instrumented Steel Model Pile.

Model Pile Load Test

Test Conditions

In this paper, clean fine silica sand F-55 was used for sample preparation in the soil tank. F-55 sand has engineering properties very similar to Ottawa ASTM standard sand (designated as ASTM C778-06 [10]), but has smaller particle sizes, with diameters ranging from 0.1 to 0.4 mm (D_{50} = 0.23 mm). F-55 is a uniform quartz sand that has a coefficient of uniformity C_u = 1.67, with rounded to subrounded particle shapes. It is poorly graded sand (SP) according to the Unified Soil Classification System (USCS). The maximum/minimum dry unit weights and the void ratios were determined according to ASTM D 4253-00 [11] and ASTM D 4254-00 [12], respectively. The engineering properties of the F-55 sand are summarized in Table 2.

It is known that the unit weight of sand deposited by the pluviation method depends primarily on the sand falling height and

Table 2. Engineering Properties of F-55 Sand.

Engineering Property	Value
Specific Gravity (G_s)	2.65
Effective Particle Size (D_{10})	0.15 mm
Mean Particle Dize (D_{50})	0.23 mm
Coefficient of Uniformity (C_u)	1.67
Coefficient of Curvature (C_c)	1.07
Max. Dry Unit Weight (γ_{dmax})	17.66 kN/m^3
Min. Dry Unit Weight (γ_{dmin})	14.62 kN/m^3
Max. Void Ratio (e_{max})	0.78
Min. Void Ratio (e_{min})	0.47

discharge rate (Turner and Kulhawy [13]). Therefore, the relative density of sand deposited in soil tank can be controlled by changing the pluviator sieve opening size and the sand falling height. In this paper, the target relative density values for dense and loose sand were about 90% and 40%, respectively. A constant sand falling height was maintained by raising the pluviator with a hoist as the level of the sand surface inside the soil tank increased. The final height of the sand samples prepared was about 1,400 mm.

Combined Pile Load Tests

After finishing sample fabrication, the model pile was driven in the center of the sand sample using a guide rod and steel hammer. For a driving energy of 29.4 N·m (J), the hammer weight and drop height were 3 kg and 1 m, respectively. The model piles were installed to a penetration depth of around 950 mm (the length of the model pile above the sand surface was almost 250 mm). After driving the pile, an H-beam and another reaction beam were assembled together to produce a system of axial and lateral reaction for the combined load tests. Two hydraulic jacking pumps and two load cells, the same used in the axial and lateral load tests, were installed together to allow combined load testing. The axial and lateral loads applied to the pile head were measured by each load cell, and the lateral deflection of the pile head was recorded by two LVDT gauges supported by two reference beams placed on both sides of the pile.

According to ASTM D3966-90 [14], antifriction devices, such as a plate and roller assembly or an antifriction plate assembly, are recommended to provide minimal restraint to the lateral movement of the test pile. In order to avoid restraining the pile head during the combined load tests, a special loading device was used in this paper as shown in Fig. 3. This device consists of two steel plates and rollers that facilitate the application of the axial load without restraining the pile head. This device was assembled on the top of the pile in order to permit the pile to respond freely to the lateral load. This assembly of plates and rollers is considered to be important for the combined load tests because, if it is not used, the restraint imposed by the axial load may reduce the lateral deflection of the pile.

Model pile test results

Fig. 4 shows the lateral load response of the model pile for combined load tests performed in dense and loose sand samples. The combined load tests were performed with axial loads equal to 0%, 25%, 50%, and 75% of the ultimate axial load corresponding to a relative settlement of 10%. The lateral deflection of the model pile head increases with increasing axial load, which means that the presence of an axial load is detrimental to the lateral capacity of driven piles in sand. Therefore, the effect of axial loads should be considered in the design of laterally loaded piles in sand. The lateral deflection of the pile head increases because of the additional bending moment along the pile induced by the axial load. Furthermore, the magnitude of the increase of the lateral deflection increases not only with the magnitude of the lateral load, but also with the axial load. Fig. 4 also shows that the effect of the axial load is greater for dense sand than for loose sand.

Fig. 5 shows the influence of the axial load on the ultimate lateral load capacity of the model pile driven in sand. In this graph, 5%, 10%, and 20% deflection represent the ultimate lateral loads corresponding to lateral deflections of 5%, 10%, and 20% of the pile diameter (0.05B = 1.5 mm, 0.1B = 3 mm, and 0.2B = 6 mm), respectively. The results show that the larger the axial load, the smaller the ultimate lateral load capacity of the model pile. For example, for a dimensionless ratio of the applied axial load to the ultimate axial load of 0.75, meaning an applied axial load of 75% of ultimate load, the decrease in the ultimate lateral load is approximately 40% and 10% for dense and loose sand, respectively.

Fig. 6 shows the influence of the axial load on the maximum bending moment of the model pile driven in sand. The maximum bending moment increases with the applied lateral load. In addition, the maximum bending moment also increases with increases in the axial load. The increase in the bending moments of the model piles tested under combined loads might be the cause for the increment in lateral deflections. In particular, the effects of the axial load on the bending moments were greater in the case of dense sand than in the case of loose sand.

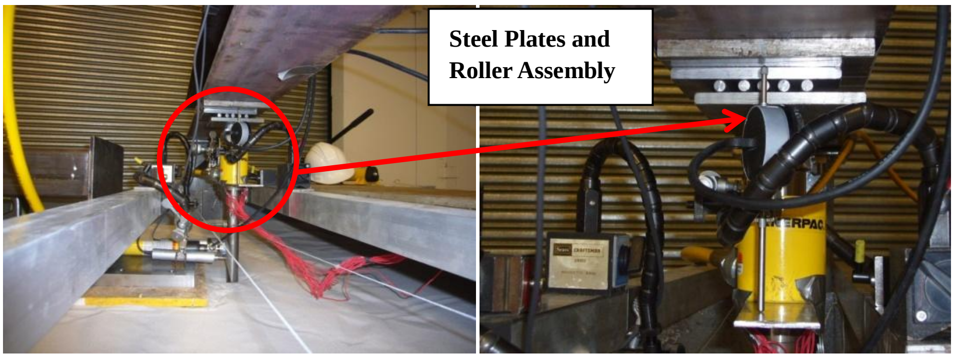
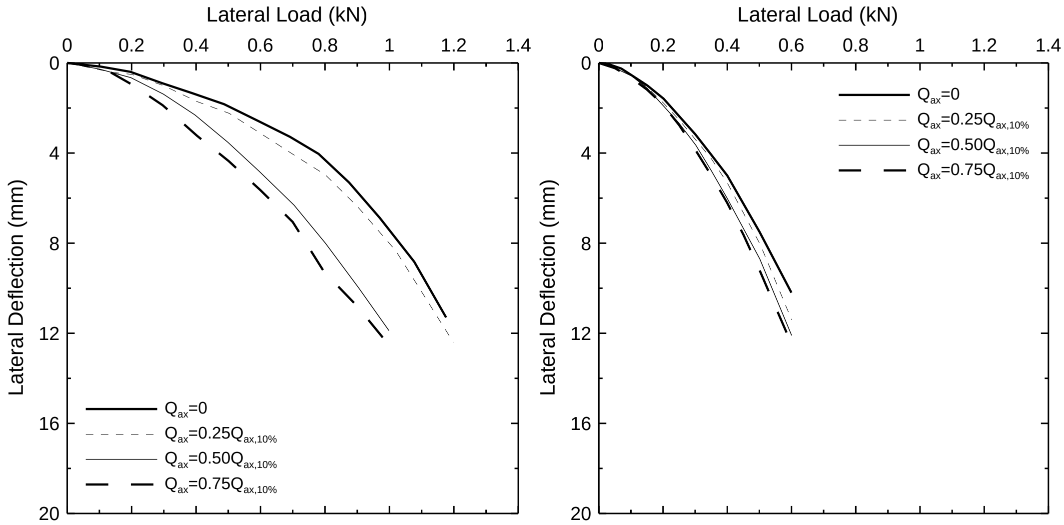
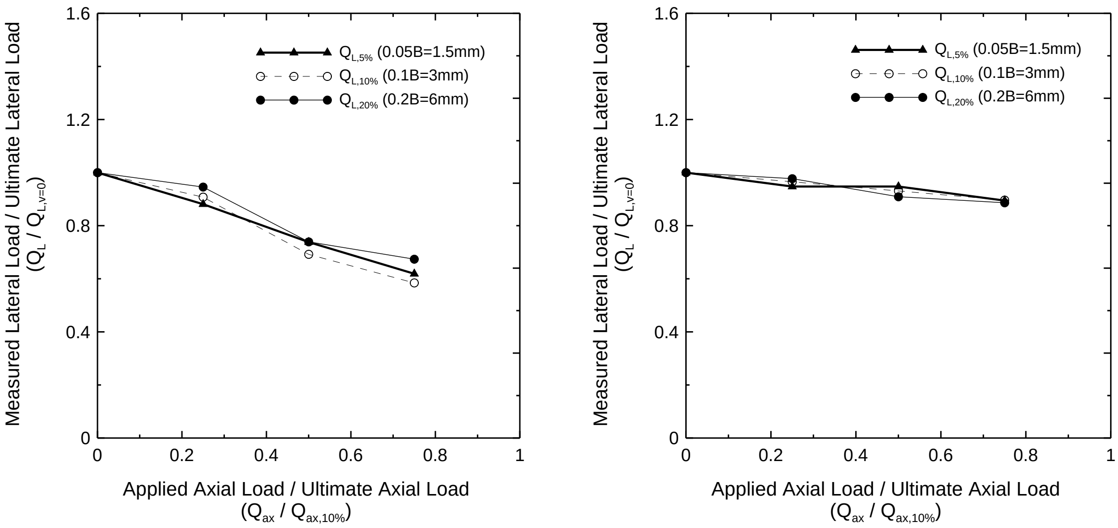


Fig. 3. Setup for the Combined Load Test in the Soil Tank.



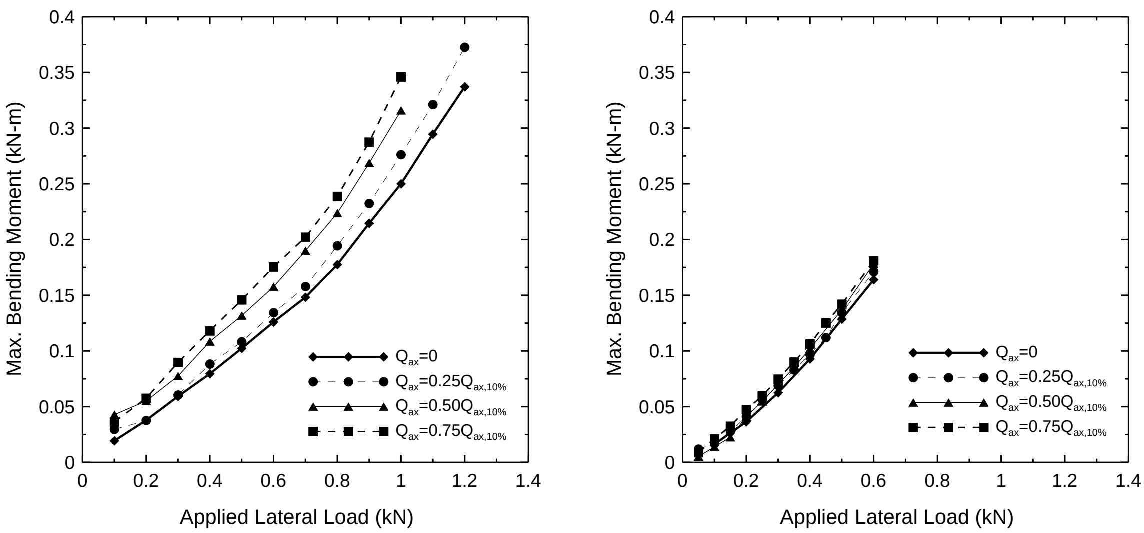
(a) Dense sand (D_R = 91%) (b) Loose sand (D_R = 38%)

Fig. 4. Combined Load Response of Model Pile Driven in Sand.



(a) Dense sand (D_R = 91%) (b) Loose sand (D_R = 38%)

Fig. 5. Influence of the Axial Load on the Ultimate Lateral Capacity of the Model Pile.



(a) Dense sand (D_R = 91%) (b) Loose sand (D_R = 38%)

Fig. 6. Influence of the Axial Load on the Max. Bending Moment of the Model Pile.

Conclusions

Only a few experimental studies have been conducted to investigate the behavior of piles subjected to combined loads based on the available literature. In particular, the results available in the literature are inconsistent with respect to the effects of axial loads on the lateral response of piles. Therefore, the main objective of this paper was to clarify the influence of axial loads on the lateral response of single piles driven in sands. The conclusions drawn from this paper can be summarized as follows:

1) The contradictions of regarding the effects of combined loading found in the experimental results are considered to stem from the restraint condition of the pile head offered by the axial loading device. For the pile load tests under combined loading, a special loading device (e.g., steel plates and roller assembly) should be employed in order to avoid restraint on the pile head.
2) The bending moment and lateral deflection of the model pile head increased substantially in the presence of axial loads. This means that the presence of non-zero axial loads is detrimental to the lateral capacity of model piles driven in sand as the presence of axial load reduces the capacity under lateral loading. The increased bending moment contributed to the increase in lateral deflection of the model piles tested in sand.
3) The test results imply that it is unconservative to design piles assuming that there is no interaction between axial and lateral loads. The test results also show that the larger the axial load, the smaller the ultimate lateral load capacity of the model pile subjected to combined loads. In addition, the effects of the axial load on the bending moments were greater for dense sand than loose sand.
4) This paper could provide insights for future studies on the load-deflection response of pile groups under combined loads. It is recommended to extend this research to axially and laterally loaded pile groups in order to investigate the influence of axial load under closer field conditions.

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