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Lateral Response of a Single Pile under Combined Axial and Lateral Cyclic Loading in Sandy Soil

Muqdad A. Kahribt [a*], Jasim M. Abbas [b]

[a] *MSc Student, College of Engineering, University of Diyala, Baqubah, Daiyla, Iraq.*

[b] *Assistant Prof, College of Engineering, University of Diyala, Baqubah, Daiyla, Iraq.*

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Abstract

According to practical situation, there have been limited investigations on the response of piles subjected to combined loadings especially when subjected to cyclic lateral loads. Those few studies led to contradictory results with regard to the effects of vertical loads on the lateral response of piles. Therefore, a series of experimental investigation into piles in dense sand subjected to combination of static vertical and cyclic lateral loading were conducted with instrumented model piles. The effect of the slenderness ratio (L/D) was also considered in this study (i.e. L/D= 25 and 40). In addition, a variety of two-way cyclic lateral loading conditions were applied to model piles using a mechanical loading system. One hundred cycles were used in each test to represent environmental loading such as offshore structures. It was found that under combined vertical and cyclic lateral loads the lateral displacement of piles decreased with an increase in vertical load whereas it causes large vertical displacements at all slenderness ratios. In addition, for all loading conditions the lateral, vertical (settlement and upward) displacements and bending moments increased as either the magnitude of cyclic load or the number of cycles increases.

Keywords: Piles; Lateral Response; Sand; Cyclic Load.

1. Introduction

In general, Pile foundations are widely used to support various important structures such as offshore platforms, jetties, wharfs, docks, dolphin structures, and bridges. These piles are used to support vertical loads, lateral loads and combination of vertical and lateral loads. Combined loading is defined as cyclic lateral loading due to environmental (wave and wind) loads action and vertical load due to self-weight of structures. In an overview of lateral loaded pile studies, the vertical and lateral responses of piles are often evaluated separately neglecting their possible interaction. This would lead to an erroneous design, as pile foundations for several types of structures are subjected to simultaneous vertical and lateral loading. The separate consideration of the vertical and lateral loading therefore cannot be expected to account properly for the pile behavior [1-4]. The methods of analysis commonly used in predicting the response of a single pile are the elastic half space method, and the nonlinear subgrade reaction method. Both of these methods assume that axial and lateral loads act independently and that there is no interaction. The behavior of pile foundations under either vertical or lateral loads has been investigated for more than a century through full-scale tests, small-model tests or numerical analysis, even though pile response under combined loads can be significantly different from that of piles under either vertical or cyclic lateral loads due to the interaction of vertical and cyclic lateral loads. The influence of vertical loads on the lateral response of pile foundations needs to be accounted for in optimum design; however, only

* Corresponding author: muqdadabd1@gmail.com

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limited numbers of studies on piles subjected to combined loads have been conducted.

A series of three dimensional finite element analysis confirmed that the presence of axial loads increases the lateral load capacity of piles in cohesionless soil and decreases it in cohesive soil [5, 6].

Pure lateral loads and combined vertical and lateral loads and its corresponding piles response were highly taken into account in recent contributions [7].

Mono and fin piles in small-scale tests were used to determine the effect of the length of fins upon the lateral displacement of cyclically loaded piles [8].

For the purpose of confirming a quality data, centrifugal experiment technique was also used to study the lateral behavior of the large-diameter mono pile, it was concluded that vertical load effects on lateral displacement in experimental results more than numerical analyses based on the p-y curves. [9].

The lateral response of single and group of piles under simultaneous vertical and lateral loads was investigated through the literature by finite element analysis, the response of the soil and piles was represented by the p-y curves, and however, these curves were improved by considering the influence high levels of axial load intensities. [10].

Finite element analyses was further extended to study the lateral response of pile embedded in both cohesive and cohesionless soil and subjected to different combination of vertical and lateral loads, It was confirmed that the presence of the vertical load and its intensity affects the lateral behavior of single pile [11].

The effect of the presence of axial loads on the lateral behavior of pile in both sands and clays has also considerable concern in the recent studies[12], a series of 3D Finite Differences (by using FLAC3D program) and the models used and verified by using data from laboratory model and full-scale tests. The results of this analysis attempts showed that the lateral pile capacity does not vary considerably with the axial load in the case of sandy soil especially at the loosest case, while increase in light form for dense and very dense cases. They found that the vertical load on pile constructed in homogeneous or inhomogeneous clay affects its lateral capacity, and it is unsuitable to design piles in clay assuming that there is no interface between the lateral and vertical loads.

Some attempts to study the behavior of non-welded composite pile (under axial and lateral loads) were done based on the pile load tests [13], both dynamic and lateral load tests were conducted to determine both the vertical and lateral behavior for the composite pile. It was argued that the composite pile showed a high amount of lateral bearing resistance compared with the design amount of the same diameter steel pile, so, the lateral and axial behavior of the composite pile ensured the connection part stability. From the result of dynamic test, it was concluded also that the drivability was verified as successful without any pile damage.

Some of the reported attempts in the literature were done by applying combination of axial and lateral on a small-scale model piles embedded in layered sand soil [14]. These attempts comprise the slenderness ratio and the results showed that the presence of a vertical load caused an increase in the lateral load capacity at all slenderness ratios but the influence of vertical load decreases with increase in slenderness ratio of piles at all vertical load levels for both types of piles.

The influence of the pile slenderness ratio of the lateral response of single pile that subjected to pure lateral load was investigated through using a three-dimensional finite element technique [15]. It was concluded that the lateral pile deformation and lateral soil resistance because of the lateral load are always influenced by the lateral load intensity and soil type as well as a pile slenderness ratio (L/D).

There are limited information's in the literature presented in term of the experimental results about the single pile in dense sandy soil under combined loading and there is a general trend to use the finite element method to treat this issue. Furthermore, the effects of static vertical loads on lateral response of single pile under cyclic loading have not been previously been studied extensively. Hence, improving the knowledge by experimental way will lead to enhance design experience. More precisely, studying the effects of cyclic loads and its corresponding displacement is very useful for long-term serviceability in offshore structure. In the present study, twelve model single piles embedded in sandy soil are tested under two-way cyclic lateral load to study the effects of presence vertical load, slenderness ratio (L/D), magnitude and number of cycles on load–deflection and bending behavior of single pile.

2. Materials and Methods

2.1. Sand

In this work, poorly grained fine to medium dry sand taken from Karbala Governorate south of Baghdad city (Iraq) is used to study the responses of piles subjected to combination loading. The grain size distribution of the sand used is shown in Figure 1, and the soil properties are given in Table 1.

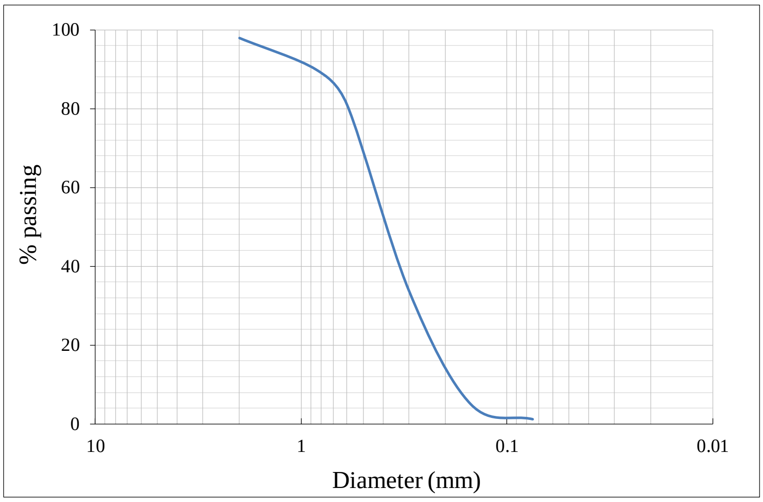


Figure 1. Sand grain size distribution

Table 1. Physical properties of sandy soil used for testing

Property	Value	Standard of the test
	Grain size analysis	
Effective size, D10 (mm)	0.18	ASTM D 422 and ASTM D 2487 (2007) [16]
D30 (mm)	0.26	--------------------------------------
Mean size, D50 (mm)	0.38	ASTM D 422 and ASTM D 2487 (2007) [16]
D60 (mm)	0.45	--
Coefficient of uniformity, Cu	2.5	ASTM D 422 and ASTM D 2487 (2007) [16]
Coefficient of curvature, Cc	0.83	ASTM D 422 and ASTM D 2487 (2007) [16]
Classification (USCS)	SP	ASTM D 422 and ASTM D 2487 (2007) [16]
Specific gravity, Gs	2.64	ASTM D 854 (2006)
Angle of Internal Friction (Ø)	35.79	ASTM D 3080-98 [17]
Cohesion (C) (KN/mm^2)	0	ASTM D 3080-98 [17]
	Dry unit weight	
Maximum, γ_d(max.) KN /m^3	17.67	ASTM D 4253 - (2000) [18]
Minimum, γ_d (min.) KN /m^3	14.83	ASTM D 4254 - (2000) [19]
Maximum void ratio, e_{max}	0.78	……………………………………..
Minimum void ratio, e_{min}	0.494	……………………………………
Initial dry unit weight, γ_d (test)	16.7	……………………………………

2.2. Model Pile

The pile's model used in the present study is made of smooth aluminium circular pipe having outer diameter of 16 mm and inner diameter of 13 mm .The length to diameter ratio (L/d) of piles are selected as 10 to 40, to simulate the behavior of short and long flexible piles, as shown in Figure 2. The mechanical properties of used piles are shown in Table 2. The piles are instrumented with 4 pairs of strain gauges on each pile attached along the shaft to measure bending strain by pasting 8 electrical- resistance-half bridge type strain gauges at distances of (0 L, l/4 L, l/2 L, and 3/4 L) from the top of the piles . To protect from damage, the gauges are covered with 1mm epoxy and wrapped by tapes.

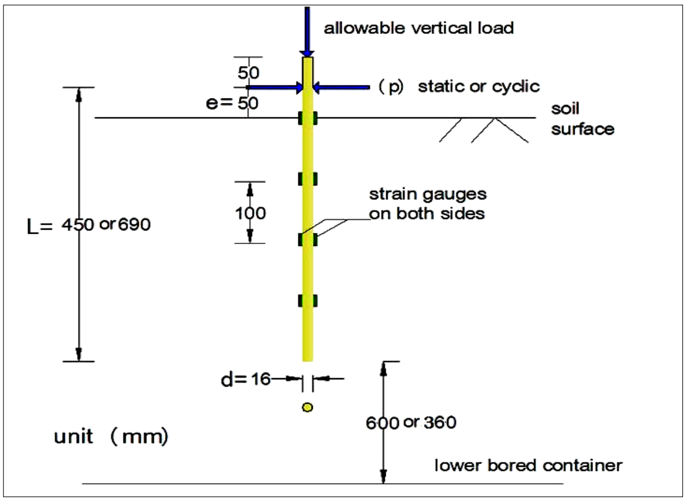


Figure 2. Sketch showing the pile model instrumented with strain gauges

Table 2. Mechanical properties of aluminum piles used

Pile no.	Cross section	Length (mm)	Outside dimension (mm)	Wall thickness(mm)	Bending stiffness, $E_P\ I_P$ (KN/mm^2)
1	Circular	480	16	1.5	124.78
2	Circular	720	16	1.5	124.78

3. Experimental Programme

As no standard apparatus for transferring cyclic lateral load on piles is available, a new multipurpose set up is designed and fabricated. A photographic view and the sketch of this apparatus are shown in Figure 3, and some of its important components are described below, as illustrated in Figure 4.

3.1. Test Tank

The soil tank was made from steel with internal dimensions 1000 mm length, 1000 mm width, and 1000 mm depth, all these sides of tank are made of steel plate 4 mm in thickness . These dimensions were chosen to prevent the tank from bulging out when filled with sand and there will be no interference between the walls of the soil tank and the failure zone around the piles.

3.2. Static Loading Device

For static loading test, the apparatus is designed in such a manner that the applying lateral pull in the pile head, a flexible wire is attached in the pile head by loading collar and other end is attached to the loading pan through frictionless pulley, which is used to change the direction of vertical load to lateral load. One dial gauge is attached to the pile head to measure the lateral deflection of the pile.

3.3. Cyclic Loading Device

The experimental set up is designed in such a manner that the cyclic loading test can be performed under load-controlled mode. The cyclic loading is applied to the piles laterally via an actuator operated by motor-gear system connected to automatic electronic circuit unit that is developed especially for this research In order to control the lateral cyclic loading in two-way by certain time periods, based on the load cells indicator. movable stainless steel rod 20 mm diameter is attached in parallel with the motor gear unit to convert the rotation to horizontal sinusoidal translation, which was finally be applied on the pile head by using two screws 19 mm diameter with two rubbers in its end. Both screws are connected to compression load cells, which in turn are fixed on holder.

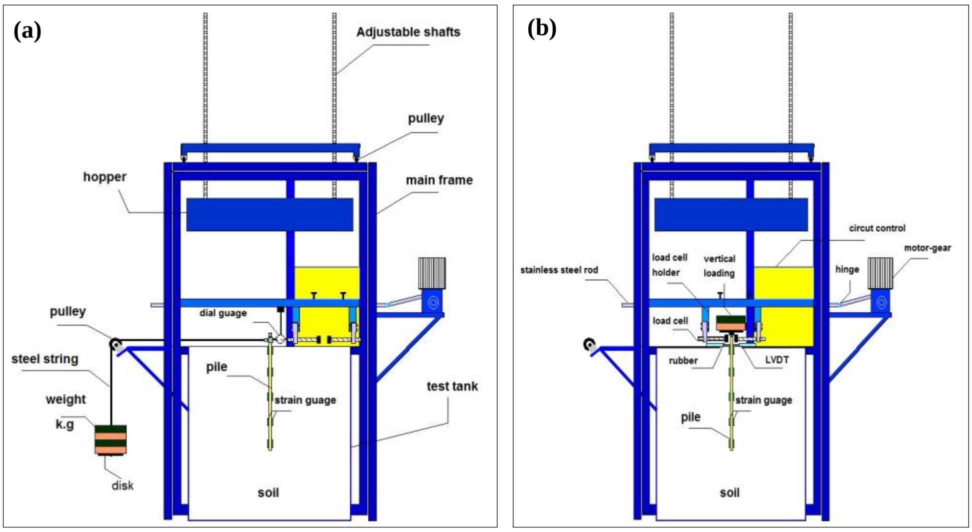


Figure 3. Schematic diagram showing: (a) Static loading device, (b) Cyclic lateral loading device

Figure 4. The multipurpose (static and cyclic) loading device

3.5. Ancillary Equipments

Numbers of ancillary equipments were attached with the apparatus, as described below:

(i) Compression Load Cells: To measure the lateral load applied on the model pile during cyclic test in progress, a load cell with ±500 kg capacity. Calibration for load cells are performed using mode "load cells' max load "and "Rated output value (mV)". (ii) Digital Dial Gauge: To measure the pile head deflection in the axial lateral direction with sensitivity 0.001mm. (iii) LVDT: A Linear Variable Differential Transducer having ±50 mm displacement measurement capacity is used. (iv) Digital Indicators: A digital indicators are used to display and record the Load Cells readings, LVDT readings and Strain gauges readings digitally.

4. Test Procedure

4.1. Sand Bed Preparation

After fixing the model piles in the test tank, the sand deposit is prepared using the sand raining technique shown in Figure 3. A special raining device is designed and constructed to obtain a uniform deposit with the desired density. The device consists of a steel frame, an upper container with the dimensions (200 × 200 × 1000 mm) and supplied with two opening strips and mechanical gates. The desired unit weight of the sand deposit in the raining method depends primarily on the drop height and the discharge rate of the sand .The height of the free fall of the sand can controlled by adjusting the elevation of the raining device with respect to the sand tank by using two adjustable shafts. The discharge rate of the sand can be controlled by selecting the appropriate size of the openings (10 mm) of the upper raining container .After filling the raining container with sand and choosing the proper height of drop, the sand is poured into the test tank by moving the box forth and rear by hand.

4.2. Static Pile Load Tests

After placing the sand at the desired relative density, a static compression and lateral loading tests are carried out on single model piles with different L/D ratio (25, 40) to assign its ultimate axial and lateral capacity separately.

4.2.1. Compression Loading Tests

The static compression loading tests are performed according to the (ASTM D 1143-07) [20].The load is applied on the pile in case of compression test by adding dead weights on the steel disk which fixed on the pile head. Subsequently the loads are applied by dead weights over the steel disk starting from the smallest with gradual increments, while the settlement of the pile head is recorded using two digital dial gauges, which is fixed to the main frame by two magnetic arms. The load settlement curve is considered to assess the pile capacity, as shown in Figure 5. Ultimate axial capacity of pile is taken as the load corresponding to a total axial movement equal to 15 % the pile diameter or width. The ultimate axial load capacity deduced as 210 N and 305 N that represent L/D ratio 25 and 40 of model piles respectively. Accordingly, the allowable vertical load (Qall.) is evaluated after taking the factor of safety equal to 2.5 for all the pile models.

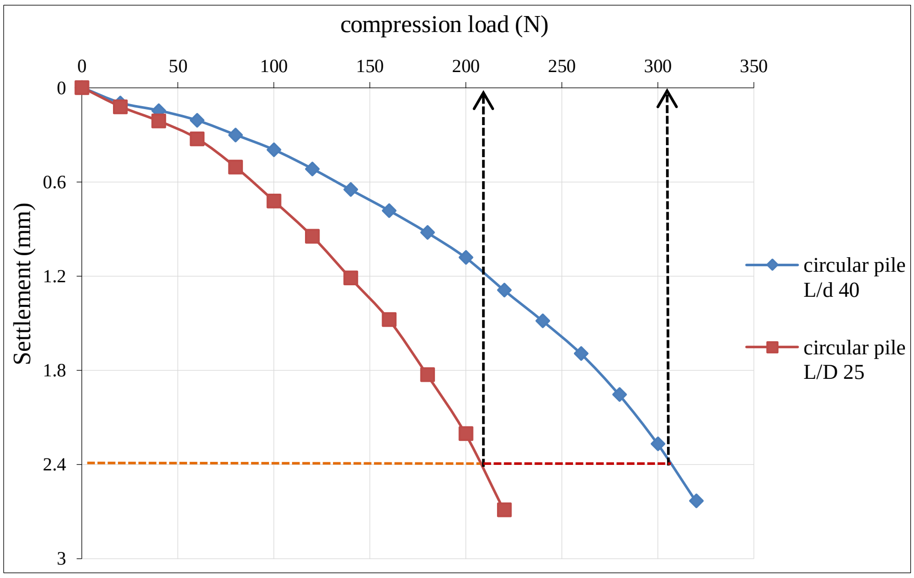


Figure 5. Axial load versus settlement for different L/D ratio of piles

4.2.2. Lateral Loading Tests

Static tests under pure static lateral load are performed to gain the ultimate lateral load capacity for piles. The lateral load is applied to the pile head through a pulley arrangement with flexible weir attached to the pile by loading collar; the other end is attached to the loading pan. Dead weights are applied over the loading pan starting from the smallest with gradual increment. Same loading sequence is maintained for all model piles. When load is placed in the loading pan, it moves down and due to the pulley it act laterally to the pile head. Due to the lateral load, the piles are deflecting in the direction of the lateral load and the digital dial gauge give the reading of the deflection of the pile. Deflections for corresponding lateral loads are noted. Then, the load-deflection curve for the single piles with L/D ratio 25 and 40 are drawn. Ultimate lateral capacity of a pile is usually obtained from load tests based on deflection criteria or point of intersection of tangents (double tangent method). [21], ultimate capacity is taken as the load corresponding to a deflection equal to 20% of the diameter of pile, or taken as a value at which the portion of load deflection curve becomes straight [22]. The criterion based on point of intersection of tangents (double tangent method) is well established and recommended by many previous researchers [23, 24]. Hence, in the present study ultimate lateral capacity of single pile is estimated using double tangent method .The ultimate lateral capacity of piles is 95 N and 115 N for the L/D ratio of 25 ,40 respectively, as shown in Figure 6.

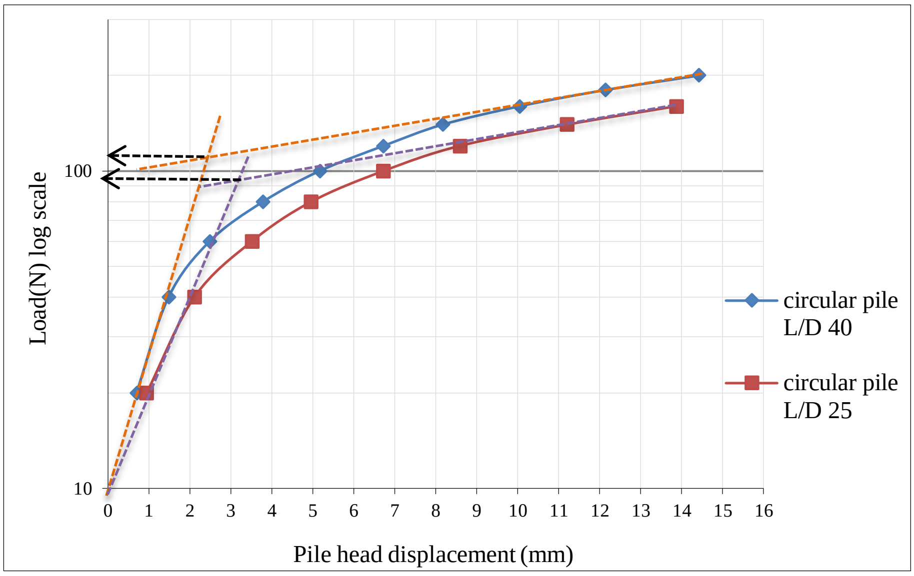


Figure 6. Lateral load versus displacement for different L/D ratio of piles

4.3. Cyclic Lateral Load Test

Two-way cyclic lateral loading representing wave loading is applied to the model single piles at different cyclic load ratios. The Cyclic Load Ratio (CLR) is defined as the ratio of magnitude of cyclic lateral load to static ultimate lateral capacity of the pile [25]. The different magnitudes of cyclic lateral load corresponding to CLR of 0.2, 0.4, 0.6 and 0.8 representing wave loading ([8, 26]) are applied to the model piles .The period of cyclic loading is kept as 10 s. A typical cyclic loading pattern is shown in Figure 7. The influence of vertical loading on response of piles subjected to cyclic lateral loading examined. Different static vertical loads are used which represent 0, 20, 40, 60, 80 and 100% of the allowable vertical load of piles. A static vertical load is first applied to the top of the pile; a two-way cyclic lateral loading test is then carried out with different magnitudes of cyclic lateral load up to 100 cycles in all the experiments while keeping the vertical load constant.

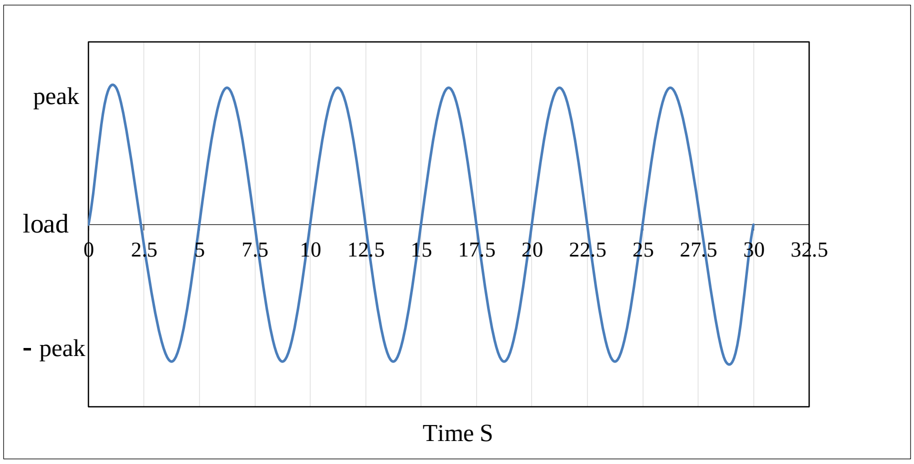


Figure 7. Typical Cyclic Loading Pattern

5. Results and Discussion

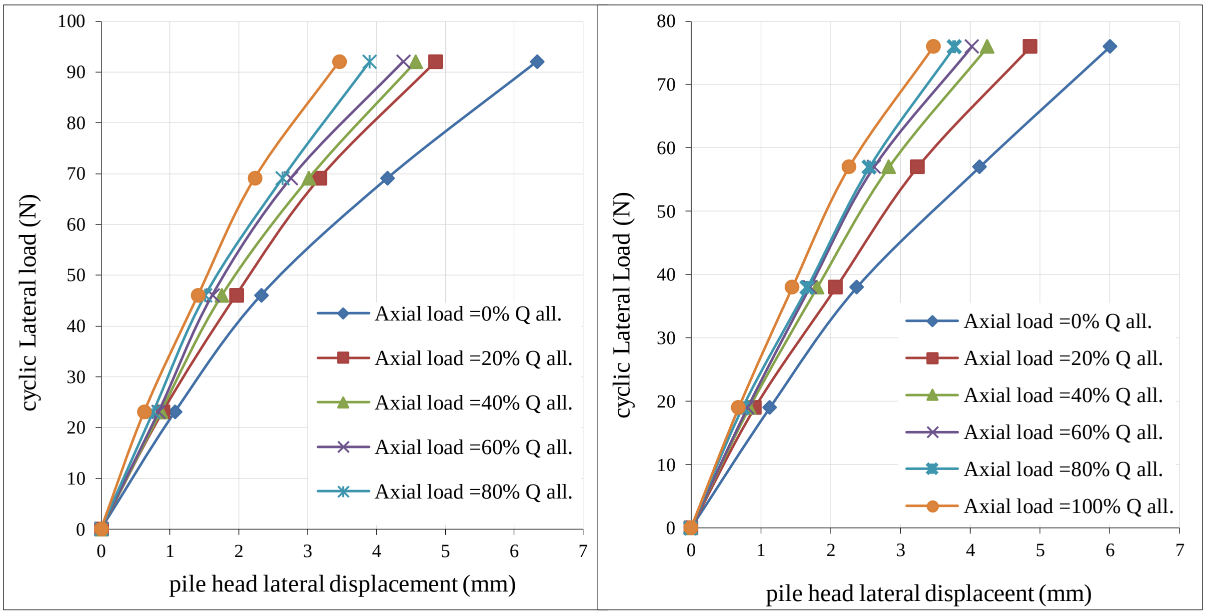
A series of laboratory tests are conducted to measure the response of piles foundation when subjected to combine cyclic loading. Twelve tests are conducted for single pile in dry sand at relative density 70% (dense) with two embedment ratio (L/d) = 25 and 40 under operating frequencies 0.2 Hz.

The results of experimental work for the effect of vertical loading on response of piles subjected to cyclic lateral loading are divided to three parts (lateral displacement at pile head, Vertical displacement (upward and settlement)at pile cap and bending moment along pile). In addition, Comparisons are provided to verify the influence of the cyclic Lateral load level (magnitude) and number of cycles.

5.1. Lateral Displacement at Pile Head

5.1.1. Influence of Vertical Load on the Lateral Displacement at Pile Head

Figure 8 show the influence of vertical load on lateral response of piles in sandy soil with different L/D ratio 25 and 40. The results show that, in piles subjected to combination of vertical and cyclic lateral loading, there is a considerable decrease in the lateral displacement under increasing the vertical load levels as compared to the pure cyclic lateral load case. Under these conditions, the combined loading on piles induces interaction effects due to simultaneous mobilization of passive earth pressure due to cyclic lateral loads and pile skin friction due to vertical load [27]. Alternatively, this issue has another interpretation; the increase in the lateral capacity of free-head piles installed in sandy soil due to the presence of vertical loads is attributed to the increase in the confining pressures in the sand deposit surrounding the upper part of the pile [3, 4].



(a) L/D=40, Qall. =122 N **(b) L/D=25, Qall. = 84 N**

Figure 8. Variation of lateral displacement with the cyclic lateral load under different vertical load levels after number of cycles =100. a) L/D=40, b) L/D= 25

5.1.2. Effect of Cyclic Load Ratio (CLR) on Pile Head Lateral Displacement

Figure 9 shows the pile head lateral displacement for model piles under different magnitudes of cyclic loading CLR. It can be seen from the figure that at low magnitude of loading (CLR <0.4), the lateral displacement increases gradually with the number of cycles but nonlinearly up to a certain number of cycles and then practically becomes constant irrespective of the increase in the number of cycles. Nevertheless, at high magnitude of cyclic loading (CLR > 0.4), there is a significant rise in lateral displacement within a few number of cycles and it gradually increases with the increase in the number of cycles. The increasing in lateral displacement is mainly due to the formation of the hole like the cone of depression around the piles near the soil surface up to a depth of four times the pile diameter from the surface, which leads to reduction of passive resistance of the soil, as illustrated in Figure 10. Critical cyclic load level defined as the cyclic load at which a dramatic increase in deflection occurs [25]. In the present study, the critical cyclic load level is corresponding to CLR of 0.60.

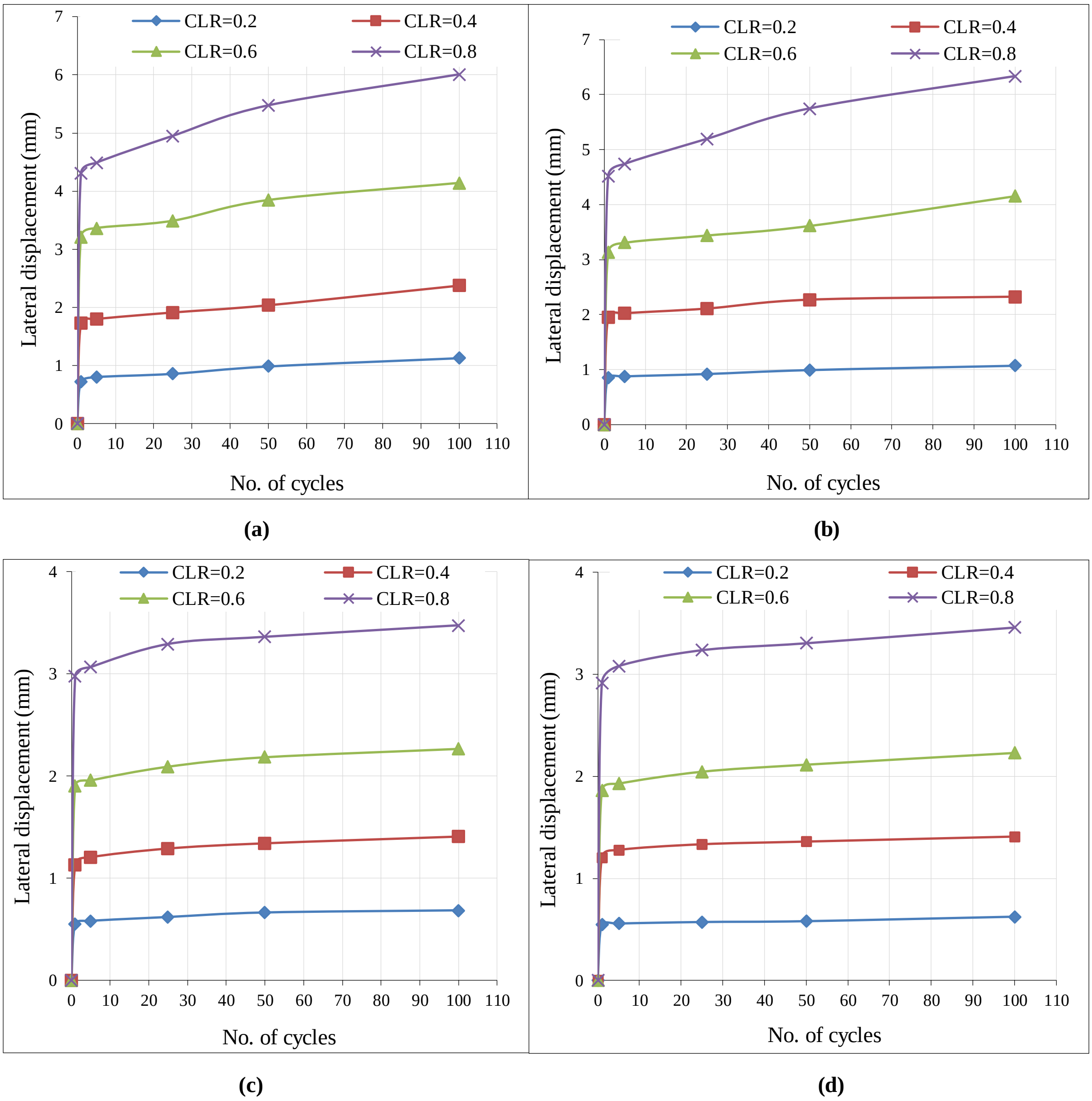


Figure 9. Effect of cyclic load ratio (CLR) on pile head lateral displacement of single pile under different vertical loads. a) L/D=25 with vertical load= 0%Qall. , b) L/D= 40 with vertical load=0%Qall. c) L/D=25 with vertical load= 100%Qall, d) L/D= 40 with vertical load= 100%Qall

Figure 10. Generate a deformation around pile model under effect different combined loads

5.1.3. Effect of Number of Cycles of Loading on Load Lateral Displacement Behaviour

The load-lateral displacement behaviour of single model piles (L/D 25 and 40) at the different number of cycles of loading is shown in Figure 11. As observed from the figure, load- lateral displacement behaviour under cyclic loading is highly nonlinear and the degree of nonlinearity increases with the number of loading cycles. This is attributed to the development of a hole at the soil–pile interface where the stress concentration occurs. With increase in the number of cycles of loading, width and depth of the hole increased progressively [28]. The size of the hole depends on the cyclic load ratio and the number of cycles. In case of the model piles subject to pure cyclic lateral load (vertical load =0%), It can be easily noticed that there is significantly increased in lateral displacement with the number of cycles, In comparison with the piles are subjected to combined load. The reason is due to occurring successively uplifting (pile rising) of pile with time, which results in the reduction of the embedment length for piles. Further, for the sandy soil under repeated loading of high magnitude and subsequent development of associated strain levels lead to dilation (expand in volume) and reduction in shear strength of sand near the piles. The dilation phenomenon was explained [29], especially for the dense sands at low confining stress, where particle overriding (and hence dilation) rather than particle crushing might be expected. It seems unlikely that the densification could account for the steady grain migration throughout the whole test, so the soil densification should have a specific limit [27]. Heaving of sand also occurs on either side of the piles at the ground surface. The combined effects of hole formation, dilation and the uplift of piles lead to significant cumulative displacement of pile with increasing number of cycles.

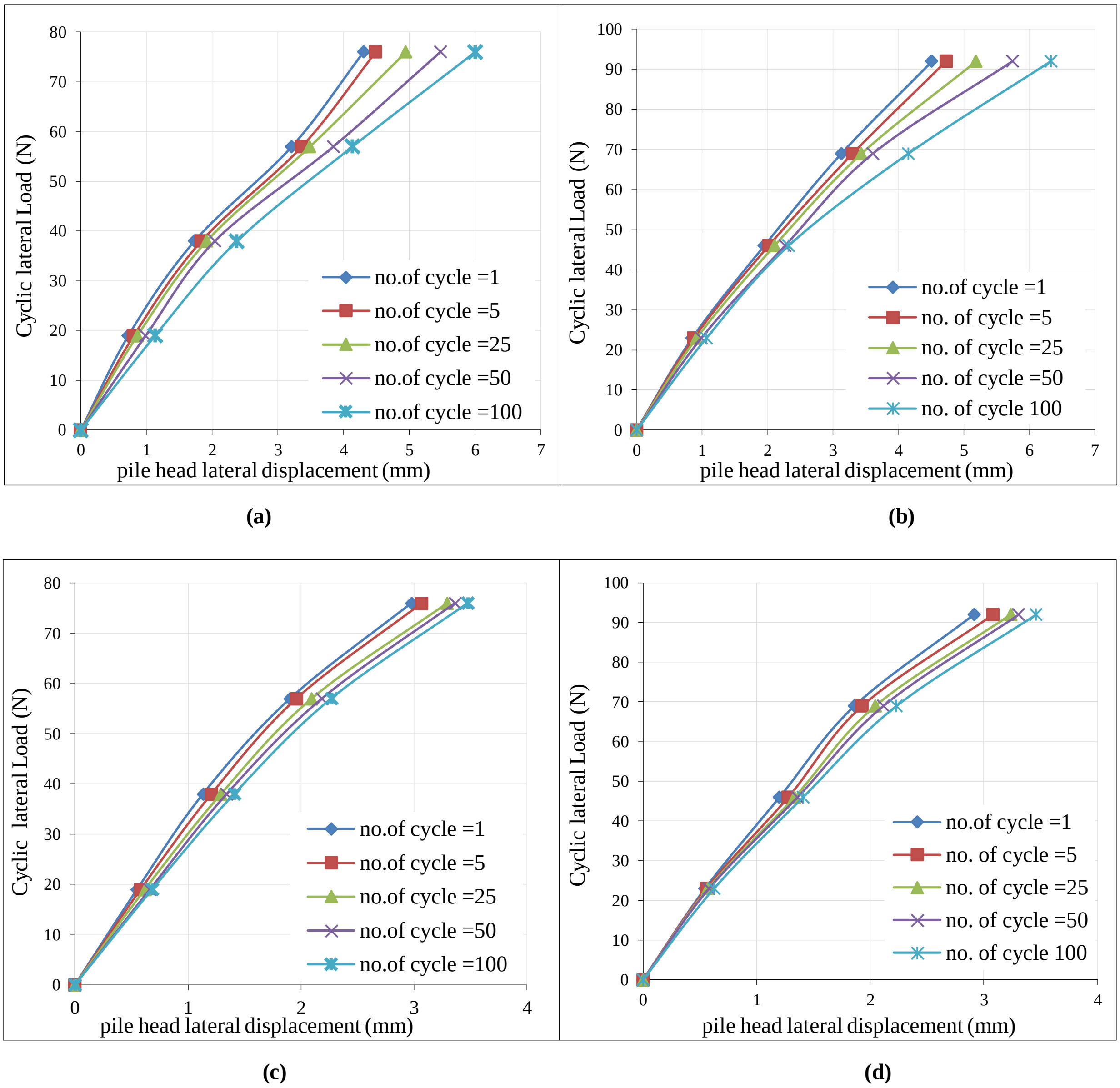
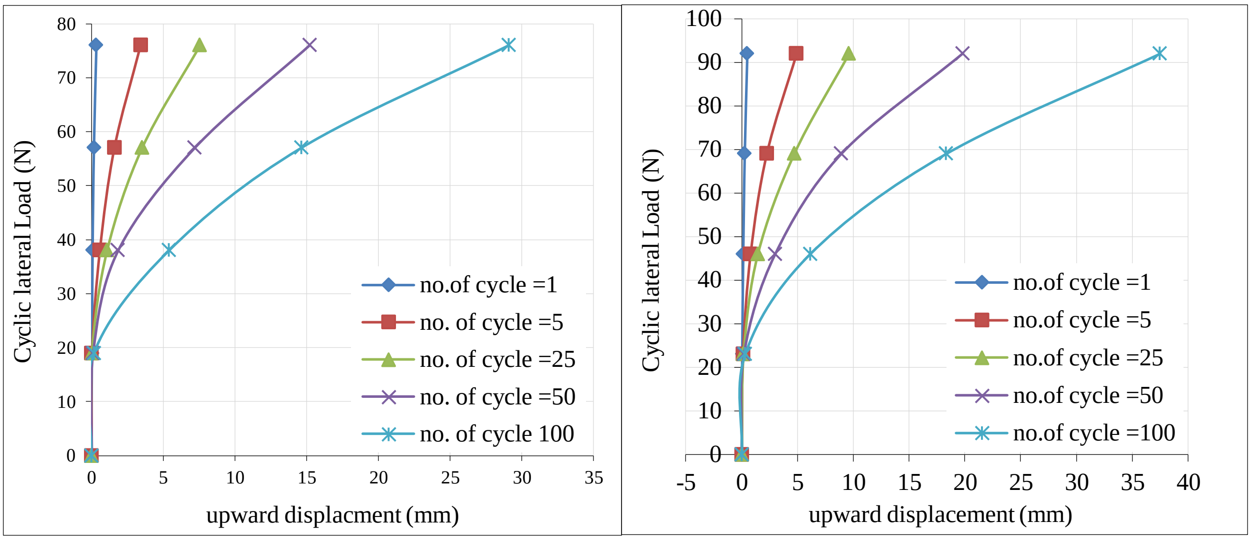


Figure 11. Effect of number of cycles of loading on load- lateral displacement behaviour of single pile under different vertical loads. a) L/D=25 with vertical load= 0%Qall. , b) L/D= 40 with vertical load= 0%Qall. c) L/D=25 with vertical load= 100%Qall, d) L/D= 40 with vertical load= 100%Qall

5.2. Vertical Displacement (Upward and Settlement) at Pile Cap

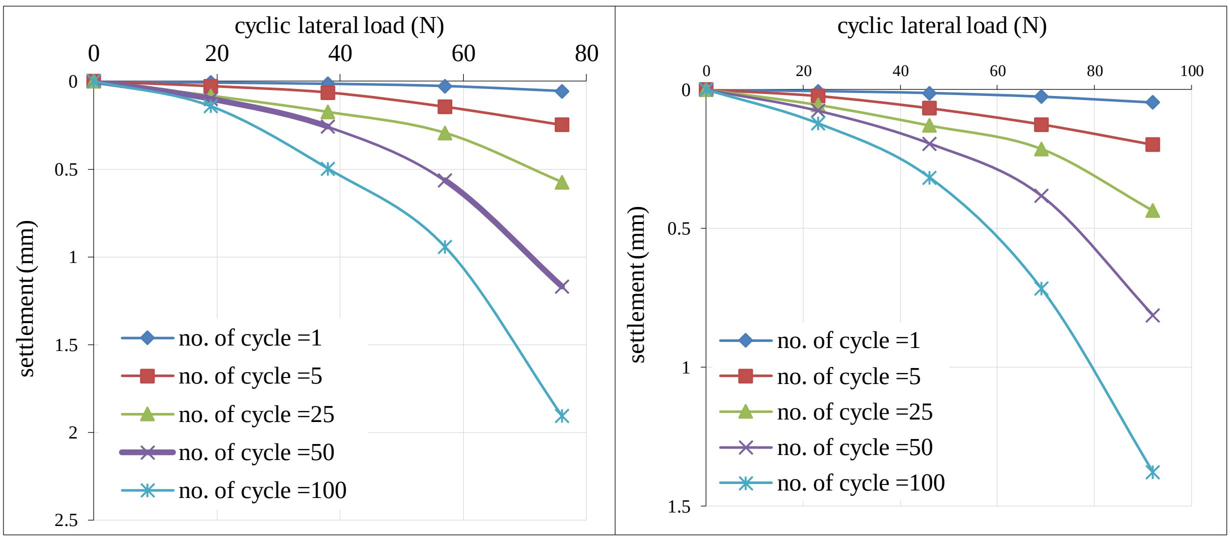
In order to explain the effect of combination loads on response of model piles in addition to the lateral displacement of pile head, the variation of vertical displacement(upward and settlement) with the difference in vertical and cyclic lateral loading levels and number of cycles are measured (as drawn) in Figures 12 to 14. From Figure 12, it can be noticed that the pile moves upward throughout the test period for model piles. This behavior means that the pile was uplifted because the soil that surrounding the piles are moved radially through applied the two-way cyclic lateral load only(without vertical load) .which induced the friction between soil and pile changed to negative skin friction causing the pile moved upward. On the other hand, the curves of cyclic lateral load versus vertical displacement (settlement) of the pile head under combined loading for different numbers of cycles are presented in Figure 13. The result shows that piles are remained in the sinking state with an increase in magnitude of vertical load levels under effect of cyclic lateral load as shown in Figure 14.

The variation of settlement at the pile cap is attributed to that the reduction in bearing is occurred as a result to develop the negative skin friction due to soil movement around the pile, which leads to push the pile upward. Therefore, the bearing load at the pile tip closes within minor to zero (floating pile). Afterward, when the pile movement stopped, the bearing load returns more than initial magnitude due to redistribution of sand particles and with existence the dead weights on pile head the pile sinks gradually .Both of upward and settlement of pile head are increased with an increase in magnitude of cyclic load and the number of cycles.



(a) **(b)**

Figure 12. Variation of vertical displacement (upward) of pile with number of cycles a) L/D=25 with vertical load = 0% Qall. , b) L/D= 40 with vertical load= 0% Qall



(a) **(b)**

Figure 13. Variation of vertical displacement (settlement) of pile with number of cycles a) L/D=25 with vertical load =100%Qall. , b) L/D= 40 with vertical load =100%Qall

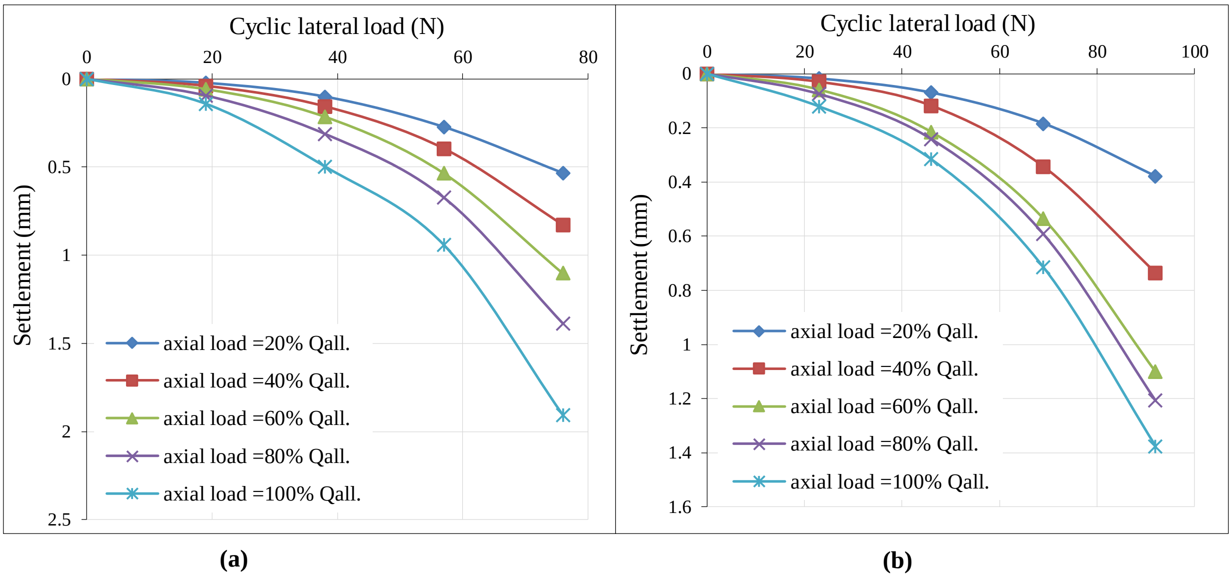


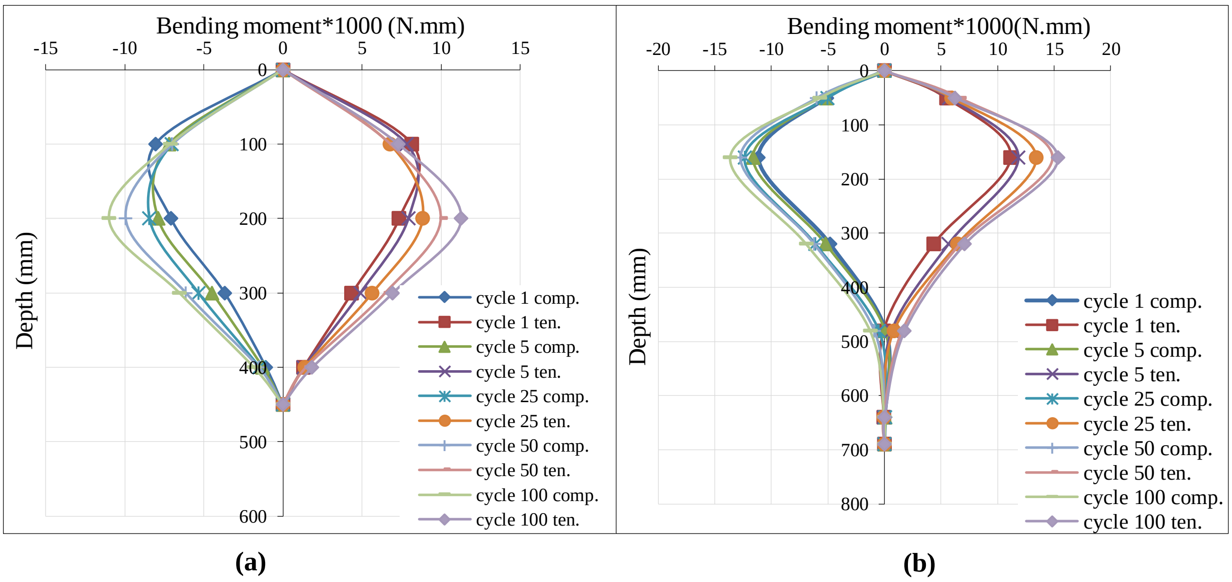
Figure 14. Variation of vertical displacement (settlement) with the cyclic lateral load under different vertical load levels after number of cycles =100.a) L/D=40, b) L/D= 25

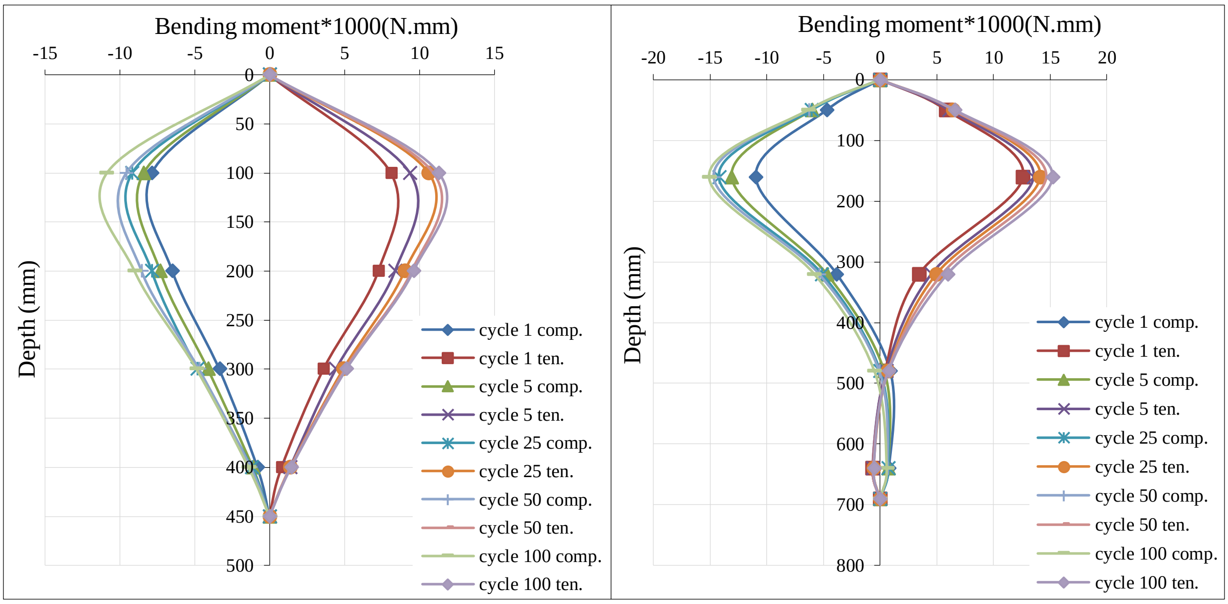
5.3. Bending Moment Profile

According to the strain data measured along the depth of the pile that fixed on both sides of pile , the bending moment at different depth can be calculated by the expression: $M=EI\varepsilon/r$. Where (E) is the young's modulus of the model pile; (I) is the moment of the inertia of the model pile; (Ɛ) is the measured strain; and (r) is the horizontal distance between strain gauge position and neutral axis, equal to half diameter of the section of pile.

The effect of cyclic loading on bending moments of model piles (L/D = 25 and 40) are shown in Figure 15 for number of cycles N = 1, 5 ,25 ,50 and 50 which are subjected to the cyclic lateral load corresponding to CLR of 0.80 and different vertical load . The bending moment profiles for both tensile and compressive halves of two-way cyclic loading show similar pattern. The most important features of these curves are that the magnitude of maximum bending moment increases with the number of cycles and the depth of occurrence of maximum bending moment travelling down the length of pile as the number of cycles increases [22]. These effects are attributed to the hole developed at the pile-soil interface, which increases in width and depth with the number of cycles. Furthermore, these figures clearly show that an increase in the number of cycles causes the pile curvature to increase, which in turn causes an increase in the bending moment along the pile due to the soil resistance values continue to decline with increasing number of cycles due to dilation of sand particles near the pile head.

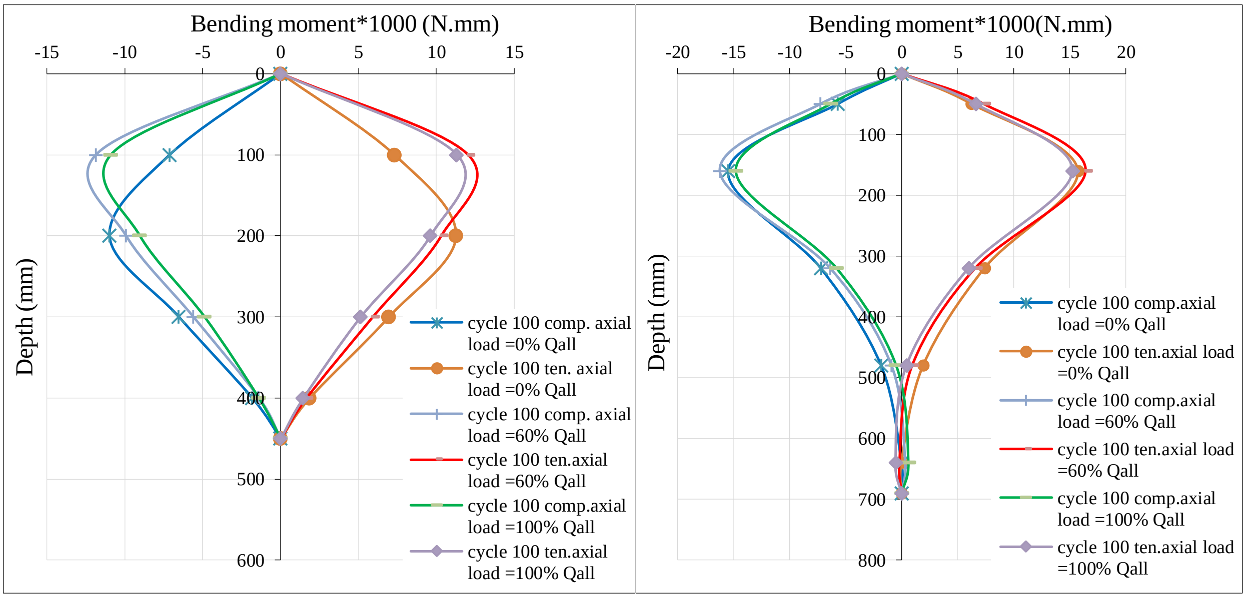
Figure 16 shows the influence of vertical loads on the bending behaviour of piles (L/d=25, 40) under combination of vertical loads (0%, 60% and 100% from allowable axial capacity load) and cyclic lateral loads corresponding to CLR of 0.80 at 100 cycles. It is observed from these figures that the magnitude of maximum bending moment for piles is decreased with increasing of vertical loads.





(c) (d)

Figure 15. Bending moment distribution in single model pile under combined vertical and cyclic lateral loads. a) L/D=40 with vertical load =0% Qall. , b) L/D= 25 with vertical load =0% Qall. , c) L/D=25 with vertical load =100% Qall. , d) L/D=40 with vertical load =100% Qall



(a) (b)

Figure 16. Comparison of measured bending moment curves for single model pile under combination of different vertical loads (0%,60% and 100% from Qall.) and same cyclic lateral loads after number of cycles=100. a) L/D=25, b) L/D= 40

6. Conclusions

Based on the discussion of the test results above-mentioned, some conclusions were summarized here.

- The response of the piles in sandy soil under cyclic lateral loads is influenced by the presence of vertical loads. Indeed; the presence of vertical loads decreases the pile head lateral displacement and maximum bending moment of piles depending on the level of vertical load.
- Behaviour of piles under pure cyclic lateral loadings (without vertical load) has been assessed through model tests. Accumulated Lateral and vertical (upward) displacements increases with both increase in cyclic loading ratio (CLR) and number of cycles. When CLR is higher than 0.6, significant increase in lateral displacement occurred due to large gap developed at the pile-soil interface within a first few cycles of loading.

- Under combined loads, accumulated lateral and vertical (settlement) displacements of the piles increases with an increase in CLR and number of cycles. However, the effect of the increase in the number of cycles on the lateral displacement of piles under combined loads is less than when piles are subjected to pure cyclic lateral load.
- In general, for all load conditions, the magnitude of compressive and tensile bending moment of piles is increased with increasing in magnitude of cyclic loading and number of cycles.
- The depth corresponding to the maximum bending moment acted on pile (L/D=25) under pure cyclic lateral loads at 100 loading cycles is deeper than that at the first cycle. However, marginal increase in the depth corresponding to the maximum bending moment is observed for piles that are subjected to combined loads in dense soil.

7. References

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