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PERFORMANCE OF A SINGLE PILE UNDER COMBINED AXIAL AND LATERAL LOADS IN LAYERED SANDY SOIL

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Abstract: A combination of axial and lateral was applied on a small scale model piles embedded in layered sand soil. Two types of piles were used (open and closed ended steel box piles), while the relative density (D_r) of the upper and lower sand layers were (55%) and (85%) respectively. The effect of slenderness ratio (L/D) were also considered in this study (L/D= 10, 15, 20, and 25). It is shown that the axial capacity of closed ended pile is greater than the open ended pile by (12 – 33) %. 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.

Keywords: *Single pile, Combined loading, Sand, Layered soil, Slenderness ratio*

سلوك ركيزة منفردة معرضة لأحمال مركبة محورية وجانبية في التربة الرملية المتطابقة

الخلاصة: مركب من القوى المحورية والجانبية تم تسليطه على نموذج ركيزة صغيرة القياس مغروزة في تربة رملية متطابقة. تم استعمال نوعين من الركائز (ركائز حديدية مربعة مفتوحة ومغلقة النهاية) بينما كانت الكثافة النسبية (D_r) للطبقة الرملية العليا والسفلى (55%) و (85%) على التوالي. تأثير نسبة النحافة تم اعتماده أيضا في هذه الدراسة. بينت النتائج أن قابلية التحمل المحوري للركيزة المغلقة النهاية أكبر من الركيزة المفتوحة بنسبة (12-33)%. وجود القوة العمودية سبب زيادة في التحمل الجانبي للركيزة لكل نسب النحافة لكن تأثير القوة العمودية يقل مع زيادة نسبة النحافة للركيزة عند كل مستويات القوة العمودية ولكلا النوعين من الركائز.

1. Introduction

Pile foundations are extensively used to support various structures built on loose/soft soils, where shallow foundations would undergo excessive settlements or shear failure. These piles are used to support vertical loads, lateral loads and combination of vertical and lateral loads. However, in view of the complexity involved in analyzing the piles under combined loading, the current practice is to analyze the piles independently for vertical loads to determine their bearing capacity and settlement and for the lateral load to determine their flexural behavior. The methods of analysis commonly used in predicting the response of a single pile are the elastic half space method [1], and the

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nonlinear subgrade reaction method [2], [3]. Both of these methods assume that axial and lateral loads act independently and that there is no interaction.

Extensive research has been performed mainly on pile foundations subjected to either vertical loads or lateral loads, even though pile response under combined loads can be significantly different from that of piles under either vertical or lateral loads due to the interaction of vertical and lateral loads. The influence of vertical loads on the lateral response of pile foundations needs to be accounted for in optimum design; however, only limited numbers of studies on piles subjected to combined loads have been conducted.

Goryunov [3] analyzed the behavior of a metal tubular pile, 500 mm in diameter with a wall thickness of 20 mm, driven to a depth of 24 m, subjected to the action of a horizontal force of 98 kN and a vertical force of 1959 kN (a typical case for marine structures). The analysis was conducted based on the elasticity theory for a beam elastically restrained in a Winkler foundation bed. The soils considered were dense, medium dense, and weak soils underlain by dense soils. The results indicated that, for a given lateral load, the presence of a vertical load increases significantly the lateral deflection at the pile head and the bending moment. It was noted that the axial load causes an additional moment at the deflected position of the pile, and the deflection increases accordingly.

Klein and Karavaev [4] performed finite element analysis (FEA) for a pile subjected to vertical and horizontal loads. The analysis was carried out for a geometrically nonlinear formulation of a reinforced-concrete end-bearing pile 30 cm × 30 cm in cross section, embedded 2 m into the ground, with the free length above the ground being 2.5 m. Their results indicated that the vertical load can both increase and decrease the pile lateral capacity. An increase in lateral capacity was observed for dense soil, while a decrease was observed for weak soil.

Jain et al. [5] 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 cm and 28.8 cm, respectively. The embedded length of the pile was 100 cm. The lateral load tests were performed with a vertical load equal to 0 (pure lateral load), 20%, 40%, and 50% of the ultimate load.

Karthigeyan et al. [6], [7] used three-dimensional finite element analysis to study the influence of vertical loads on the lateral response of piles installed in loose and dense sandy soils. The concrete pile was 1,200 mm × 1,200 mm in cross section and 10 m in length. The results showed that, for a given lateral load, the pile lateral deflection decreased with increasing vertical load. The influence of the vertical load on the lateral pile response was more significant in dense sand than in loose sand by showing that the presence of vertical loads increased the lateral load capacity of single piles by as much as 40%.

Rajagopal and Karthigeyan [8] focused on the study of piles subjected to pure lateral loads and combined vertical and lateral loads through 3D finite element. They concluded that the lateral load capacity of piles in sandy soils increases by as much as 40% with the presence of vertical loads. Besides, the influence of combined loads reduced with increasing L/D and remains constant beyond an L/D ratio of 25 in sandy soils.

Centrifugal experiment was conducted by Choo et al. [9] for the obtainment of quality data regarding lateral behavior of the large-diameter monopile. Numerical results based on the p-y analysis were compared to centrifuge experimental results and showed that the vertical load effect on lateral displacement was much greater in experimental results than in numerical analysis results.

2. Experimental Work

In this study, sand is used as a foundation soil; it is placed in a container (model tank) in two layers (medium & dense) with different depths according to the length of pile, where the medium layer overlying the dense layer.
Two types of piles (open and closed-ended steel box piles) were used to carry out static vertical, horizontal, and combinations of these loads.

2.1. Material properties

The sand used for this study, was obtained from the local markets. Prior to testing, this sand was oven dried at (105°C) for (24 hr) then passed on sieve (No. 16) to remove all particles greater than (1.18mm). The results of the sieve analysis test are shown in Figure (1). The sand is classified according to the Unified Soil Classification System (USCS), as poorly graded sand (SP) with a coefficient of uniformity C_u=2.77 and the coefficient of gradation C_c=1.23 .

The specific gravity (G_s) of the sand was found to be 2.65. The minimum and maximum dry unit weights (γ_{min}, γ_{max}) were 14.1 kN/m³ and 18.0 kN/m³ respectively, while the minimum and maximum void ratios (e_{min}, e_{max}) were found to be 0.444 and 0.844 respectively.

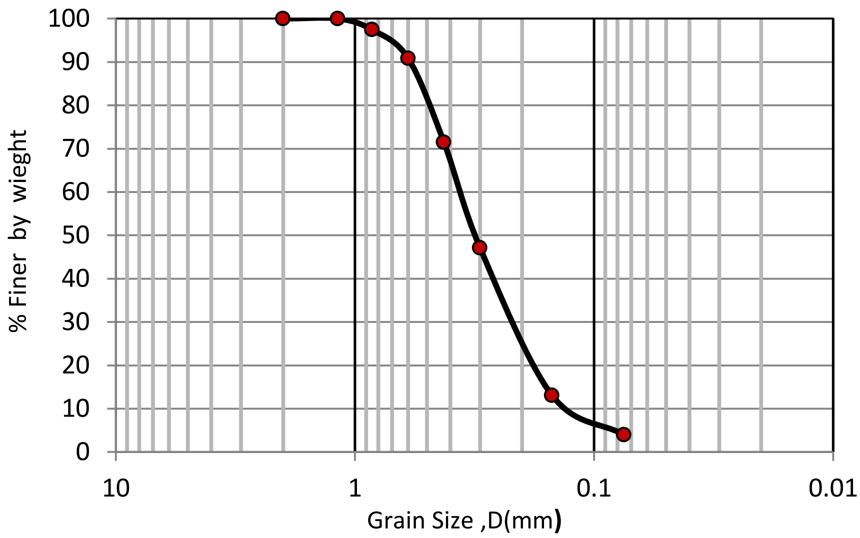


Figure 1: Grain size distribution curve for the sand

Table (1) shows the corresponding dry unit weight values of the sand used in preparation and placement in the model tank.

Table 1: Relative densities and the corresponding dry unit weight values for sand placement

Type of sand	Relative density (D_r%)	Void ratio (e)	Dry unit weight, γ_d (kN/m^3)	Internal friction (φ)
Medium	55	0.624	16.01	39^o
Dense	80	0.524	17.06	34^o

2.2 Model piles

Two model piles of square cross section were used during the experimental work under axial and lateral load tests, open-ended and closed-ended steel box piles.

Table (2) shows the outside dimension, wall thickness and embedment length of each pile. Both of the free standing length and the penetration depth of the pile were kept constant at a distance of (10 cm) throughout the pile loading tests as shown in figure (2).

Table 2: Dimensions of the model piles

Steel Pile type	Dimensions (mm)	Thickness (mm)	Depth ratio (L/D)			
			10	15	20	25
Open-ended Closed-ended	30×30	2	300	450	600	750

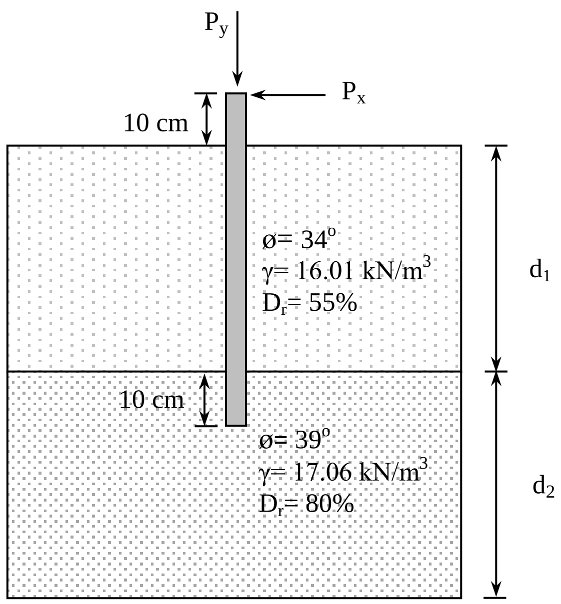


Figure 2: Pile penetration through layered sandy soil

2.3 Sand placement in the model tanks

The sand deposit inside the model tank was prepared using the sand raining technique. A special raining device was manufactured to provide a uniform deposit with the desired density. The device consists of a steel frame, an upper funnel with the opining size of (10 mm) connected to the hand lever by steel rope to allow funnel to move upward, the horizontal of movement of the funnel was achieve by hand.

2.4 Testing Procedure of Compression Tests and Lateral Loading Tests

After placing the sand at the desired relative density, two types of model piles (open- and closed ended steel box piles) were driven in sand by using drop hammer. The combined vertical and lateral loads were applied in two stages. In the first stage, vertical load was applied and then in the second stage, lateral loads were applied incrementally while keeping the vertical load constant.

The static compression loading tests are performed according to the (ASTM D1143–1994) for axial loading tests and (ASTM D3966–1990) reapproved 1995 for lateral loading tests by the procedure of the maintained load (MLT) test.

Forty eight compression tests were carried out on model piles of both open and closed-ended steel box. Each pile was loaded, concerning compression testing program, the pile is loaded until failure, and each increment is sustained by the pile with corresponding final settlement is recorded. The load settlement curve is considered to assess the pile capacity using available methods. Figure (3) shows the schematic details of loading frame.

2.5 Pile Subjected to Axial Load

Eight pile tests under compression were performed to reach the ultimate pile load capacity of two layered sandy soil, which can be divided into two groups:-

A- Open-ended steel box pile.

B- Closed-ended steel box pile.

Four tests were performed for each group and divided into four categories based on (L/D) ratios. The load settlement behavior curves for two types of pile are shown in Figure (4).

2.5.1 Pile Load Test and Prediction of pile load capacity

Analytical methods were used to calculate the capacity of a single pile subjected to axial load. In this study, Meyerhof [10] Tomlinson [11], and Coyle & Castello [12] methods were used to evaluate the end bearing capacity of a pile.

Model piles were subjected to slow maintained load test procedure to assess load-settlement curves and to obtain the observed pile load capacity at failure (P_f). The term 'failure' as used in load tests of this study indicates a rapid progressive lateral movement of the pile under a constant or decreasing load.

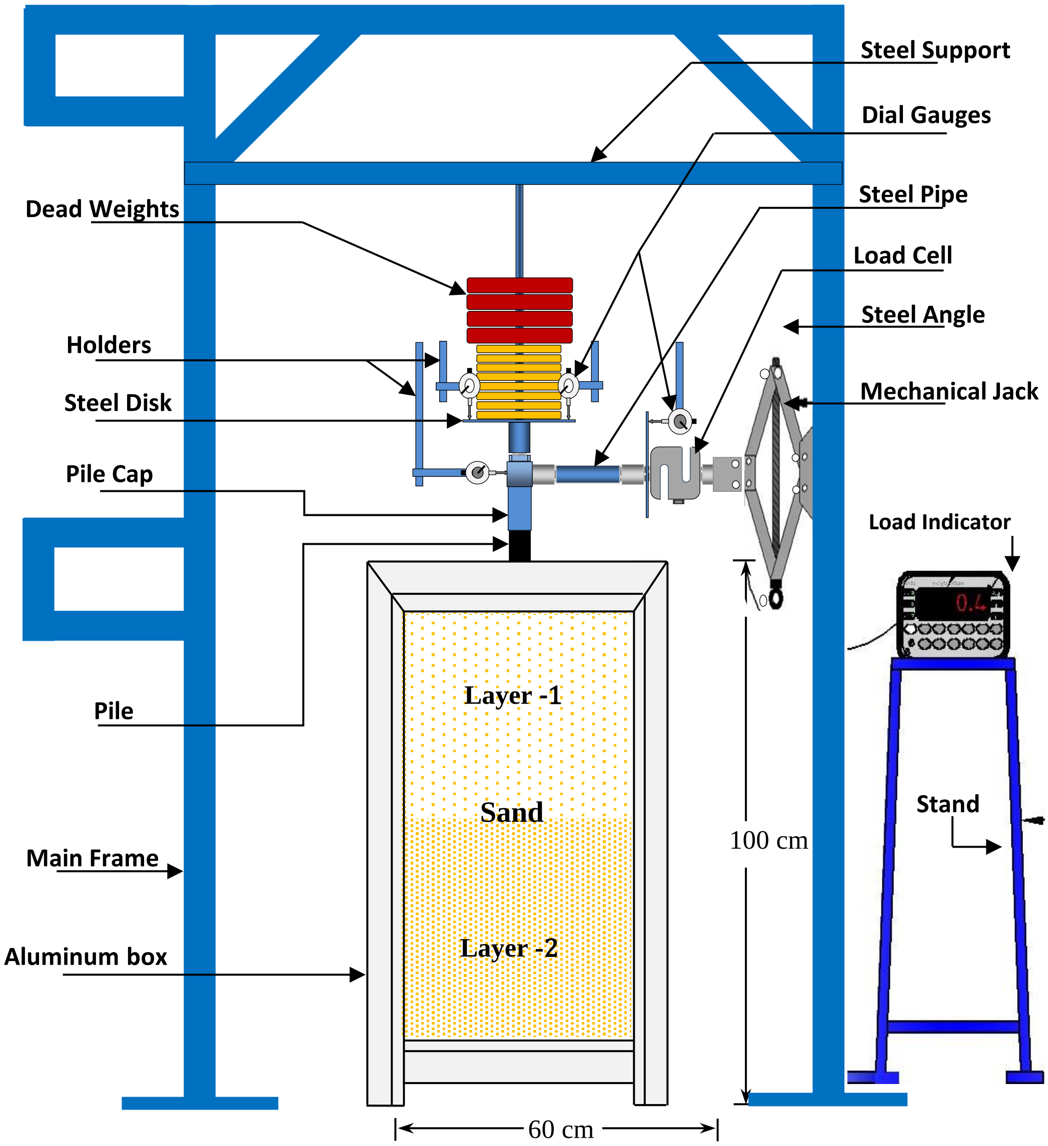
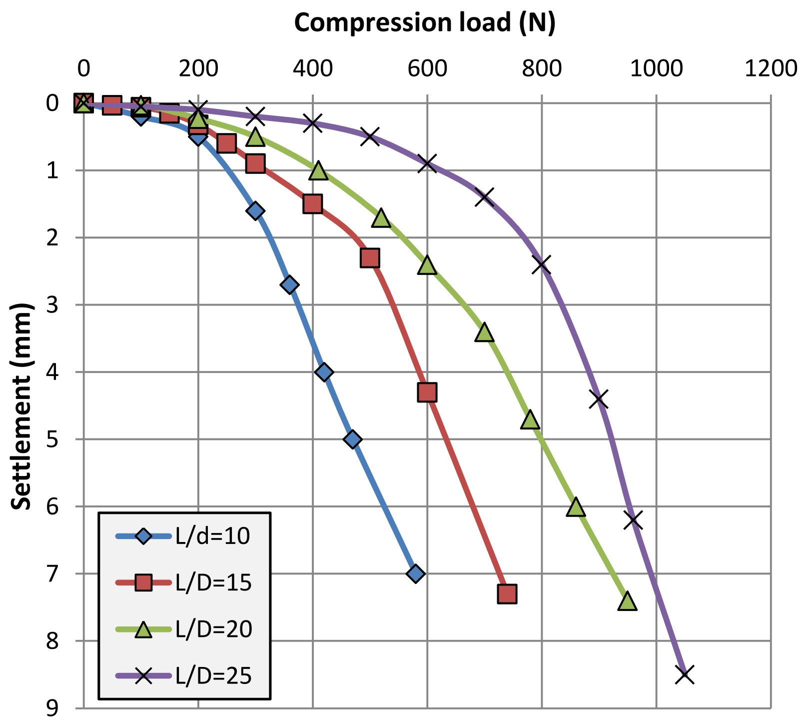


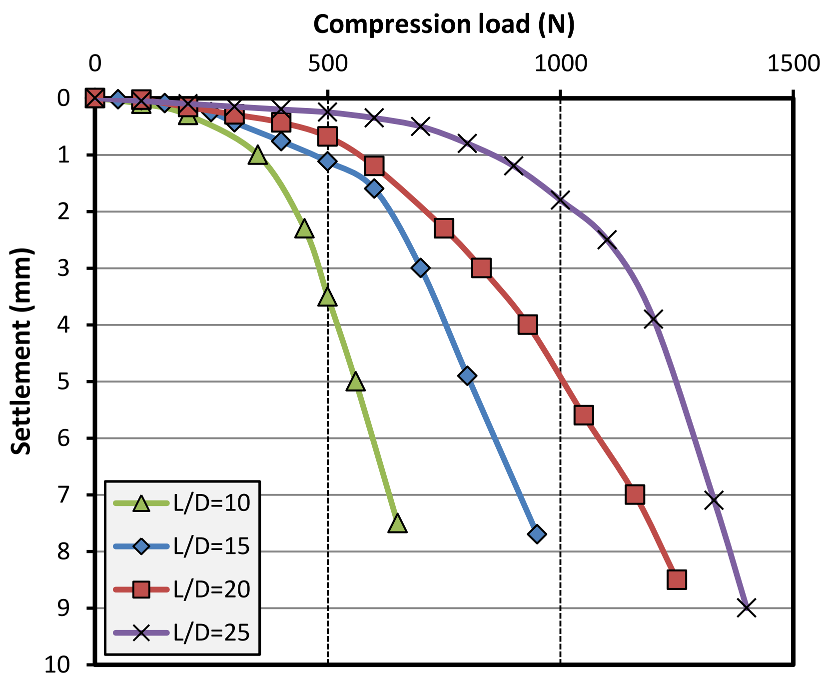
Figure 3: Schematic details of loading frame.

Results of the predicted and observed axial pile load capacities are presented in Table (3). The load-settlement curves for the two types of model piles are illustrated in Figure (4).

From the pile-load test results, it can be clearly observed that the values of (P_f) for closed-ended steel box pile are greater than that of open-ended steel box pile by (12%) for L/D= 10, (28%) for L/D= 15, (31.5%) for L/D= 20 and (33%) for L/D= 25 . This confirm with Al-Ma'adhidi [13] who suggested a reduction factor for calculating the bearing capacity of open-ended steel pipe piles by static formula, and this reduction factor is equal to (0.49).



(a) Open-ended steel box pile



(b) Closed-ended steel box pile

Figure (4) Relationship between compression load-settlement for two types of piles

Table 3: Summary of the predicted and observed pile load capacities under axial load

Embedded length of pile (mm)	Slenderness ratio (L/D)	Thickness of sand layer (mm)		Predicted pile load capacity (N)			Observed pile load capacity (N)	
		d1	d2	Meyerhof	Tomlinson	Coyle & Castello	Open ended pile	Closed ended pile
300	10	200	700	1295	595	406	580	650
450	15	350	550	1955	879	635	740	950
600	20	500	400	2602	1123	871	950	1250
750	25	650	250	3291	1417	1111	1050	1400

2.6 *Pile Subjected to Lateral Loads*

Eight tests under pure lateral load were performed to reach the ultimate pile load capacity of two layered sandy soil divided into two types of piles:-

A- Open-ended steel box pile.

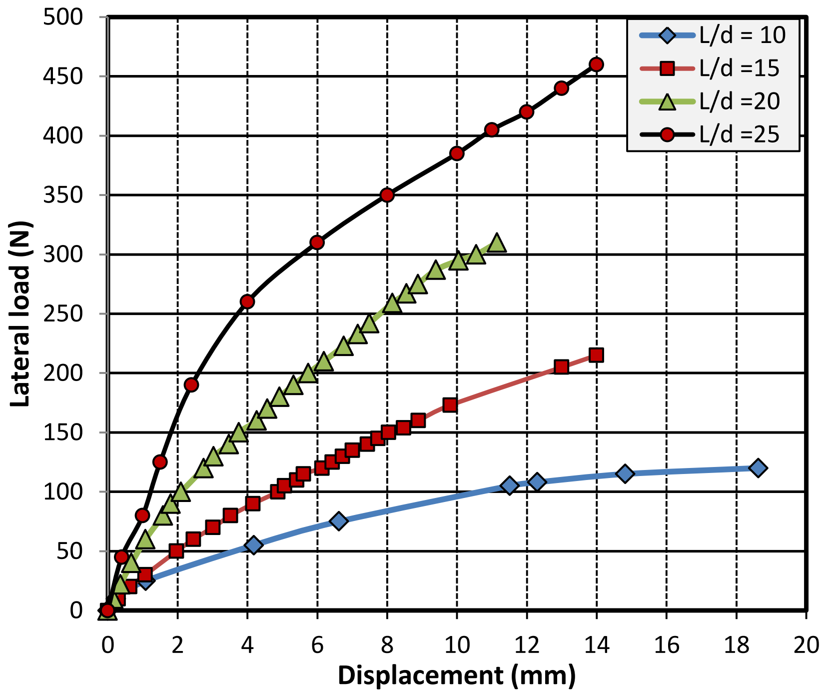
B- Closed-ended steel box pile.

Four tests were performed for each type and divided into four categories depend on (L/D= 10, 15, 20 & 25) ratios. The load settlement behavior curves are shown in Figure (5).

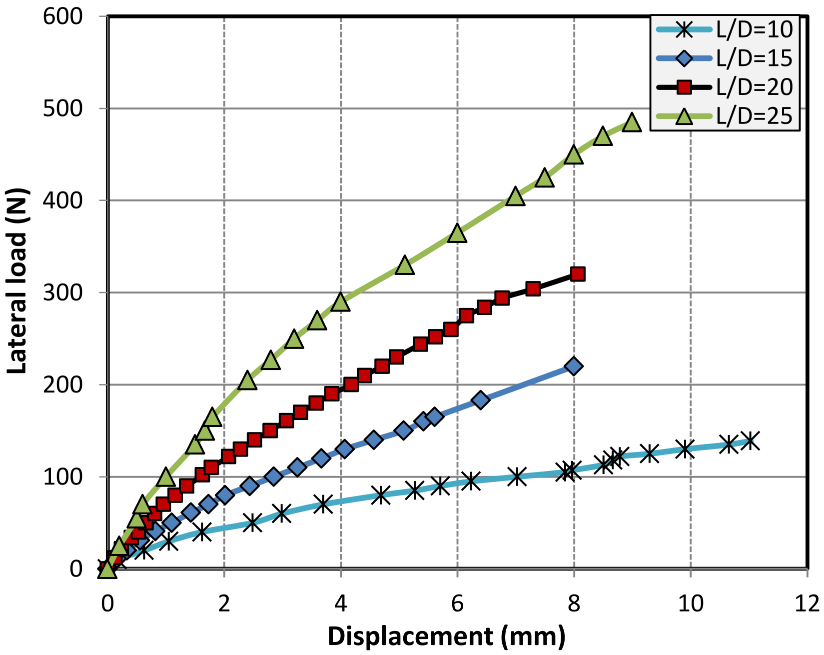
2.6.1 Ultimate lateral load prediction

Numerous methods are used to calculate the ultimate lateral load of piles. In this study, Broms [14] and Meyerhof et al. [15] methods were used to evaluate the ultimate lateral load of a pile. Model piles were subjected to slow maintained load test procedure to assess load-settlement curves and to obtain the observed pile load capacity at failure (P_f). The term 'failure' as used in load tests of this study indicates a rapid progressive lateral movement of the pile under a constant or decreasing load. Results of the predicted and observed ultimate lateral load for two types of pile are presented in Table (4). The lateral load-displacement curves for the two types of pile are illustrated in Figure (5).

It can be seen from Figure (5) that, the load-displacement curves are non-linear hyperbolic shape. From the ultimate lateral load tests results, it can be clearly observed that the value of (P_f) for closed-ended steel box pile was greater than that of open-ended steel box pile by (16%) for L/D= 10, (2%) for L/D= 15, (3%) for L/D= 20, and (5%) for L/D= 25. The ultimate lateral load increases with increasing the (L/D) ratio in two types of the modeled piles.



(a) Open-ended steel box pile



(b) Closed-ended steel box pile

Figure (5) Relationship between lateral load-displacement for two types of piles.

Interpreted pile load capacity is achieved by (Intersection method) to obtain pile load capacity interpreted from lateral load-displacement curves obtained from test results. Table (5) shows the values of interpreted pile load resistance.

Table 4: Summary of the predicted and observed ultimate lateral loads

Embedded length of pile (mm)	Slenderness ratio (L/D)	Thickness of sand layer (mm)		Loading eccentricity, e (mm)	Predicted pile load capacity (N)		Observed pile load capacity (N)	
		d1	d2		Meyerhof	Brom	Open ended pile	Closed ended pile
300	10	200	700	100	61	63	120	139
450	15	350	550		144	150	215	220
600	20	500	400		262.5	275	310	320
750	25	650	250		425.1	438	460	485

Table 5: Summary of the predicted, observed & interpreted ultimate lateral loads

Pile type	Pile width (mm)	Pile length (mm)	(L/D) ratio	Predicted ultimate lateral load (N)		Observed ultimate lateral load (N)	Interpreted ultimate load (N)
				Meyerhof	Broms	Failure load (p_f)	Intersection method
Open-ended steel box	30	300	10	61	63	120	104
		450	15	144	150	215	125
		600	20	262.5	275	310	270
		750	25	425.1	438	460	360
Closed-ended steel box	30	300	10	61	63	139	80
		450	15	144	150	220	145
		600	20	262.5	275	320	275
		750	25	425.1	438	485	330

2.7 Piles Subjected to Combined Axial and Lateral Loads

Pile tests under combined axial and lateral loads were performed to reach the ultimate pile load capacity of two layered sandy soil. Sixteen tests were performed for each type divided into four categories depending on (L/D) ratios.

Each category of tests was divided into four tests according to percentage of (Q_{ult}) value.

To study response of the model piles under combined vertical and lateral loads, the influence of vertical load equal to ($0.2Q_{ult}$, $0.4Q_{ult}$, $0.6Q_{ult}$, $0.8Q_{ult}$) has been considered, where Q_{ult} is the ultimate vertical load capacity of the pile. The values of Q_{ult} were chosen from Tomlinson [11] method.

2.7.1 Influence of vertical load on the lateral response of piles

Figures (6) and (7) show the influence of vertical response of piles in layered sandy soils. It is noted that there is a considerable increase in the lateral load capacity under increased vertical load levels.

The results show that, in piles subjected to combination of vertical and lateral loading, there is an increase in lateral capacity under the presence of vertical loads. Under these conditions, the vertical load has an important role for mobilizing the end bearing capacity, also, frictional capacity along the perimeter due to the adhesion between soil and pile. Therefore, the mobilized shear stresses of soil around the pile are higher in the presence of vertical load as compared to the pure lateral load case.

2.7.2 Influence of pile slenderness ratio (L/D) on the lateral response of piles

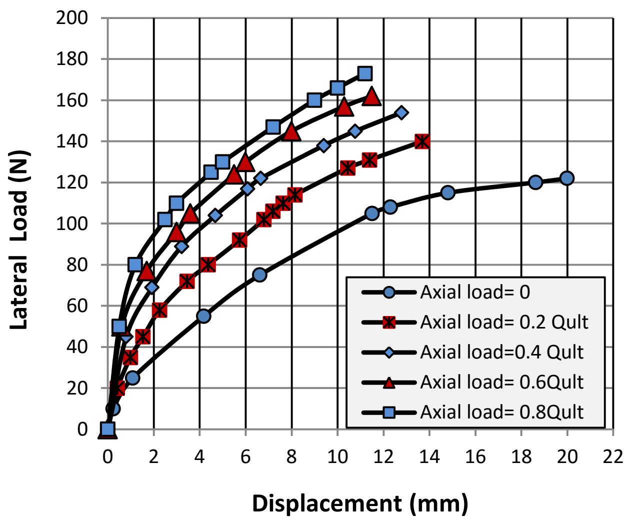
The slenderness ratio means ratio of length to width of pile. To show the influence of slenderness ratio (L/D) on lateral response of pile under combined vertical and lateral loads, piles were analyzed with different lengths and widths on sandy soil. Based on numerical results obtained, the Percentage Variation in lateral Capacity (PVC) with respect to different levels of vertical loads is calculated for various L/D ratios with respect to various pile lengths (L) and widths (D) considered in the analysis. The PVC is defined as follows in terms of the Lateral Load Capacity With Vertical load (LCWV) and the Lateral load Capacity under Pure Lateral loading (LCPL), Karthigeyan et al [6]

$$\mathrm{PVC} = \frac{\mathrm{LCWV}-\mathrm{LCPL}}{\mathrm{LCPL}} * 100\% \qquad (4\text{-}1)$$

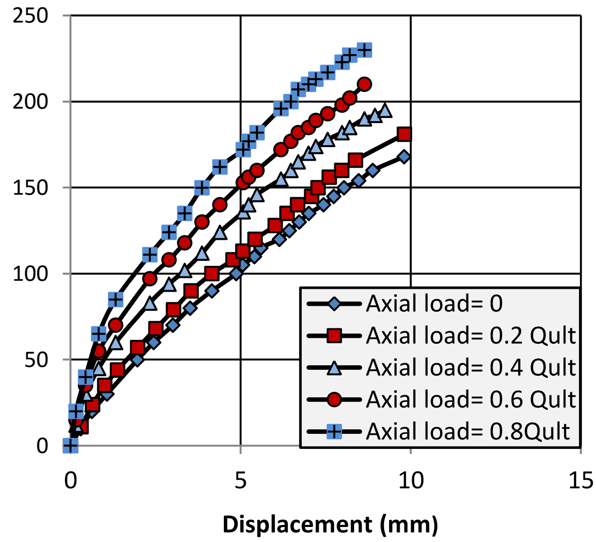
where:

PVC: Percentage variation in lateral capacity.
LCWV: Lateral load capacity with vertical load.
LCPL: Lateral load capacity under pure lateral loading.

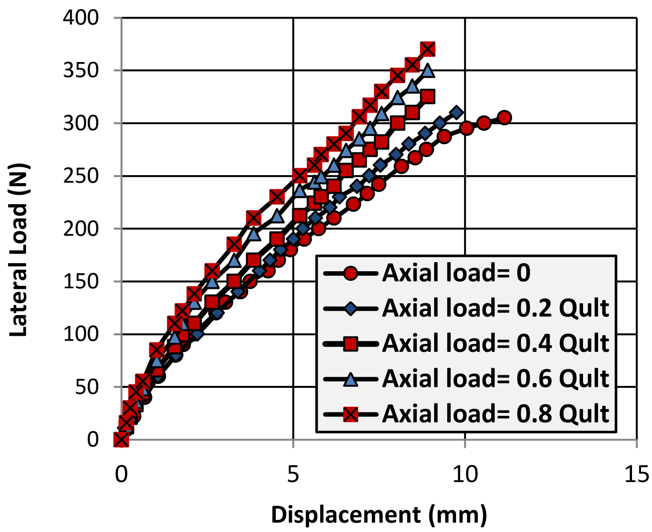
Tables (6) and (7) show the values of (PVC %) at various L/D. From these tables and Figures (8) and (9), the results show that the presence of a vertical load increase the lateral load capacity at all slenderness ratios but the influence of a vertical load decreases with increase in slenderness ratio of piles at all vertical load levels for both types of piles. The reason for this can be directly attributed to the reducing intensity of vertical pressure at larger depths due to load dispersion effects.



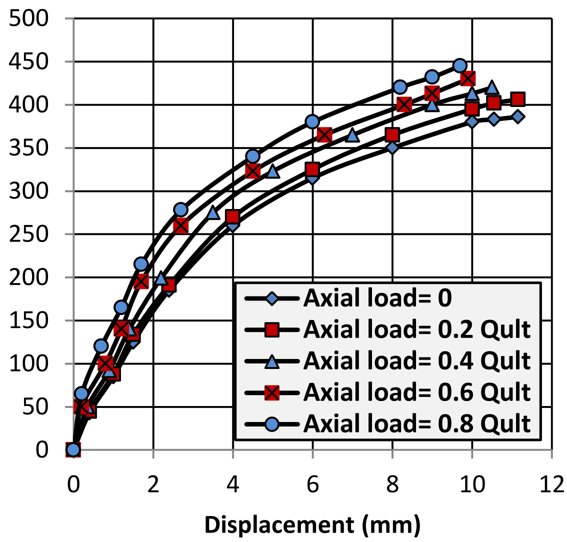
a) L/D=10, Q_{ult}=595 N



b) L/D=15, Q_{ult}=879 N

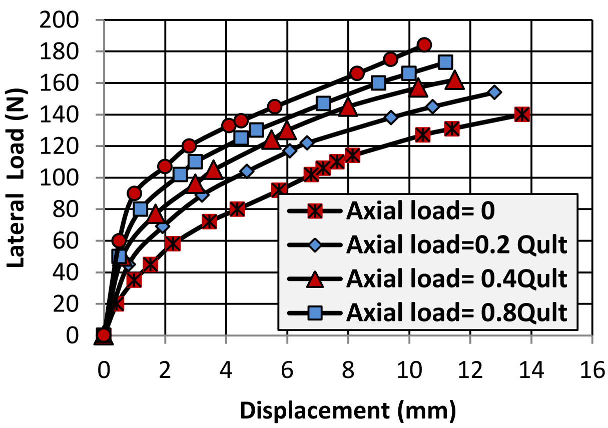


c) L/D=20, Q_{ult}=1123 N

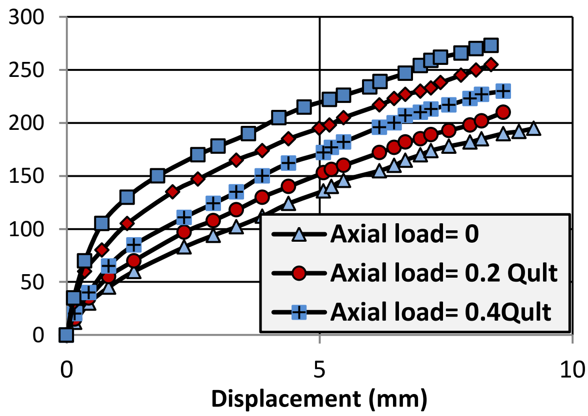


d) L/D=25, Q_{ult}=1417 N

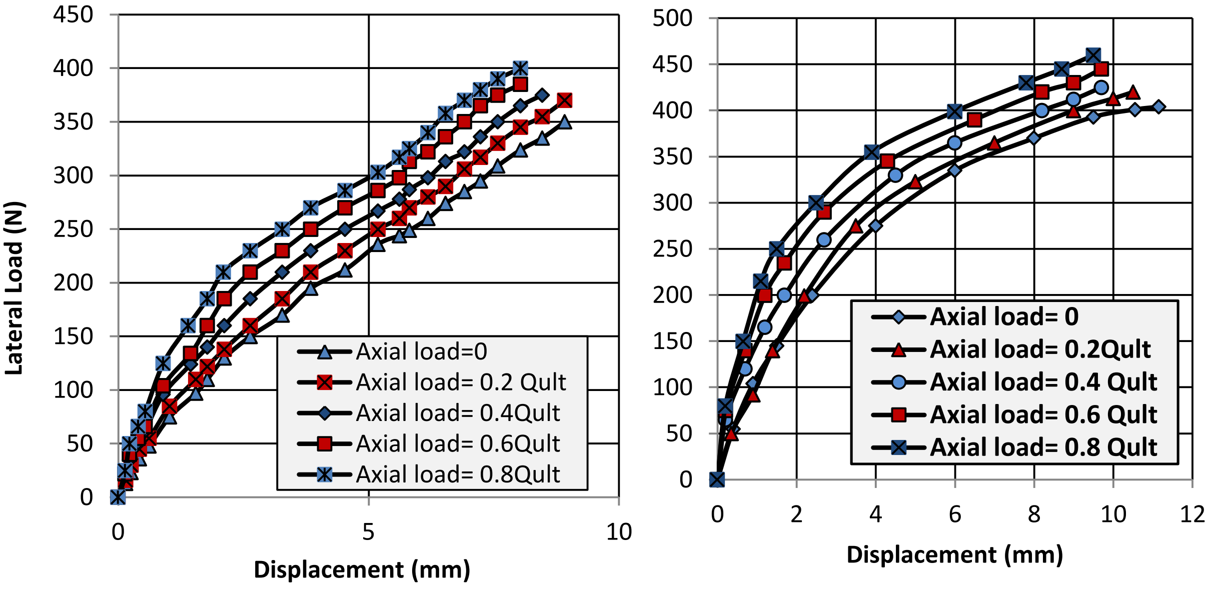
Figure (6) Influence of vertical load on laterally loaded open-ended steel pile.



a) L/D=10, Q_{ult}=595 N



b) L/D=15, Q_{ult}=879 N



c) L/D=20, Q_{ult}=1123 N **d) L/D=25, Q_{ult}=1417 N**

Figure (7) Influence of vertical load on laterally loaded closed-ended steel pile.

Table (6) Percentage variation in lateral capacity (PVC) in open-ended pile

Open-ended steel box pile				
L/D	LCPL (N)	LCWV (N)		PVC%
10	45	$0.2Q_{ult}$	68	51
		$0.4Q_{ult}$	85	89
		$0.6Q_{ult}$	95	110
		$0.8Q_{ult}$	110	144
15	69	$0.2Q_{ult}$	79	14.5
		$0.4Q_{ult}$	95	38
		$0.6Q_{ult}$	112	62
		$0.8Q_{ult}$	125	81
20	130	$0.2Q_{ult}$	135	4
		$0.4Q_{ult}$	147	13
		$0.6Q_{ult}$	160	23
		$0.8Q_{ult}$	175	35
25	215	$0.2Q_{ult}$	222	3.2
		$0.4Q_{ult}$	241	12
		$0.6Q_{ult}$	260	21
		$0.8Q_{ult}$	287	33

Table (7) Percentage variation in lateral capacity (PVC) in closed-ended pile

Closed-ended steel box pile				
L/D	LCPL (N)	LCWV (N)		PVC%
10	68	$0.2Q_{ult}$	87	30
		$0.4Q_{ult}$	100	47
		$0.6Q_{ult}$	115	69
		$0.8Q_{ult}$	130	91
15	95	$0.2Q_{ult}$	110	15.8
		$0.4Q_{ult}$	125	31.6
		$0.6Q_{ult}$	143	50
		$0.8Q_{ult}$	157	65
20	160	$0.2Q_{ult}$	170	6
		$0.4Q_{ult}$	190	19
		$0.6Q_{ult}$	220	37.5
		$0.8Q_{ult}$	232	45
25	235	$0.2Q_{ult}$	245	4
		$0.4Q_{ult}$	275	17
		$0.6Q_{ult}$	300	27.7
		$0.8Q_{ult}$	325	38

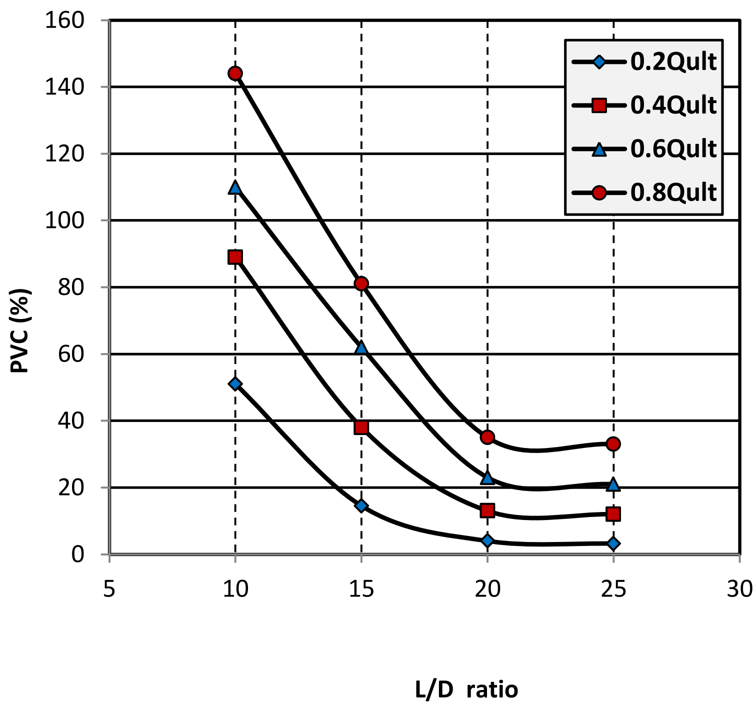


Figure (8) Percentage variation in lateral capacity at various (L/D) ratios for open-ended steel pile.

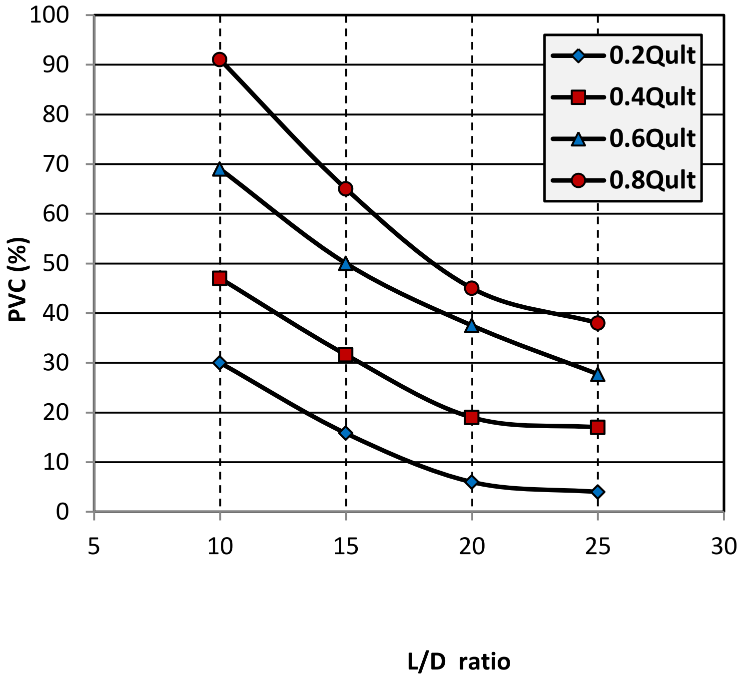


Figure (9) Percentage variation in lateral capacity at various (L/D) ratios for closed-ended steel pile.

3. Conclusions

Based on the analysis of the experimental results obtained from 48 laboratory axial and lateral and combined load tests for open and closed-ended steel box piles embedded in sandy soils, the following conclusions can be summarized:

1. The observed pile load capacity increases with increasing (L/D) ratio for the two types of piles.
2. The observed pile load capacities for the closed-ended steel box pile was greater than that of open-ended steel box pile by (12%) for L/D=10, (28%) for L/D=15, (31.5%) for L/D=20 and (33%) for L/D=25.
3. Meyerhof (1976) method overestimated the predicted end bearing capacity for open-ended steel box pile, while Tomlinson [11] and Coyle & Castello [12] methods are more suitable to predict end bearing capacity for open-ended steel box pile.
4. The observed lateral load for closed-ended steel box pile is greater than that of open-ended steel box pile by (16%) for L/D=10, (2%) for L/D=15, (3%) for L/D=20 and (5%) for L/D=25.
5. The ultimate lateral load increases with increasing the (L/D) ratio in two types of piles used.
6. The presence of a vertical load had increases the lateral load capacity for all slenderness ratios but the influence of vertical load decreases with increasing slenderness ratio of piles at all vertical load levels for both types of piles.

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