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EFFECT OF VERTICAL LOAD ON THE BEHAVIOR OF LATERALLY LOADED PILE GROUPS IN SANDY SOIL

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ملخص البحث :
تستخدم الخوازيق ليس فقط لمقاومة الأحمال الرأسية ، ولكن أيضاً للأحمال الأفقية و المزيج من الأحمال الرأسية والأفقية و في حالة التطبيقات الساحلية و البحرية تكون الأحمال الجانبية مرتفعة بشكل ملحوظ بقدر ما بين 10-20٪ من الأحمال الرأسية وفي مثل هذه الحالات تعتبر دراسة تأثيرات التفاعل بسبب الأحمال الرأسية والجانبية المشتركة أمرًا ضروريًا.

تم التخطيط للإختبارات التجريبية المقدمة هنا في البحث لدراسة تأثير الحمل الرأسى على سلوك الخازوق المفرد و مجموعات الخوازيق المحملة جانبياً في الرمل مع الأخذ في الإعتبار تأثير عدد الخوازيق في المجموعة وطول الخازوق المدفون في التربة (أى L / D). تم إجراء ستة وعشرون اختباراً مقسمة إلى مجموعتين من التجارب على خازوق مفرد ومجموعات الخوازيق . في المجموعة الاولى G_1 تم إجراء عشرون اختبارًا على خازوق مفرد و مجموعات الخوازيق 2×1، 2×2 و3×2 بمسافة بينية (أى S / D) = 3 ، نسبة نحافة (L/D) = 15 وقطر الخازوق 10مم عند خمس مراحل من التحميل الرأسي ($0.00, 0.25V_{ult}, 0.5V_{ult}, 0.75V_{ult}, V_{ult}$). و في المجموعة الثانية G_2 تم إجراء ستة اختبارات على مجموعة الخوازيق 3×2 (أفضل حالة فى المجموعة الاولى G_1) ذات مسافة بينية = 3 ، وقطر الخازوق 10 مم و نسبة نحافة (L/ D) = 20, 25 و 30 عند مرحلتين من التحميل الرأسي ، دون تحميل رأسى (V = 0.00) ومع وجود حمل رأسى مقداره $0.75V_{ult}$ (أفضل نتائج المجموعة الاولى G_1). وبعد تحليل نتائج الاختبارات تبين أن قدرة التحميل الجانبية للخازوق المفرد ومجموعات الخوازيق تزداد نتيجة لزيادة الحمل الرأسى و تزداد المقاومة الجانبية القصوى بزيادة عدد الخوازيق بالمجموعة وكذلك تزداد المقاومة الجانبية القصوى بزيادة نسبة النحافة (L/D) من 15 الى 20, 25 و 30 .

ABSTRACT

Piles are not only used to support vertical loads, but also lateral loads and combination of vertical and lateral loads. in case of coastal/offshore applications, the lateral loads are significantly high of the order of 10–20% of the vertical loads and in such cases, studying the interaction effects due to combined vertical and lateral loads is essential. The experimental tests presented herein the research were planned to study the effect of the vertical load on the behavior of laterally loaded single pile and pile groups in sand with considering influences of number of piles in the group and Length of pile buried in the soil (i.e. L/D). Twenty – six tests divided into two groups of experiments were conducted on a single pile and pile groups. In the first group (G_1), twenty tests were conducted on a single pile and 2x1, 2x2 and 3x2 pile groups with pile spacing (i.e S/D) of 3 , slenderness ratio (i.e. L/D) of 15 and pile's diameter of 10 mm at five stages of vertical loading, (0.00, o.25V_{ult}, o.5V_{ult}, o.75V_{ult} and V_{ult}). In the second group (G_2), six tests were performed on 3x2 pile groups,(the best case from the first group G_1) , with pile spacing of 3, pile's diameter of 10 mm and slenderness ratio (i.e. L/D) of 20, 25 and 30 at two stages of vertical loading, without a vertical load (V=0.00) and with a vertical load , V = 0.75V_{ult} (the best results from the first group G_1) .The results of the tests show that the lateral carrying capacity of a single pile and pile groups increases as a result of increasing in the vertical load, the ultimate lateral resistance increases as the number of piles in the group increase, and the ultimate lateral resistance increases by increasing the slenderness ratio (i.e. L/D) from 15 to 20, 25 and 30.

Keywords: short piles, pile groups, laterally loaded, slenderness ratios, vertical load

1. Introduction

Pile foundations are extensively used to support various structures built on loose/soft soils where shallow foundations would undergo excessive settlements or have low bearing capacity. These piles are not only used to support vertical loads, but also lateral loads and combination of vertical and lateral loads. in case of coastal/offshore applications, the lateral loads are significantly high of the order of 10–20% of the vertical loads and in such cases, studying the interaction effects due to combined vertical and lateral loads is essential, which calls for a systematic analysis. There is hardly any concerted effort to study the influence of vertical load on the lateral response of piles and the literature on combination of vertical and lateral loads is scanty. The limited information on this aspect based on the analytical investigations **[1]** reveals that for a given lateral load, the presence of vertical load increases the lateral deflection. However, laboratory **[2, 5, 7]** and field investigations **[3, 4],** suggest a decrease in lateral deflection under presence of vertical loads. Three-dimensional finite element analyses **[8, 10, 11]** have shown that the influence of combined loading on the lateral response of piles is to significantly increase the lateral capacity in sand. This paper presents the experimental results to investigate the effect of vertical load on the behavior of laterally loaded pile groups in sandy soil.

2. Experimental work

2.1 Description of The model components

The following sections present a detailed description of the model components shown in photo 1 and photo 2 as well as the methods of carrying out the experiments.

2.1.1 Soil characteristics

The soil medium used in the present study was sand. The sieve analysis was carried out to determine the mechanical properties of tested sand. The direct shear tests were carried out on three samples to determine the angle of shearing resistance of the tested sand. Specific gravity test was also carried out on three samples to determine the specific gravity at 20°C of the tested sand. The natural unit weight (γ_{nat}) of the tested sand was estimated1.60 t/m^3. From the direct shear test and estimated natural unit weight, the relative density (D_r) was estimated to be 50 %. The following classification parameters are determined as indicated in table1.

Therefore, according to the Egyptian code of soil mechanics and foundation **[9]**, the sand could be described as medium sand.

Table 1: Properties of sand soil

The Property	Symbol	value
Coefficient of Curvatures	C_c	0.86
Coefficient of Uniformity	C_u	2.01
Soil natural unit weight	γ_{nat}	1.60 t/m^3
Specific Gravity (at 20° C)	G_S	2.47
Soil relative density in percentage	D_r	50 %
Angle of internal friction	φ	33 º

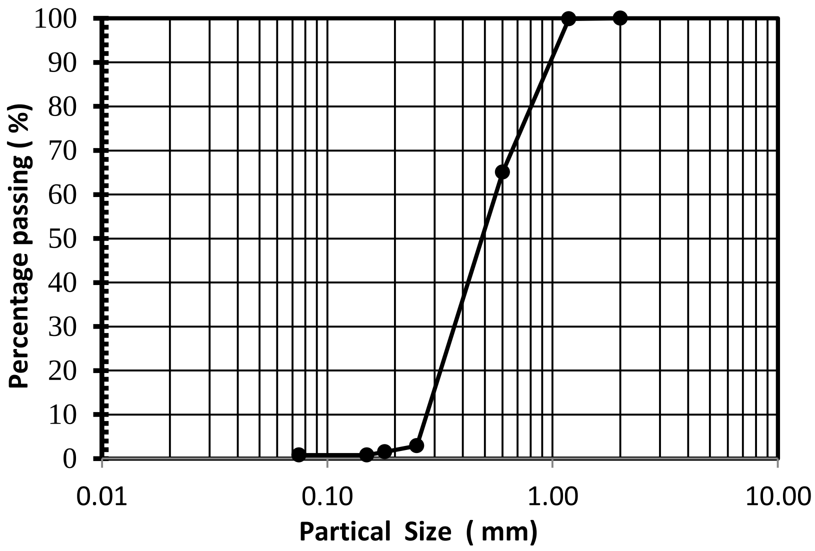

Fig.1: Grain Size Distribution Curve for the tested sand

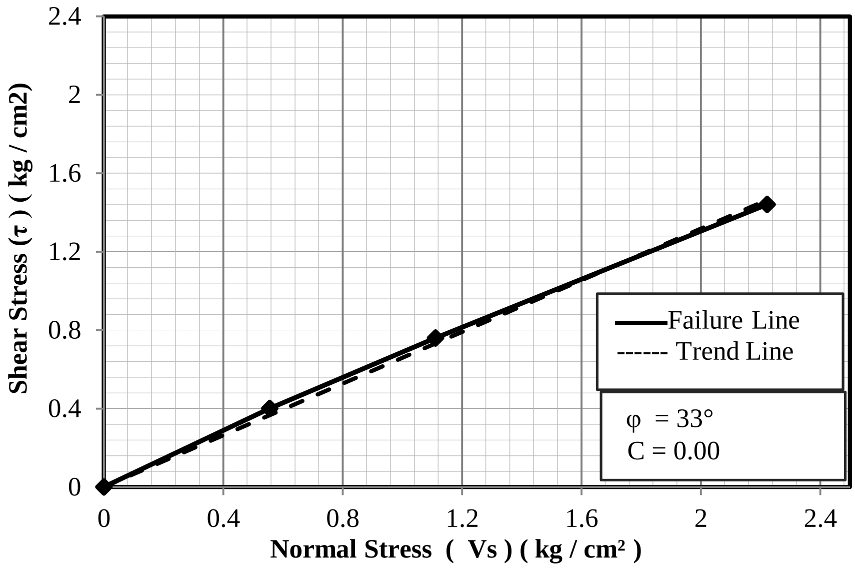

Fig. 2: The direct shear test result

2.1.2 Piles Details

In the research, the pile was treated as a short pile. Therefore, the longest length of the pile used in experiments behave as short pile (i.e. L /D = 30). The piles used in the experiments were steel hollow pipes of 10 mm outside diameter (i.e. D) and 1.5 mm wall thickness (i.e. d = 7 mm) as illustrated in fig 3 and as indicated in table 2 .

2.1.3 Pile Cap Description

Rigid steel plates of 10 mm thickness were used for caps. This thickness of the caps was selected to ensure complete fixation between the piles and the caps, hence, any possible deformation in the cap is not allowed. Moreover, the piles were embedded enough and rigidly fixed to the cap so that no rotation takes place in the pile head.

Table 2: the details of piles used in the experiments

Details of piles	Property
Type of pile	steel hollow pipes
Outside diameter , D	10 mm
Thickness of wall , t	1.5 mm
Moment of inertia I_p	3.73×10^{-2} cm^4
Modulus of elasticity E_p	2.135×10^6 kg / cm^2
Length of pile	15, 20 , 25 , 30 cm

2.1.4 Steel Tank Description

The steel tank is a cubic steel box of dimensions 1.00 m (length) × 1.00 m (width) ×1.00 m (height). The tank is resting on a movable rolling frame base. The tank dimensions were selected to prevent any effects for the boundary walls on the behavior of the piles. Since edge effects are significant particularly if the size of the tank is too small relative to the size of the model piles. the edge effects can be neglected if the distance between the edge and the model pile not less than (8 to 12) times the pile width in the direction of loading and (3 to 4) times the pile width normal to the direction of loading **[6]**.

2.1.5 Main Frame

The main frame has the dimensions of 1500 mm (clear width) × 2150 mm (Clear height), and consists of two vertical columns and horizontal beam. Each column has cross section of CHANNEL NO.140 mm and fixed in the concrete floor.

2.1.6 Loading System

A hydraulic jack was used to generate vertical load that converted to horizontal load by the system. The hydraulic jack was fixed at the middle span of the horizontal beam of the main frame by two U shape anchors. The verticality of the hydraulic jack had been checked in the two perpendicular directions of the horizontal level surface and vertical level surface. The different steel weights had been used as a vertical load placed on the piles. Photo1 and photo 2 show the details of model components.

2.1.7 Measuring Devices systems

Three dial gauges of 0.01 mm accuracy were mounted over the test model; one dial gauge was used to measure the lateral displacement of the caps at each load level. The two other dial gauges were used to measure the vertical displacement due to the vertical load.

2.2 Test procedure

The experiments were started with placing the sand soil in the steel tank in layers. The maximum layer thickness was 100 mm. the total height of the tank was divided into intervals from the inner side by making signs every 100 mm height to help to put the specified weight in a specified volume to get the required soil density of 1.6 t/m^3 by compaction. The pre- weighted quantity was placed and compacted with adjusted to 100 mm high. The process was repeated until reaching the specified height inside the test tank. The piles were installed into the soil by driving. A steel hammer weighting 0.5 kg was used to achieve uniform stroke for the pile driving to reach the required elevation. After driving all piles in the group, the cap was fixed to the piles by using two nuts as illustrated in fig 3. In the case of laterally loading without a vertical load, lateral loading is carried out incrementally till reaching to the failure load. In the case of laterally loading in the presence of a vertical load, pre- weighted steel weights were placed on a single pile or the piles group as a vertical load then, the vertical displacement is measured and the lateral loading is carried out incrementally till reaching to the failure load, i.e. the dial gauge reading increase without increasing in the lateral load and in the same time it was detected that the proving ring readings were decreased.

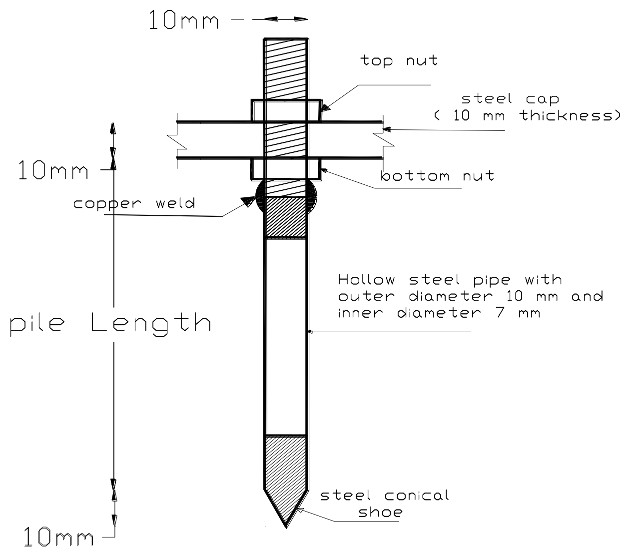

Fig 3: Details of connection between the pile and the cap

Photo 1: The steel tank

Photo 2: The model components

3. Experimental Results

3.1 Lateral Load – displacement curves for the first group

A series of twenty tests were performed on a single pile, 2×1, 2×2, and 3×2 pile groups to investigate the effect of vertical load on the behavior of laterally loaded piles. These tests were performed on piles of 10 mm diameter and with pile spacing (i.e. S/D) ratio of 3 and slenderness ratio (i.e. L/D) of 15.

3.1.1 Lateral Load – displacement curve of single pile

Five tests were performed on a single pile with L/D ratio of 15 at five stages of vertical loading. Fig 4 shows the effect of vertical load on the lateral load- displacement curve of a single pile.

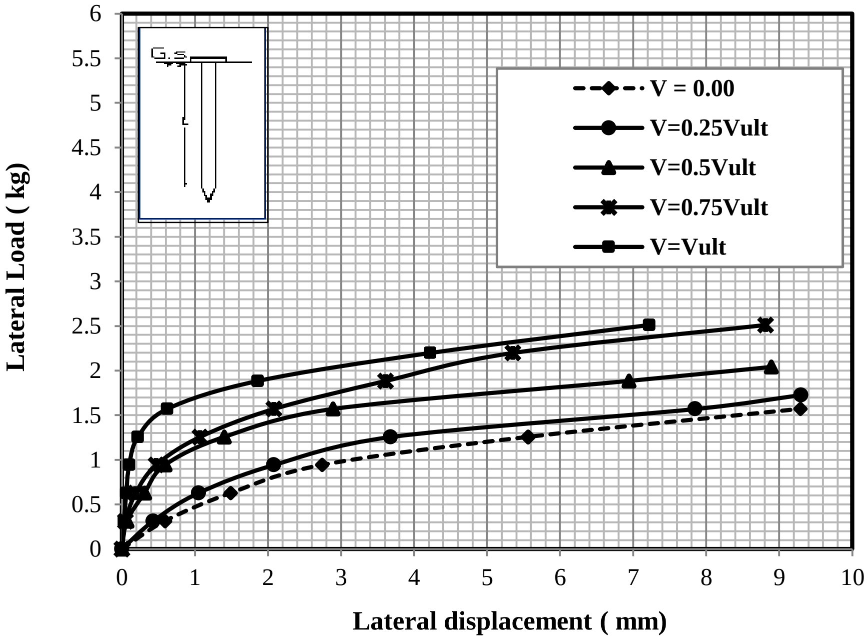

Fig. 4: Lateral load – displacement curve of single pile

3.1.2 Lateral Load – displacement curve of 2×1 pile groups

Five tests were performed on 2x1 pile groups with L/D ratio of 15 and pile spacing (i.e. S/D) of 3 at five stages of vertical loading. Fig 5 shows the effect of vertical load on the lateral load- displacement curve.

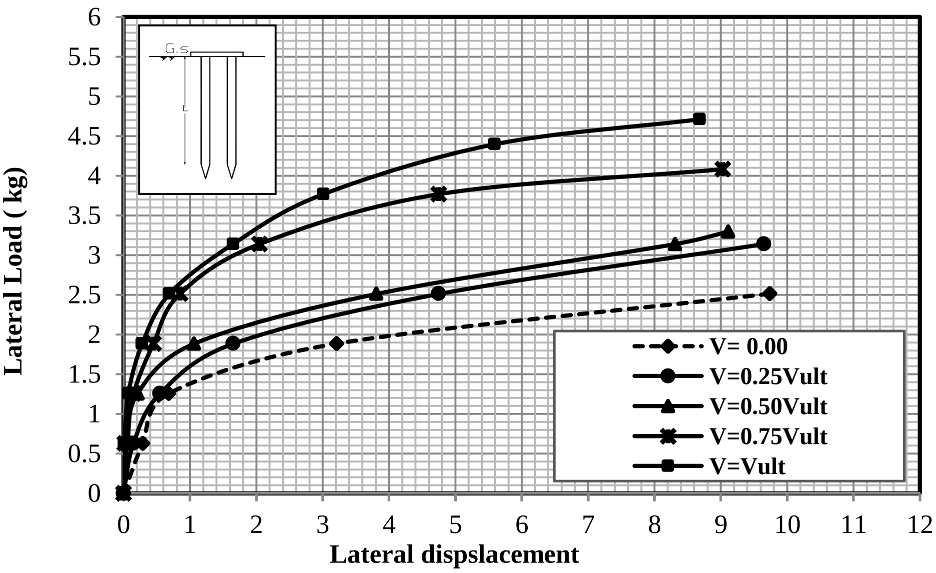

Fig. 5: Lateral load – displacement curve of 2×1 pile group

3.1.3 Lateral Load - displacement curve of 2×2 pile groups

Five tests were performed on 2×2 pile groups with L/D ratio of 15 and pile spacing (i.e. S/D) of 3 at five stages of vertical loading. Fig 6 shows the effect of vertical load on the lateral load- displacement curve of 2×2 pile groups.

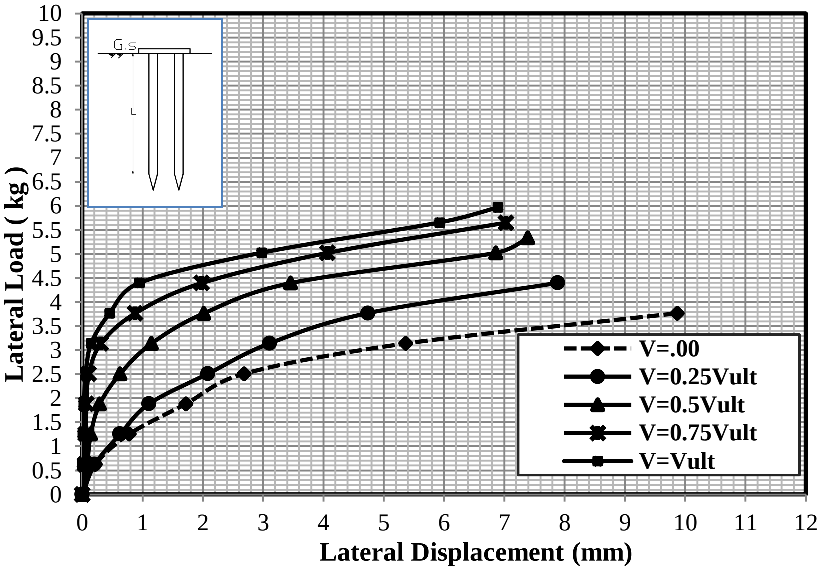

Fig. 6: Lateral load – displacement curve of 2×2 pile groups

3.1.4 Lateral Load - displacement curve of 3×2 pile groups

Five tests were performed on 3×2 pile groups with L/D ratio of 15 and pile spacing (i.e. S/D) of 3 at five stages of vertical loading. Fig 7 shows the effect of vertical load on the lateral load- displacement curve of 3×2 pile groups.

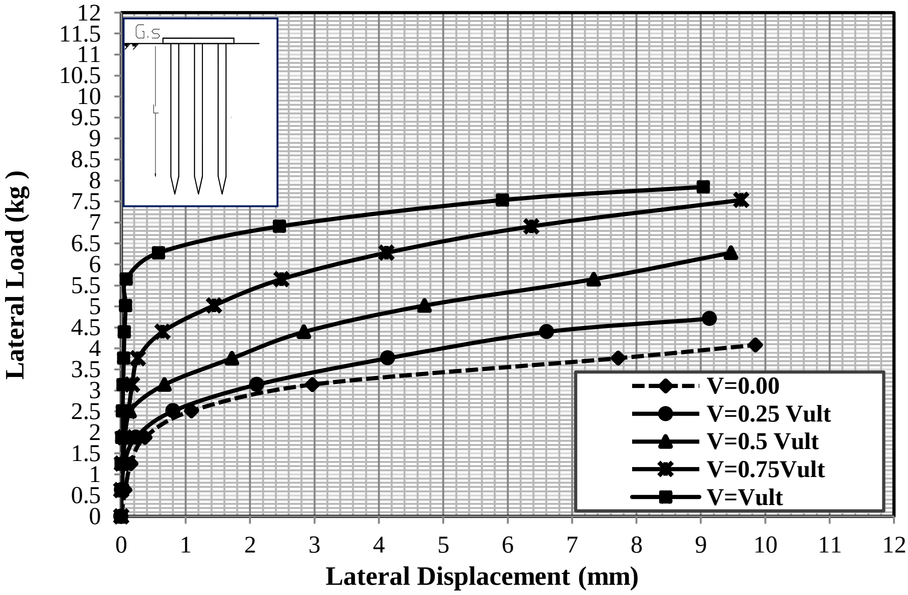

Fig. 7: Lateral load – displacement curve of 3×2 pile groups

3.1.5 The comparison between the single pile and the pile groups

The results of the tests on 2×1,2×2,and 3×2 pile groups were compared with the results of tests performed on the single pile for all cases of loading, (0.00, 0.25V_{ult}, 0.50V_{ult}, o.75V_{ult}, and V_{ult}) . The comparisons were carried out to study the effect of the number of piles in the group on the lateral load – displacement curves with the absence of a vertical load and with the presence of a vertical load.

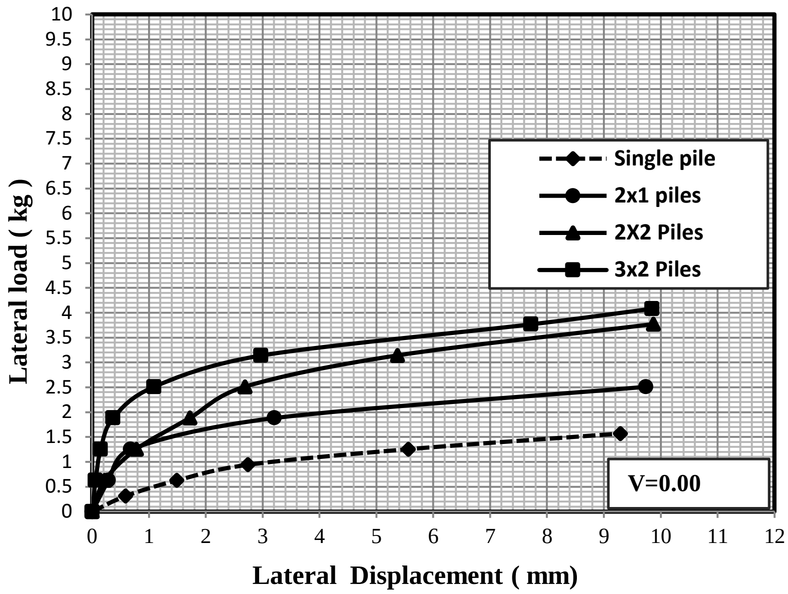

Fig. 8: Lateral load – displacement curve in the absence of a vertical load

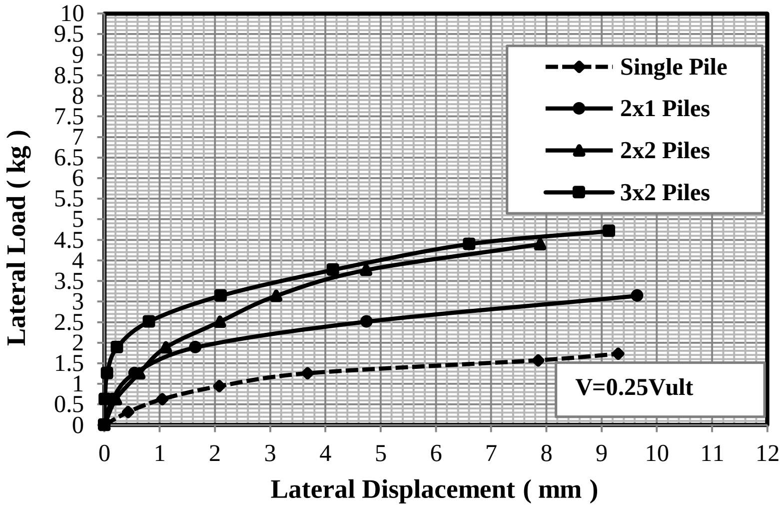

Fig. 9: Lateral load – displacement curve with a vertical load = 0.25V_{ult}

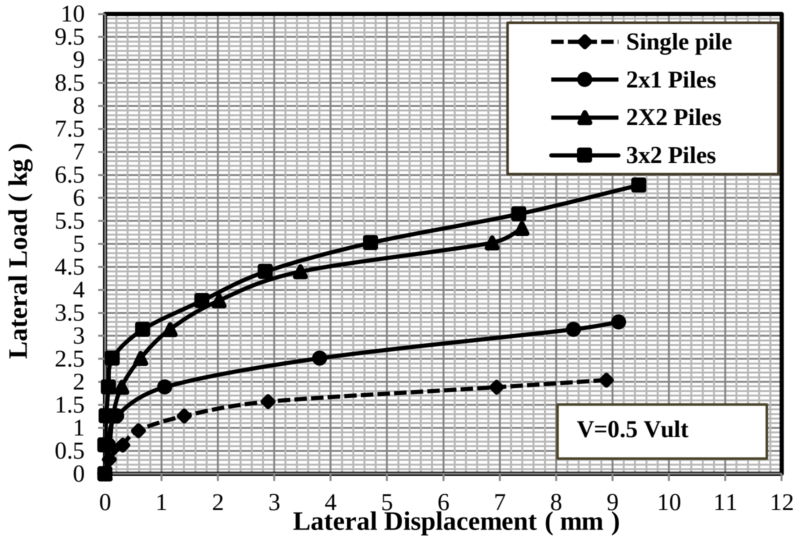

Fig. 10: Lateral load – displacement curve with a vertical load = 0. 50V_{ult}

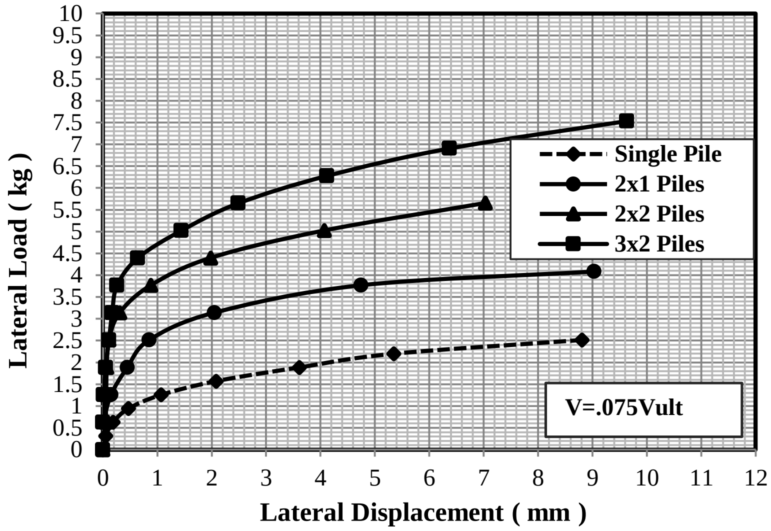

Fig. 11: Lateral load – displacement curve with a vertical load =0.75V_{ult}

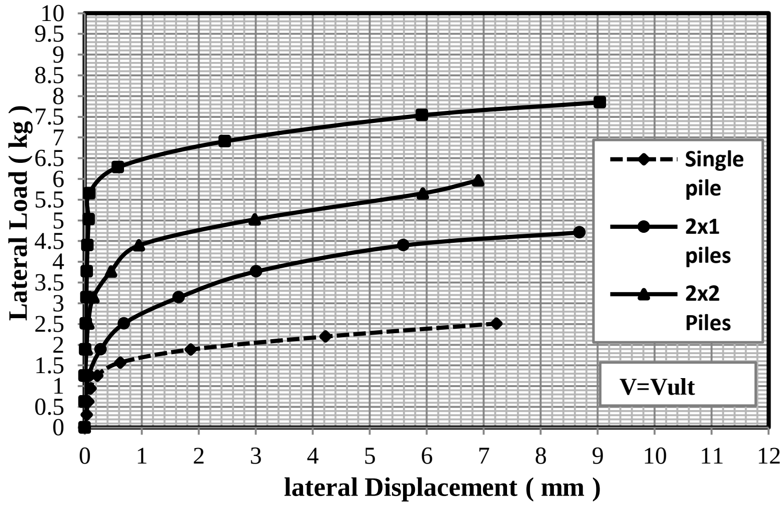

Fig. 12: Lateral load – displacement curve with a vertical load = V_{ult}

3.1.6 Effect of the vertical load on the ultimate lateral capacity

The rate of improvement in the ultimate lateral capacity due to presence of a vertical load was determined as shown in table 4 and fig 13.

Table 3: The ultimate lateral capacity of single pile and pile groups

V/V_{ult}	single pile	(2×1) pile groups	(2×2) pile groups	(3×2) pile groups
	L.C	L.C	L.C	L.C
0.00	1.57	2.512	3.768	4.082
0.25	1.727	3.14	4.396	4.71
0.50	2.041	3.297	5.338	6.28
0.75	2.512	4.082	5.652	7.536
1.00	2.515	4.71	5.966	7.85

Table 4: Rate of improvement in lateral capacity due to presence a vertical load

V/V_{ult}	single pile	(2×1) pile	(2×2) pile	(3×2) pile
	% of increase	% of increase	% of increase	% of increase
0.00	0	0	0	0
0.25	10	25	16.67	15.38
0.50	30	31.25	41.67	53.85
0.75	60	62.5	50	84.61
1.00	60	87.5	58.33	92.3

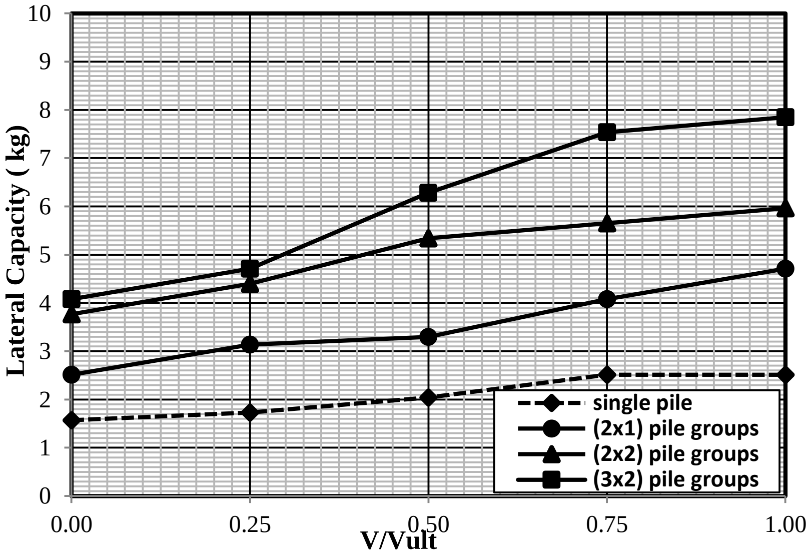

Fig. 13: ultimate Lateral capacity – vertical load ratio curve

3.2 Lateral Load – displacement curves of the second group

Six tests were conducted on the piles of the second group of experiments, which includes 3×2 pile groups to study the effect of vertical load on the behavior of laterally loaded pile groups and also the influences of L/D ratios were presented. These tests were performed on piles with 10 mm diameter and S ⁄ D ratio of 3 at L⁄D ratio of 20, 25, and 30. As shown in fig 14,fig 15 & fig16

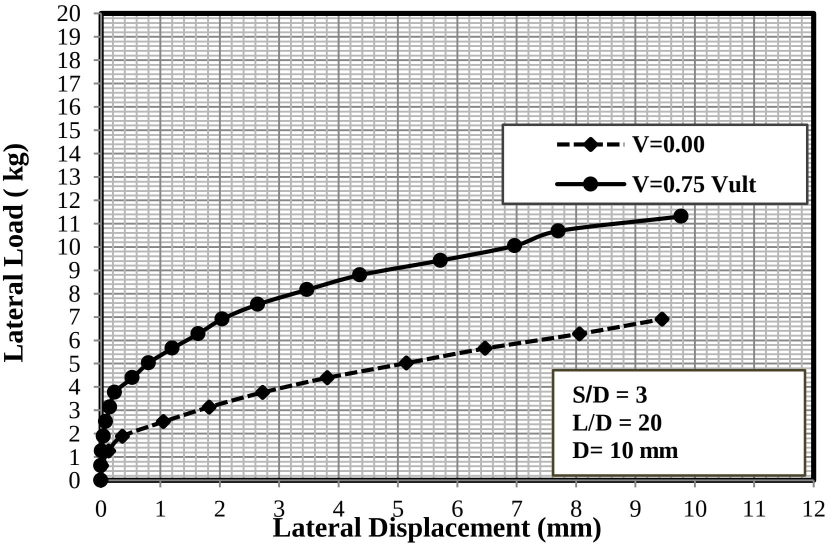

Fig. 14: Lateral load–displacement curve of 3×2 pile groups At L/D = 20

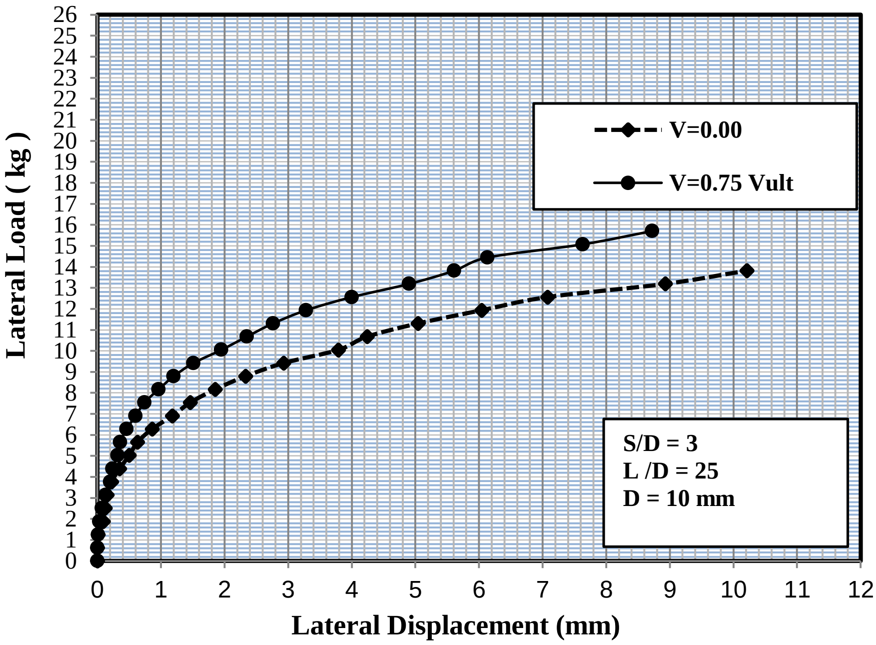

Fig. 15: Lateral load–displacement curve of 3×2 pile groups At L/D = 25

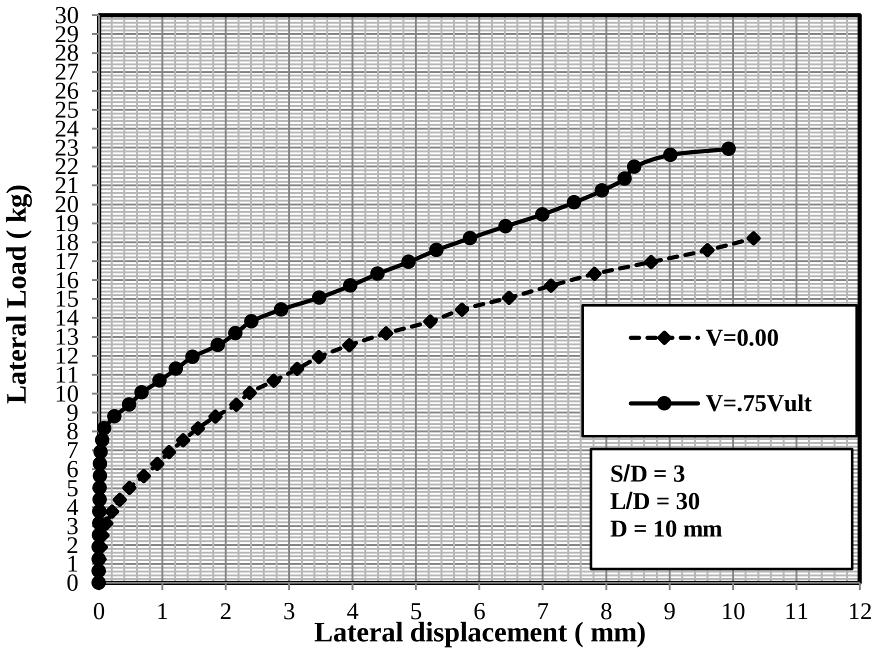

Fig. 16: Lateral load–displacement curve of 3×2 pile groups At L/D = 30

3.2.1 Effect of L/D ratio on Lateral Load - displacement curve

A comparison was carried out between the tests results of 3x2 pile groups at L/D ratios of 15, 20, 25 and 30. This comparison was in two cases of loading, with the absence of vertical load (i.e. V= 0.00) and with the presence of a vertical load (i.e. V= 0.75Vult) as indicated in tables, (5 & 6) and as shown in fig 17.

Table 5: The ultimate lateral capacity at different L/D ratios

vertical load	Ultimate Lateral capacity			
	L/D ratio			
	15	20	25	30
0.00	4.082	6.908	13.816	18.212
$0.75V_{ult}$	7.54	11.304	15.7	22.922

Table 6: Effect of L/D ratio on the ultimate lateral capacity

Vertical load	Percentage of improvement (%)		
	L/D ratio		
	20	25	30
0.00	69.23	238.46	346.15
0.75Vult	49.92	108.22	204.01

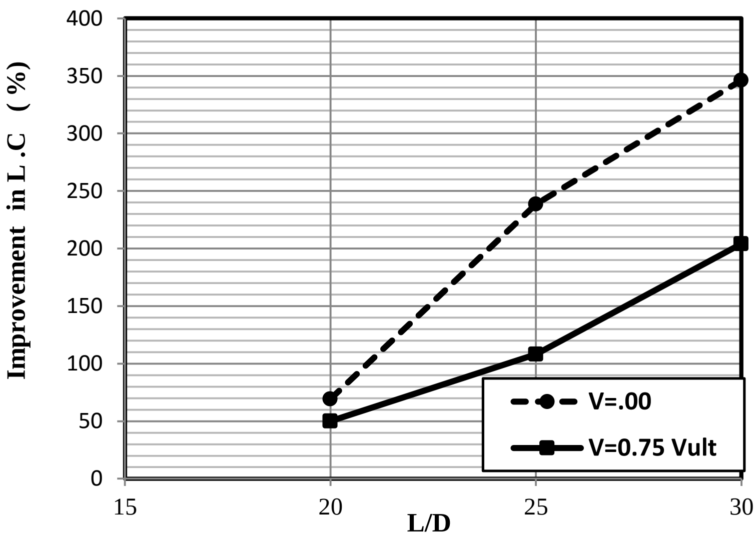

Fig. 17: Improvement percentage –L/D Ratio curve of 3×2 pile groups

4. Analysis and Discussion of Test Results.

4.1 Lateral Load – displacement curves for the first group

Referring to the results of experimental tests, the analysis and discussion of the results were presented for twenty tests of the first set of experiments.

4.1.1 Lateral Load – displacement curves of a single pile

As shown in fig 4, the lateral resistance increases and the lateral displacement decrease as a result of increasing the vertical load.

4.1.2 Lateral Load - displacement curves of 2×1, 2×2 and 3×2 pile groups

As shown in fig 5, fig 6, and fig 7, the lateral resistance of the 2×1, 2×2, and 3×2 pile groups increases while the lateral displacement decreases because of increasing the vertical load.

4.1.3 Influence of the number of piles on the lateral capacity

The comparisons were carried out between the results of tests performed on a single pile and 2×1, 2×2 and 3×2 pile groups. As shown in figs (8, 9, 10, 11 & 12), the lateral resistance increases and the lateral displacement decrease as the number of piles increases. This result is due to increased soil mass resistance by increasing the number of piles in the group.

4.1.4 Effect of the vertical load on the ultimate lateral capacity

As indicated in tables (3& 4) and as shown in fig 13, a significant improvement in the lateral resistance due to the presence of a vertical load equal $0.75V_{ult}$ of the single pile and pile groups where, The improvement percentages of the single pile, 2×1, 2×2, and 3×2 pile groups are equal to 60 %, 62.50 %, 50 %, and 84.61 % respectively. The high improvement percentage in the ultimate lateral resistance of 3×2 pile groups is due to increased volume of the resistant soil (i.e. passive soil pressure). The decrease in the improvement percentage of 2×2 pile groups is due to the group effect (i.e. shadowing effect). the ultimate lateral capacity increases as a result of increasing in the vertical load because of the compaction occurred to the soil around the piles, which results in an increase in the angle of internal friction (i.e. ϕ) and thus, increases soil resistance in the front of the piles (i.e. passive soil pressure)

4.2 Lateral Load – displacement curves of the second group

Referring to the results of second group of experiments, the analyses and discussions of the results were presented for six tests. The influence of L/D ratio was also presented and discussed.

4.2.1 Effect of L/D ratio on Lateral Load – displacement curve

Referring to fig 14, fig 15, and fig 16, the lateral capacity of 3×2 pile group increases and the lateral displacement decreases due to the presence of a vertical load equal $0.75V_{ult}$ at L/D ratios of 20, 25, and 30. As shown in fig 17 and as indicated in table 5 & 6, there is a significant effect of slenderness ratio (i.e. L/D) on the behavior of the laterally loaded piles. The best results obtained were at the L/D ratio of 30, where the improvement percentage in the ultimate lateral capacity with the absence of a vertical load was 346.15 % and in the presence of a vertical load (i.e. = $0.75V_{ult}$) was 204.01 %. This result is due to the increase in the volume of soil in the front of the piles as L/D ratio increases.

Conclusions

1. The lateral carrying capacity of single piles and pile groups (i.e., 2×1, 2×2, &3×2) increases and the lateral displacement decreases as a result of increasing in the vertical load because of the compaction occurred to the soil around the piles, which results in an increase in the angle of internal friction (i.e. ϕ) and thus, increases soil resistance in the front of the piles (i.e. passive soil pressure).
2. At a vertical load equal 0.75Vult, the ultimate lateral capacity increases significantly as the number of piles in the group increases.

3. The improvement percentage in the ultimate lateral resistance of 2×1 pile group is higher than the improvement percentage of 2×2 pile groups because of the group effect (i.e. shadowing effect).
4. The improvement percentage in lateral resistance of 3×2 pile group at L/D ratio of 15 and S/D ratio of 3 with the presence of a vertical load of 0.75Vult is 84.61 %.
5. The maximum improvement percentage in the ultimate lateral capacity of 3×2 pile groups is due to increased volume of the resistant soil (i.e., passive soil pressure).
6. The lateral carrying capacity of pile groups increases and the lateral displacement decreases with increasing the slenderness ratio (i.e. L / D).
7. The improvement percentage in lateral resistance of 3×2 pile groups at L/D ratio of 30 and S/D ratio of 3 with the presence of a vertical load of $0.75V_{ult}$ is 204.01 %.

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