Experimental Study on Pile Groups Settlement and Efficiency in Cohesionless Soil

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Abstract — **Experimental investigation of the behavior of pile groups in sand under axial compression load is very important for studying the settlement and group efficiency. There is no simplified method for settlement prediction of pile groups. However, experimental investigation is one way to predict the allowable settlement. The various efficiency ratios are based simply on experience without any relationship to soil mechanics principles. The purpose of the current study is to investigate the ultimate capacity, settlement and efficiency of pile groups in sandy soil. An experimental program was conducted to study the group effect on ultimate capacity, settlement and efficiency. However, the experimental program consisted of testing single pile and pile groups of two, three and four piles in sand under axial compression load. The spacing between piles was three pile diameters. The program consisted of installing test piles in dense compacted sand placed in a soil chamber, and subjected to compressive axial load. The pile head loads, displacement, strains along the piles shaft were measured simultaneously. The obtained test results indicated that the ultimate capacity of single pile inside pile groups increases with increasing number of piles. However, the settlement of pile groups at the ultimate load was found to be more than the settlement of single pile. In addition, it was found that group efficiency of pile groups (2, 3 and 4 piles) increases with increasing the number of piles. However, for number of piles in pile group more than four no significant change has been obtained. In addition, the group efficiency was found to be ranging from 1.25 – 1.47 as by using modified chin method (1970) for the determination of ultimate capacity of piles.**

Keywords— Piles; capacity; analysis; loading test; pile groyp; group efficiency; strain gauges; experimental.

1. INTRODUCTION

As far as settlement prediction is concerned, a pile group has special treatment. There is no simplified method for settlement prediction of pile groups. However, experimental investigation is one way to predict the allowable settlement of pile groups. The allowable loading on pile groups is sometimes determined by the so-called efficiency formulae, in which the efficiency of the group is defined as the ratio of the average load per pile when failure of the complete group occurs, to the load at failure of a single comparable pile. The various efficiency ratios are based simply on experience without any relationship to soil mechanics principles.

Ismael, N. F. (2001) studied the behavior of bored pile groups in cemented sands by a field testing program. The program consisted of axial load tests on single bored piles in tension to determine the shaft resistance with assumption that shaft friction is equal in case of tension and compression. Compression test on two pile groups each consisted of five piles. The spacing of the piles in the groups was two and three-pile diameters. The calculated pile group efficiencies were 1.22 and 1.93 for a pile spacing of two and three-pile diameters, respectively [1].

Al-Mhaidib, A. I. (2006) investigated the behavior of pile groups in sand under different loading rates. A total of 60 tests were conducted in the laboratory using model steel piles embedded in medium dense sand. The model piles have an outside diameter of 25 mm and embedment length of 500 mm. Five different configurations of pile groups (2 · 1, 3 · 1, 2 · 2, 2 · 3, 3 · 3) with center to center spacing between the piles of 3d,6d and 9d (d is the pile diameter) were tested. The piles were subjected to axial compressive loads under four different loading rates: 1.0, 0.5, 0.1 and 0.05 mm/min [2].

Tomlinson, M. and Woodward, J. (2008) presented that the supporting capacity of a group of vertically loaded piles can be considerably less than the sum of the capacities of the individual piles comprising the group. In all cases the elastic and consolidation settlements of the group are greater than those of a single pile carrying the same working load as that on each pile within the group. This is because the zone of soil which is stressed by the entire group extends to a much greater width and depth than the zone beneath the single pile. [3]

Zhang, Q. Q. et al (2013) presented a simplified method for settlement prediction of single pile and pile group using a hyperbolic model. A simplified approach for nonlinear analysis of the load-displacement response of a single pile and a pile group was presented using the load-transfer approach. A hyperbolic model was used to capture the relationship between unit skin friction and pile-soil relative displacement developed at the pile-soil interface and the load-displacement relationship developed at the pile end. As to the nonlinear analysis of the single pile response, an iterative computer program was developed using the proposed hyperbolic model [4].

Singh P. K., and Arora, V. K (2014) studied the behavior of load settlement characteristics of different cross section shapes (rectangular, square and circular) pile groups subjected to axial load conditions. The behaviors of thirteen pile groups were studied. The spacing of piles at the bottom of pile cap was constant and equal to 2.5d in each case where d is the diameter of the pile. Tests were conducted in laboratory under controlled density conditions using dry, clean, uniform sand. Only deflections at ground level were measured [5].

Plaban, Deb., and Pal, S. K. (2016) conducted a prototype tests on model pile groups of configuration 1×1, 2×2, and 3×3, for embedment length to diameter ratios (L/D) of 5, 6, 7 and 8, and spacing 3 times of diameter, subjected to vertical loads. The model piles used for the test were 250 mm in length with 25mm diameter. Plaban, Deb., et al used 3D finite element modeling on ABAQUS to analyze the effect of soil properties, pile length-to-diameter ratio and time dependent load-settlement behavior on the capacity of a pile [6].

Pham, A. T. (2016) presented a new method for analysis group efficiency of frictional piles in granular soils. This method was based on consideration of the shear around the perimeter of the group defined by the plan dimensions and the bearing capacity of the block dimension at the points. However, the analysis presented in the study was based on frictional resistance of piles combine to point load. [7].

Ahmadi, M. M. (2016) presented that stiffness of the pile cap also confirmed that it influence significantly the distribution of the structural loads to the individual piles. The results from numerical analysis and full-scale field test were presented to analyze the group efficiency of pile [8].

Elsamny, M. K. et al (2017) investigated the bearing capacity and behavior of piles in sand for single pile and group of two piles. An experimental research program was conducted to study the distribution of the friction along the pile shaft and the load to be transferred by the tip of the pile in cohesionless soil as well as the group effect of two piles. The experimental program consisted of testing single and group of two piles in sand under axial compression load. The spacing between piles was three pile diameters. The program consisted of installing test piles in dense sand placed in a soil chamber. The calculated pile group efficiency was 1.43 [9].

However, the purpose of the present study is to investigate the effect of number of piles in pile groups on the settlement and group efficiency.

2. EXPERIMENTAL PROGRAM

The experimental research program was conducted to study the effect of number of piles on the pile groups settlement and efficiency in cohesionless soil. The settlement of single pile and groups of pile groups were measured. In addition, the piles were instrumented by five strain gauges along the steel reinforcement. Furthermore, the piles were tested in a setup under compressive axial loads. The pile head loads, displacement, strains along the piles as well as loads at the pile tip were measured simultaneously. The program consisted of installing test piles in dense compacted sand placed in a soil chamber subjected to compressive axial loads. The sand was placed and compacted in fifteen centimeters layers using mechanical compactor. The densities of the compacted sand were measured by sand cone tests from which the angle of internal friction was determined. The average of the angle of internal friction was found to be 36. In total, four load tests were performed in axial compression. First load test was carried out on single pile while the second, third and fourth loading tests were carried out on pile groups of two, three and four piles. The load capacities of the piles were established. In addition, the loads at pile tips were measured by load cells.

The test program was carried out on the followings:

- Group (1) – Single pile
- Group (2) – Group of two piles
- Group (3) – Group of three piles
- Group (4) – Group of four piles

2.1. Pile Characteristics

The followings are the used materials, concrete dimensions and reinforcement details:

2.1.1. Used Material

a. Yellowish graded sand has been used as fine aggregate in concrete mix design.

b. The coarse aggregate used in the concrete mix was crushed stone having sub-angular particle shape.

c. The ordinary Portland cement was used for all experimental work. The cement conform the specification for Portland Cement BS EN 197-1-CEM 42.4N.

d. Clean drinking fresh water free from impurities was used for mixing and curing the specimens.

e. Hot rolled deformed reinforcement steel was used as reinforcement for the specimens.

f. The average nominal cube strength was found to be 2.00 kN/cm^2

2.1.2. Concrete Dimensions and Reinforcement Details

A total of ten precast concrete cylindrical piles with (150) mm outside diameter and (1500) mm length were casted. Pile concrete dimensions and reinforcement details are shown in Figs. [1] to [4] for single pile, group of two piles, group of three piles and group of four piles respectively.

2.1.3. Strain Gauges

The strain gauges were mounted on the steel reinforcement as shown in Fig. [5] for internal measurements. The strain gauges used were manufactured by TOKYO SOKKI KENKYUJO CO. LYD and were. The type used was PFL-30-11-3L, which has a resistance of 120.4 ± 0.5nd % Ohms at 11ºC, and a gauge factor of 2.13 ± 1.0%. The strain gauges wires, extending to ground level, were connected to a strain indicator. The instrumentation was carried out to determine the axial load transfer along the piles during the tests.

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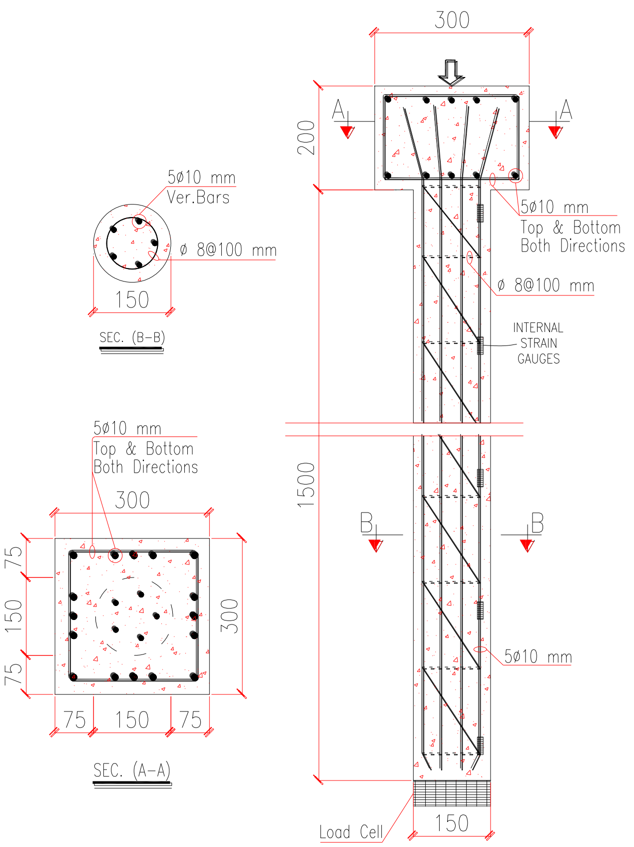

Fig. [1] Concrete Dimension and Reinforcement for Group (1) – Single Pile

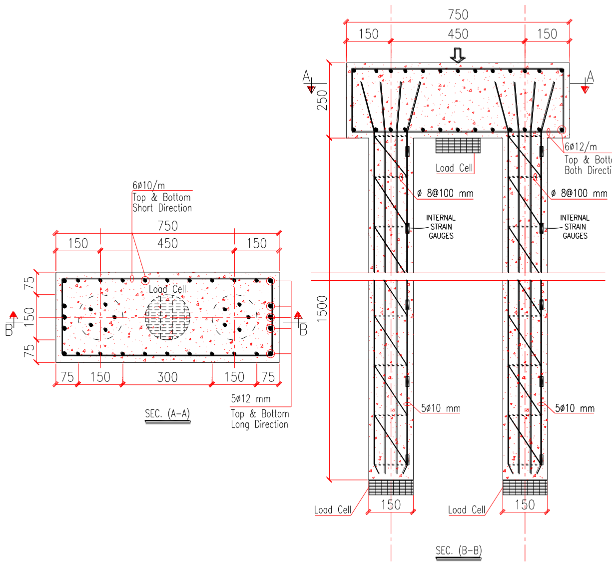

Fig. [2] Concrete Dimension and Reinforcement for Group (2) – Group of Two Piles

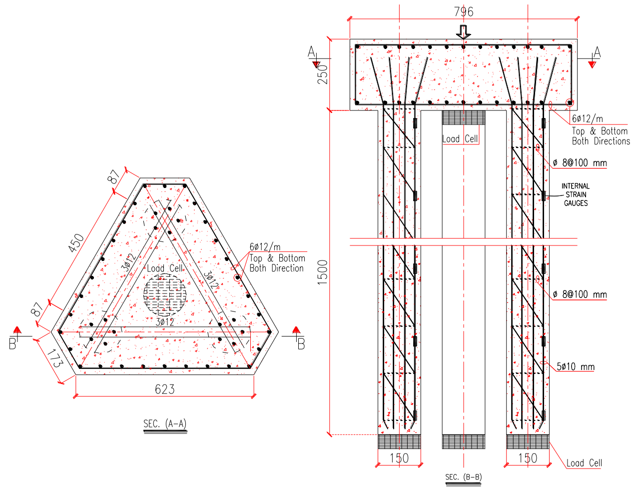

Fig. [3] Concrete Dimension and Reinforcement for Group (3) – Group of Three Piles

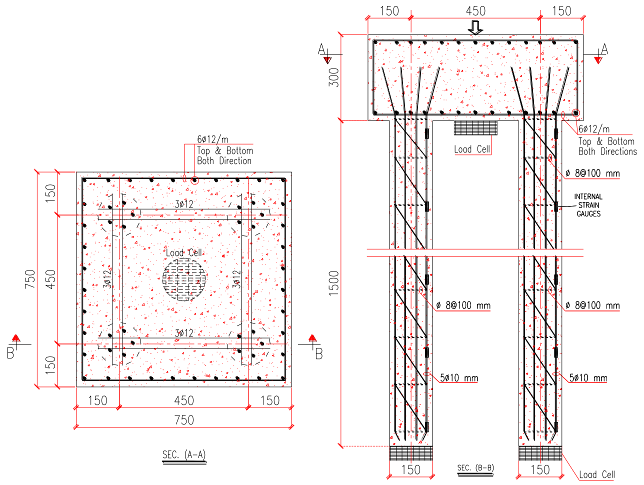

Fig. [4] Concrete Dimension and Reinforcement for Group (4) – Four Piles

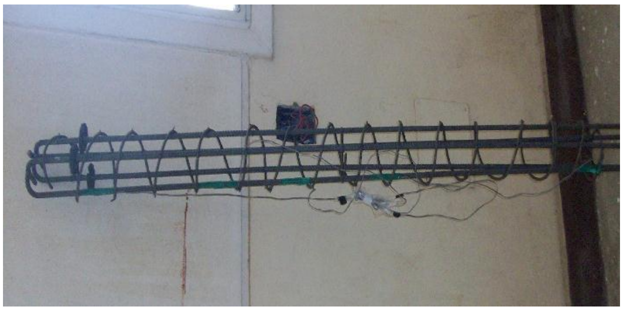

Fig. [5] Internal Strain Gauges

2.1.4. Casting of Piles

All specimens were casted in cylindrical tubes (forms) shown in Fig. [6]. A mechanical vibrator was used as shown in Fig. [7]. Pile forms were removed and pile specimens were cured.

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Fig. [6] Description of Forms

Fig. [7] Casting of Piles

3. PREDICTION OF ULTIMATE PILE LOAD FROM THEORETICAL APPROACHES

The ultimate load for single pile calculated in this study was determined by different theoretical approaches, Table [1] summaries the calculated ultimate capacities for single pile.

Table [1] Ultimate Single Pile Loads from Theoretical Approaches

Method	Ult. load -single pile (kN)
Egyptian Code (2001)	30.00
Meyerhof (1976)	29.00
Vesic (1977)	25.00
Janbu (1976)	39.00
Coyle and Castello (1981)	25.00

4. TESTING SETUP AND PROCEDURE

The pile specimens were divided as follows:

Single pile denoted as group (1) and was axially loaded. The pile groups of two, three and four piles were also axially loaded and denoted as group (2), group (3) and group (4) respectively. All pile groups were loaded up to 1.50 time's ultimate load according to the Egyptian Code, 2001 static formula. In the present study each of single pile and pile groups of two, three and four piles were loaded in 12 increments according to the Egyptian Code, 2001. Each increment was maintained for a certain time a shown in Table [2]. The measurements of load at top of pile were recorded using jack load gauge at the top. Dial gauges readings were taken for each loading increment for settlement measurement. However, load cells were placed at the tip of piles and underneath the pile cap to measure the transferred load. In addition, strains readings along pile shaft were recorded. Table [3] represents the experimental program and the theoretical calculated ultimate loads values from different theoretical methods for single pile and pile groups of two, three and four piles.

Table [2] Increment of Load and Minimum Interval Time for Each according To Egyptian Code (2001) for Tested Pile Groups

	Load %	Time
Loading	25	1.00 hr
	50	1.00 hr
	75	1.00 hr
	100	3.00 hrs
	125	3.00 hrs
	150	12.00 hrs
	Load %	Time
Unloading	125	15 min.
	100	15 min.
	75	15 min.
	50	15 min.
	25	15 min.
	0	4.00 hrs

4.1. Loading Frame

Loading frame was manufactured to resist the expected maximum loads that might occur during the test as shown in Fig. [8].

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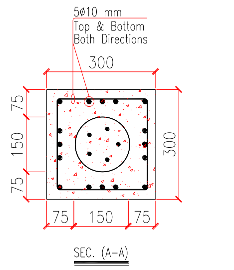
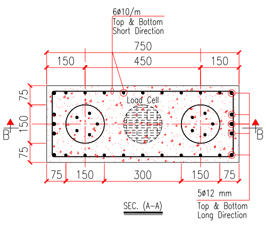
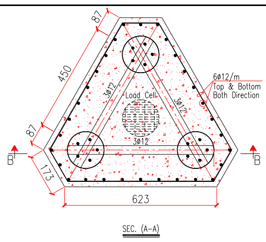
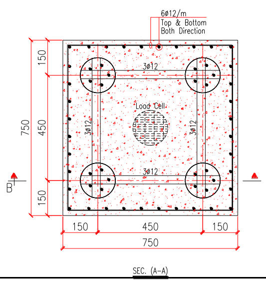
4.2. Loading Jack

The testing load was applied using a 1000 kN hydraulic jack located at the top of the tested pile or piles group as shown in Fig. [9].

Table [3] Theoretical Calculated ultimate loads Values from Different Methods

Group	Pile Arrangement	Q_{ult} (theoretical) (kN)				
		(1)	(2)	(3)	(4)	(5)
Group (1)		30	29	25	39	25
Group (2)		60	58	50	78	50
Group (3)		90	87	75	117	75
Group (4)		120	116	100	156	100

Where:

(1) Egyptian Code (2001), [10]
(2) Meyerhof (1976), [11]
(3) Vesic (1977), [12]
(4) Janbu (1976), [13]
(5) Coyle and Castello (1981), [14]

Fig. [8] Loading Frame

Figure [9] Loading Jack

4.3. LOAD AND SETTLEMENT MEASUREMENTS

The load was measured at the tip of piles and underneath the pile caps by an 800 kN load cells connected to the data acquisition system as shown in Figs. [10], [11]. In addition, the load was measured by the loading jack.

4.3.1 group (1) – single pile

The vertical alignment has been done as shown in Fig. [12]

The pile was embedded in the sand such that the total embedment depth of the pile was 1500 mm after filling the soil chamber with 150 mm compacted layers of sand using mechanical compactor as shown in Fig. [13]. Moreover, the vertical displacements of the pile cap were measured by four dial gauges with accuracy of 0.01 mm as shown in Fig. [14].

Fig. [10] Load Cell

Fig. [11] Data Acquisition System

Fig. [12] Vertical Alignment of the Pile for Group (1) – Single Pile

Fig. [13] Placing Compacted Soil around Tested Pile for group (1) – Single Pile

Fig. [14] Loading Jack and Dial Gauges Setup for Group (1) – Single Pile

4.3.2 GROUP (2) – GROUP OF TWO PILES

The vertical alignment has been done as shown in Fig. [15]

The piles were embedded in the sand such that the total embedment depth of the piles was 1500 mm after filling the soil chamber with 150 mm compacted layers of sand using mechanical compactor as shown in Fig. [16]. Moreover, the vertical displacements of the pile cap were measured by six dial gauges with accuracy of 0.01 mm as shown in Fig. [17].

Fig. [15] Vertical Alignment of Piles for Group (2) – Group of Two Piles

Fig. [16] Placing Compacted Soil around Tested Pile Groups for group (2) – Group of Two Piles

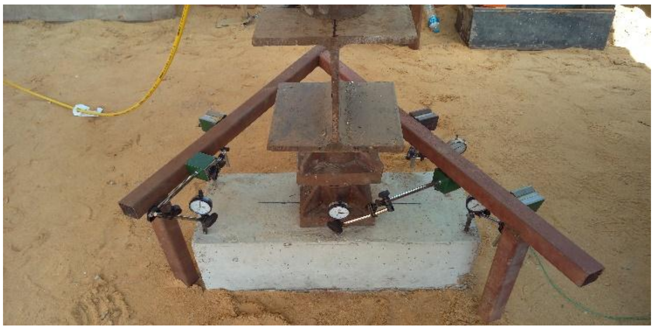


Fig. [17] Loading Jack and Dial Gauges Setup for Group (2) – Group of Two Piles

4.3.3 Group (3) – Group of Three Piles

The vertical alignment has been done as shown in Fig. [18]

The piles were embedded in the sand such that the total embedment depth of the piles was 1500 mm after filling the soil chamber with 150 mm compacted layers of sand using mechanical compactor as shown in Fig. [19]. Moreover, the vertical displacements of the pile cap were measured by six dial gauges with accuracy of 0.01 mm as shown in Fig. [20].

Fig. [18] Vertical Alignment of the Piles for Group (3) – Group of Three Piles

Fig. [19] Placing Compacted Soil around Tested Pile Groups for group (3) – Group of Three Piles

Fig. [20] Loading Jack and Dial Gauges Setup for Group (3) – Group of Three Piles

4.3.4 Group (4) – Group of Four Piles

The vertical alignment has been done as shown in Fig. [21]

The piles were embedded in the sand such that the total embedment depth of the piles was 1500 mm after filling the soil chamber with 150 mm compacted layers of sand using mechanical compactor as shown in Fig. [22]. Moreover, the vertical displacements of the pile cap were measured by six dial gauges with accuracy of 0.01 mm as shown in Fig. [23].

Fig. [21] Vertical Alignment of the Piles for Group (4) – Group of Four Piles

Fig. [22] Placing Compacted Soil around Tested Pile Groups for group (4) – Group of Four Piles

Fig. [23] Loading Jack and Dial Gauges Setup for Group (4) – Group of Four Piles

5. ULTIMATE CAPACITY DETERMINATION OF PILES

Modified Chin Method (1970) has been used for ultimate pile capacity determination as follows: [15]

i. The relation between settlement and the ratio of settlement to the applied load has been drawn as straight line.

ii. The ultimate load is obtained from the slope of the straight line by the following relationship:

$$Q_{ult} = \frac{1}{1.2b}$$

Where: Q_{ult} = Ultimate capacity of piles (kN)

b = Slope of straight line (relation between Δ and (Δ /Q).

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Δ = Measured settlement increment.

Q = Load increment.

6. EXPERIMENTAL TEST RESULTS

The followings test results were obtained:

i. The ultimate capacities of pile and pile groups were determined by the Modified Chin method (1970) from load settlement readings. The ultimate capacities were obtained from the slope of the straight line as shown in Figs. [24], [25], [27] and [28] for single pile, group of two piles, group of three piles and group of four piles respectively. The obtained ultimate bearing capacities values by Modified Chin Method for all groups as well as for single pile inside the groups are listed in Table [4].

ii.

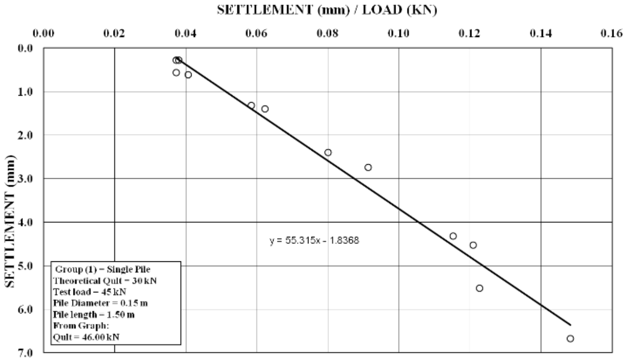

Fig. [24] Determining the Ultimate Load by Modified Chin method (1970) for Group (1) - Single Pile

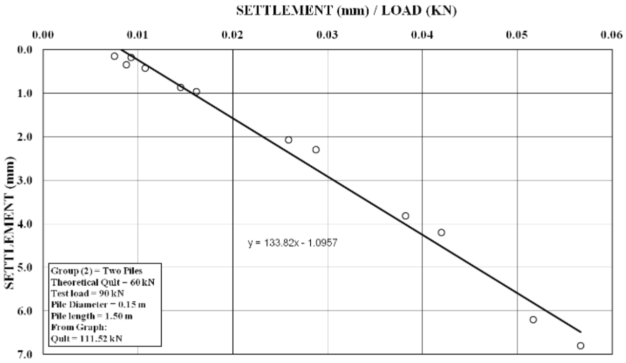

Fig. [25] Determining the Ultimate Load by Modified Chin method (1970) for Group (2) – Group of Two Piles

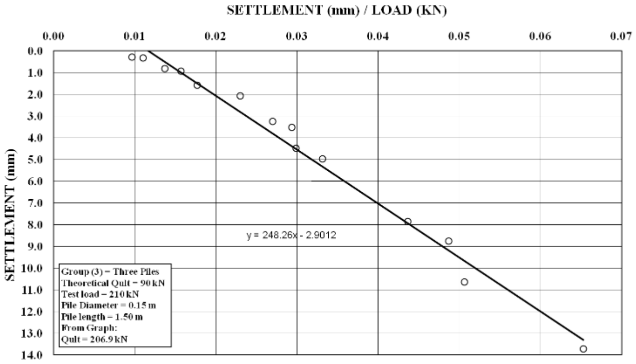

Fig. [26] Determining the Ultimate Load by Modified Chin method (1970) for Group (3) – Group of Three Piles

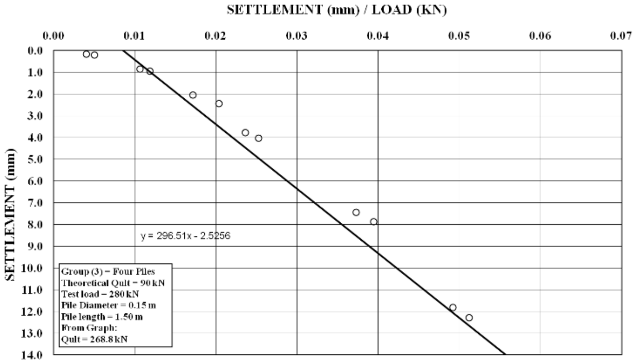

Fig. [27] Determining the Ultimate Load by Modified Chin method (1970) for Group (4) – Group of Four Piles

Table [4] Ultimate Pile Capacities obtained from Load Test by Modified Chin Method (1970)

Group	$Q_{ult-group}$ (kN)	Q_{ult} for single pile inside the group (kN)
Group (1) – single pile	45.59	45.59
Group (2) – group of two piles	114.00	57.00
Group (3) – group of three piles	198.40	66.13
Group (4) – group of four piles	268.80	67.20

6.1. Determination Of Ultimate Capacity Of Single Pile And Pile Groups

The ultimate capacities for single pile and pile groups were determined by Modified Chin Method (1970) and are listed in Table [4]. The relationship between numbers of piles and ultimate capacity for single pile from group (1) and single pile inside groups (2, 3 and 4) is shown in Figs. [28], [29].

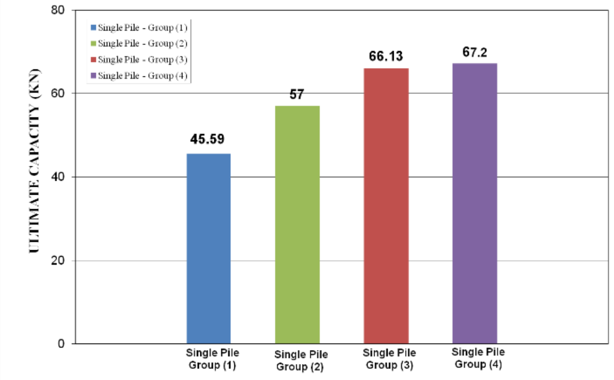

Fig. [28] Ultimate Capacities by Modified Chin method (1970) for Single Pile for group (1) and single pile inside groups (2, 3 and 4)

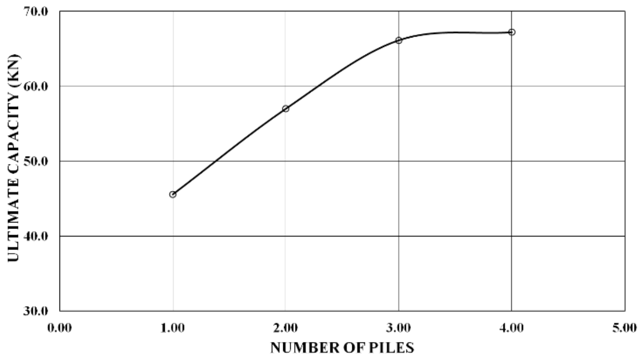

Fig. [29] The Relationship between Numbers of Piles and Ultimate Capacity for Single Pile from Group (1) and Single Pile Inside Groups (2, 3 And 4)

6.2. Determination of Settlement Of Single Pile And Pile Groups

The relationship between number of piles and settlement at the ultimate capacity for single pile and pile groups is shown in Figs. [30], [31].

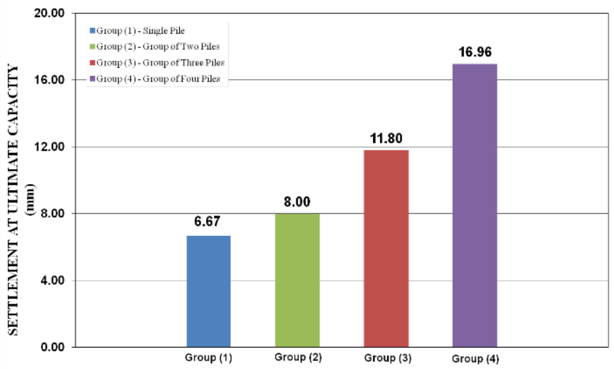

Fig. [30] Settlement by Modified Chin method (1970) at Ultimate Capacity for Single Pile for group (1) and single pile inside groups (2, 3 and 4)

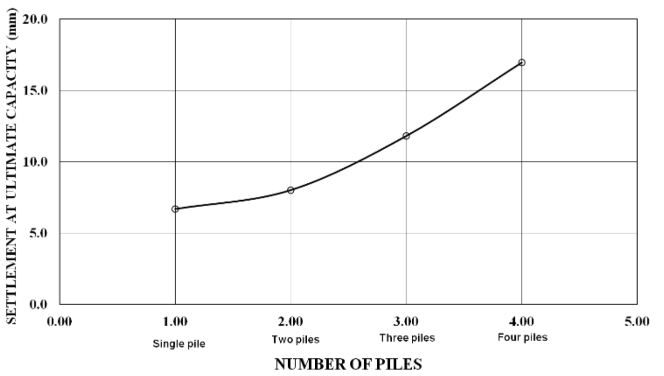

Fig. [31] The relationship between Number of Piles and Settlement for Single Pile and Single Pile inside Pile groups (2, 3 and 4) as by Modified Chin Method (1970)

6.3. Determination Of Pile Group Efficiency

The efficiencies of pile groups at ultimate capacities were determined and the relationship between numbers of piles and efficiency of pile groups is shown in Figs. [32], [33].

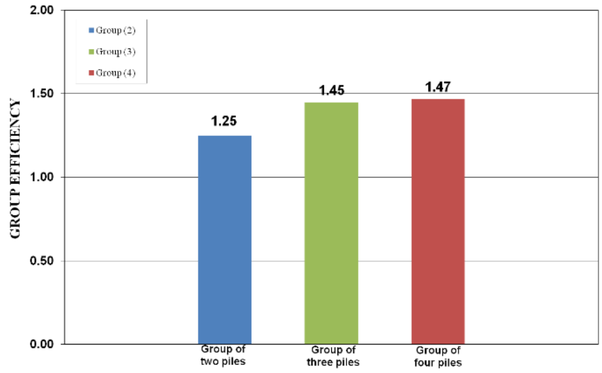

Fig. [32] Group Efficiency

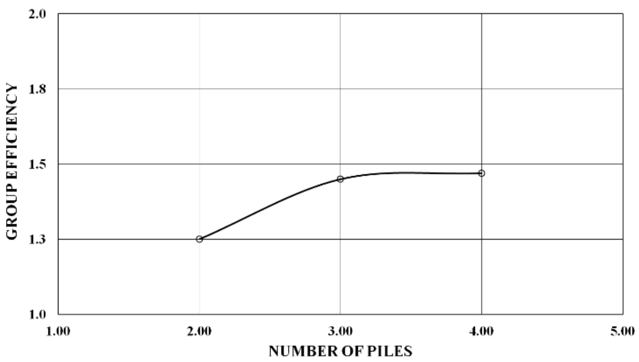

Fig. [33] The relationship between Number of Piles and Group Efficiency for Pile Groups (2, 3 and 4)

7. CONCLUSIONS

From the present study, the followings conclusions are obtained:

i. The ultimate capacity for single pile inside the group increases with increasing the number of piles.

ii. For groups of piles (2, 3 and 4), the settlement at ultimate capacity increases with increasing the number of piles.

iii. Group efficiency of pile groups (2, 3 and 4) piles increases with increasing the number of piles. However, for number of piles in pile groups more than four no significant change has been obtained.

iv. The group efficiency was found to be ranging from 1.25 to 1.47 as by using Modified Chin method (1970) for the determination of the ultimate capacity of piles.

v. It was found that the settlement of pile groups is greater than of single pile at the ultimate capacity. However, this confirms Tomlinson, M. and Woodward, J. (2008) explanation.

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