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Experimental Evaluation of Bearing Capacity and Behaviour of Single Pile and Pile Group in Cohesionless Soil

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***Abstract*— Determination of bearing capacity of piles is a complex geotechnical task. Piles are designed to be able to carry and transfer the loads of the structure to the deeper hard strata located at some depth below the ground surface. The purpose of the present study is to investigate 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. However, 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, and subjecting them to compressive axial load. In total, two load tests were performed in axial compression. First load test was carried out on single pile while the second loading test was carried out to study the group effect of two piles. The pile head loads, displacement, strains along the piles shaft as well as the pile tip were measured simultaneously. Furthermore, the load under pile cap transferred directly to soil through pile cap has been determined. The obtained results indicated that for single pile 86% of the applied load is carried out by side friction of pile and 14% by tip resistance. In addition, it was found that for group of two piles 96 % of the applied load is carried out by friction and 4 % by tip resistance. However, the group efficiency is found to be 1.43**

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

1. INTRODUCTION

Piles are designed to carry and transfer the loads of the structure to the bearing soil strata or rock located at some depth below the ground surface. The behavior of pile groups, however, is more complex and has not been adequately examined. To verify the true load carrying capacity, in-situ pile load tests are replied on.

Altaee, A., et al. (1993) analyzes the results from a static loading test on 11.0 m long piles. The test piles were square, nominally 285 mm diameter precast concrete piles. When loading the pile, the stress path followed by the soil along the pile shaft is that of simple shear, constant volume deformation. The analysis indicates that the critical-depth concept is not valid. When the residual loads were removed from the analyses, the distribution of both shaft and toe resistances are similar to that reported from full-scale pile tests supporting the critical-depth concept [1].

Liew, S. S., et al (2000) introduced two instrumented test piles installed and loaded at the site to verify the design of the bored pile foundation. Vibrating wire strain gauges and extensometers were installed in the test piles to reveal the load transfer behavior along the pile. The two test piles were installed at different subsoil conditions, in which the first pile is a rock socketted pile whereas the second pile is a soil friction pile [2].

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 and compression on two pile groups each consisting of five piles. The spacing of the piles in the groups was two and three-pile diameters. Test results on single pile indicated that 70% of the ultimate load was transmitted in side friction that was uniform along the pile shafts. The calculated pile group efficiencies were 1.22 and 1.93 for a pile spacing of two and three-pile diameters, respectively [3].

Omer, J. R., et al. (2002) presented a full-scale pile testing carried out to assess whether the proposed design methods would meet the required load capacity and settlement criteria for the working piles. Five fully instrumented large diameter bored cast in situ piles, up to 30 m deep, were installed in weathered mudstone and tested under vertical loading. The results of the pile tests revealed that the calculation methods for shaft and base capacity suggested in the site investigation report are reasonably consistent but too conservative. Also, seven existing load capacity calculation methods were applied to the test piles and found to be relatively unreliable [4].

Kim, M. G., et al (2004) presented the load settlement and load distribution behaviors of single ACIP (Augured Cast-In-Place) pile tipped in dense sand layer. The ACIP test pile was instrumented along the pile length with sixteen vibrating wire sister bars and subjected to axial load test in order to investigate the load-settlement and distribution behaviors [5].

Kai, L. S., et al. (2006) presented that the load distribution along the shaft and at the base was normally derived from computations based on the measured changes in strain gauge readings and pile properties [6].

Ali, F. H., et al (2008) introduced the use of strain gauges normally used to monitor the compression of pile during static pile load test. The method also has the ability to monitor loads

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and displacements at various levels along the pile shaft and toe of instrumented piles [7].

Abd-Samee, W. N. (2012) performed analysis for field pile load test data to estimate the ultimate load for friction piles. The analysis was based on three pile load test results. The tests were conducted at the site of The Cultural and Recreational Complex project in Port Said, Egypt. Three pile load tests were performed on bored piles of 900 mm diameter and 50 m length [8].

Singh P. K., et al (2014) studied the load settlement characteristics of rectangular, square and circular pile groups under axial load conditions. The behaviors of thirteen pile groups were studied. The spacing of piles at the bottom of pile cap was kept 2.5d in each case where d is diameter of the pile. The piles were arranged in planes perpendicular to the direction of load and were symmetrical. Tests were conducted in laboratory under controlled density conditions using dry, clean, uniform sand. Only deflections at ground level were measured [9].

Plaban, Deb., et al (2016) investigated the behavior of single and group pile in multiple layered soils. 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 were conducted. The model piles used for the test were 250 mm in length with 25mm diameter and a test tank of dimension 700mm × 700mm × 600mm was used. 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 [10].

However, the purpose of the present study is to investigate the pile axial load in sand for single pile and group of two piles. The load-settlement characteristics of single and of group of piles were determined with the same embedded lengths of piles.

2. EXPERIMENTAL PROGRAM

The experimental research program was conducted to study the distribution of the friction along the pile shaft and the load transferred by the tip of the pile in cohesionless soil and the group effect of two piles. The piles were instrumented by five strain gauges along the steel reinforcement. 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. Furthermore, the load underneath pile cap transferred directly to soil through pile cap was measured. The program consisted of installing test piles in dense sand placed in a soil chamber, and subjecting them 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, two load tests were performed in axial compression. First load test was carried out on single pile while the second loading test was carried out to study the group efficiency of the two piles. The load capacity of the piles was established and the load distribution and reaction of the surrounding sand along their walls were determined at various depths. In addition, the loads at pile tip and underneath the pile cap were measured by load cells.

The test program was carried out on the followings:

- Group (1) – Single pile
- Group (2) – Two piles

2.1. Pile Characteristics

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

2.1.1. *Used Material*

a. Yellowish brown 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 three 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] and [2] for single pile and pile group of two piles respectively.

2.1.3. Strain Gauges

The strain gauges were mounted on the steel reinforcement as shown in Fig. [3] 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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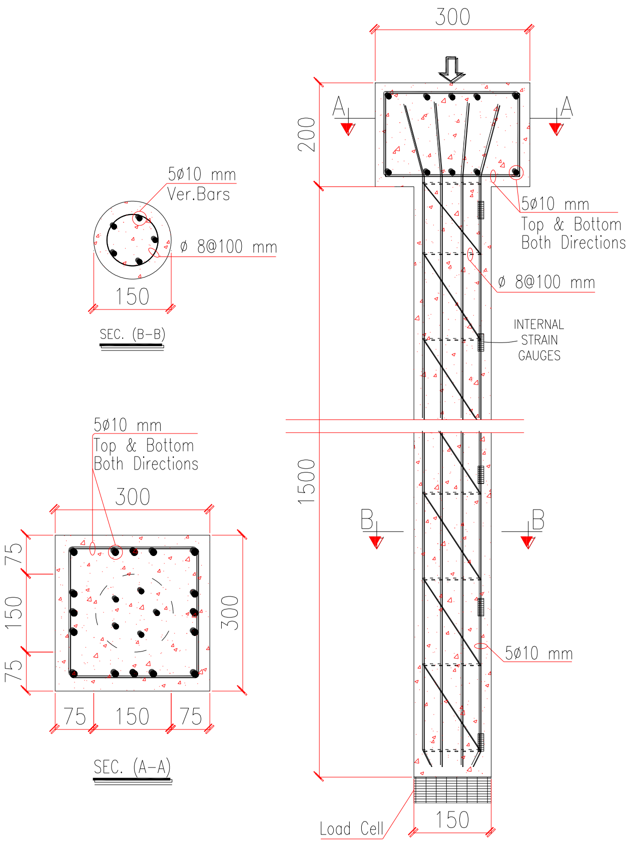


Fig. [1] Concrete Dimension and Reinforcement for Group (1) – Single Pile

2.1.4. Casting of Piles

All specimens were casted in cylindrical tubes (forms) shown in Fig. [4] and a mechanical vibrator was used as shown in Fig. [5]. Pile forms were removed and pile specimens were cured.

Fig. [4] Description of Forms

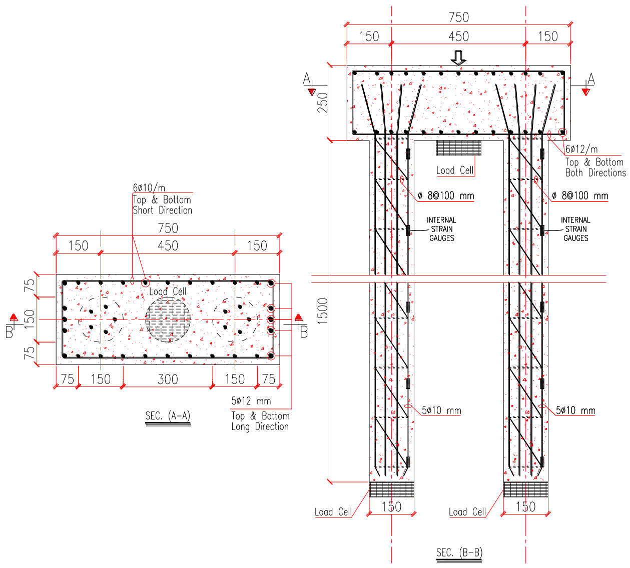


Fig. [2] Concrete Dimension and Reinforcement for Group (2) – Two Piles

Fig. [3] Internal Strain Gauges

Fig. [5] Casting of Piles

3. PREDICTION OF ULTIMATE PILE LOAD FROM THEORETICAL APPROACHES

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

Table [1] Ultimate Single Pile Loads from Theoretical Approaches

Design Method	Ultimate load (kN)
Egyptian Code (2001)	30.00
Meyerhof (1976)	28.90
Vesic (1977)	25.00
Janbu (1976)	39.30
Coyle and Castello (1981)	25.00

4. TESTING SETUP AND PROCEDURE

The pile specimens were divided into two categories:

The first category is single pile that denoted as group (1) and was axially loaded. The second category is pile group of two were axially loaded that denoted as group (2). Single pile was 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 group of two piles were loaded in 12 increments according to the Egyptian Code, 2001. Each increment was maintained for a certain time a shown in Tables [2], [3]. 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 along pile shaft were recorded. Table [4] represents the theoretical calculated ultimate loads values from different theoretical methods for single pile and group of two piles.

Table [2] Increment of Load and Minimum Interval Time for Each according To Egyptian Code (2001) for Group (1) - Single Pile

	Load %	Time	Load (kN)
Loading	25	1.00 hr	7.50
	50	1.00 hr	15.00
	75	1.00 hr	22.50
	100	3.00 hrs	30.00
	125	3.00 hrs	37.50
	150	12.00 hrs	45.00
Unloading	Load %	Time	Load (kN)
	125	15 min.	37.50
	100	15 min.	30.00
	75	15 min.	22.50
	50	15 min.	15.00
	25	15 min.	7.50
	0	4.00 hrs	0.00

Table [3] Increment of Load and Minimum Interval Time for Each according To Egyptian Code (2001) for Group (2) –two Piles

	Load %	Time	Load (kN)
Loading	25	1.00 hr	20.00
	50	1.00 hr	40.00
	75	1.00 hr	60.00
	100	3.00 hrs	80.00
	125	3.00 hrs	100.00
	150	12.00 hrs	120.00
Unloading	Load %	Time	Load (kN)
	125	15 min.	100.00
	100	15 min.	80.00
	75	15 min.	60.00
	50	15 min.	40.00
	25	15 min.	20.00
	0	4.00 hrs	0.00

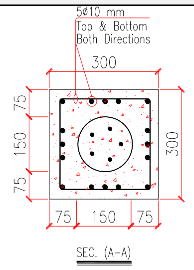
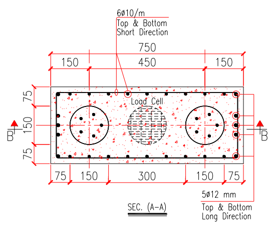
4.1. Loading Frame

Loading frame was manufactured to resist the expected maximum loads that might occur during the test as shown in Fig. [6].

4.2. Loading Jack

The testing load was applied using a 300 kN hydraulic jack located at the top of the tested pile or piles group as shown in Fig. [7].

Table [4] 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

Where:

(1) Egyptian Code (2001)
(2) Meyerhof (1976)
(3) Vesic (1977)
(4) Janbu (1976)
(5) Coyle and Castello (1981

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Fig. [6] Loading Frame

Figure [7] Loading Jack

4.3. Load and Settlement Measurements

The load was measured at the tip of piles and underneath the cap by an 800 kN load cells connected to the data acquisition system as shown in Figs. [8], [9].

The piles were slightly embedded in the sand such that the total embedment depth of the piles were 1500 mm after filling the soil chamber with 150 mm compacted layers of sand using mechanical compactor as shown in Figs. [10], [11] taking into consideration centric vertical alignment a shown in Figs. [12], [13].

The vertical displacements of each pile (pile cap) were measured by four dial gauges in case of single pile loading test and six dial gauges in case of group of two piles with accuracy of 0.01 mm as shown in Figs. [14], [15]

Fig. [8] Load Cell

Fig. [9] Data Acquisition System

Fig. [10] Placing Soil around Tested Pile for group (1) - Single Pile

Fig. [11] Placing Soil around Tested Pile for group (2) – Group of Two Piles

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

Fig. [13] Vertical Alignment of the Pile for Group (2) – Group of Two Piles

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

Fig. [15] Reference Beams and Dial Gauges Setup for Group (2) – Group of Two Piles

5. EXPERIMENTAL TEST RESULTS

The followings were obtained:

i. For single pile, the ultimate load was determined by the slope tangent method from load settlement readings at the point of intersection of the initial and final tangents of the load settlement curve. This point is marked in Fig. [16] for single pile by a vertical arrow at a load of 28 kN. As well as, the ultimate load was determined by Modified Chin method 1970 as shown in Fig. [17], Brinch Hansen method (1963) as shown in Fig. [18] and Buttler & Hoy tangent method as shown in Fig. [19]. The obtained ultimate bearing capacities values by different methods for group (1) – single pile are listed in Table [5].

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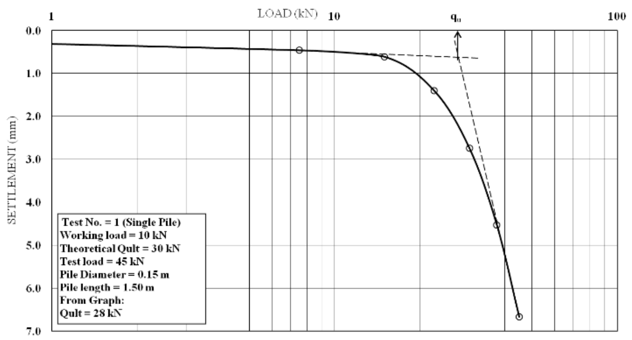

Fig. [16] Determining the Ultimate Load by Tangent method for Group (1) - Single Pile

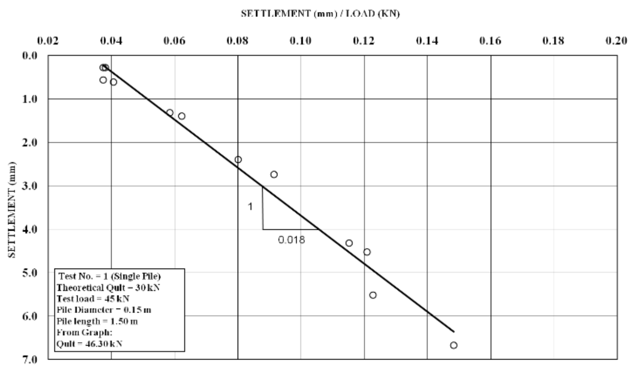

Fig. [17] Determining the Ultimate Load by Modified Chin Method, for Group (1) - Single Pile

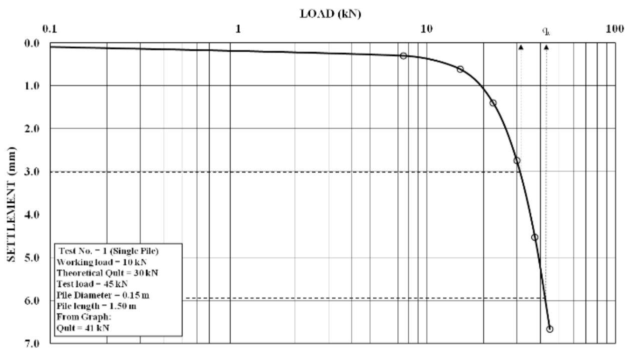

Fig. [18] Determining the Ultimate Load by Brinch Hansen Method (1963), for Group (1) - Single Pile

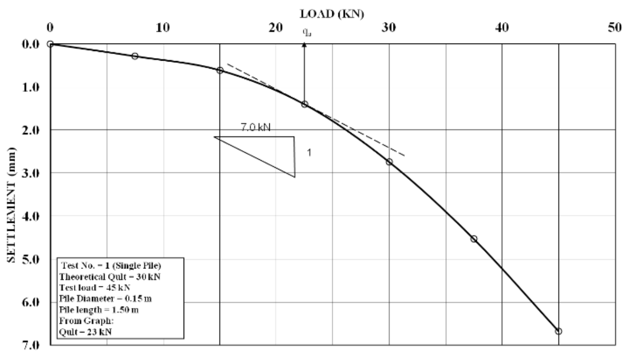

Fig. [19] Determining the Ultimate Load by Butler and Hoy Tangent method, for Group (1) - Single Pile

Table [5] Ultimate Pile Loads obtained from Load Test by different Methods

Design Method	Ultimate load (kN)
Tangent Method	28.00
Modified Chin Method	46.30
Brinch Hansen (1963)	41.00
Buttler and Hoy Method	23.00

ii. For single pile the distributions of load at pile tip measured from load cell and along pile shaft measured from strain gauges were as shown in Fig. [20]. The base resistance measured by the load cell at the ultimate load (28.0 kN) is found to be 3.85 kN. This indicates that 86 % of the pile ultimate capacity was transmitted by friction and 14 % by base resistance. Fig. [21] shows the relationship between load at pile head and the percentage of load transferred to pile tip measured by load cell for single pile.

iii. For the group of two piles the ultimate load was determined by the slope tangent method from load settlement readings. Fig. [22] shows the relationship between load and settlement for group of two piles and single pile from group of two piles. The obtained ultimate load of the pile group of two piles was 83 kN. However, the ultimate load determined by Tangent method is shown in Fig. [23] and by Modified Chin method 1970 is shown in Fig. [24]. However, the ultimate load determined by Brinch Hansen method (1963) is shown in Fig. [25] and by Buttler & Hoy tangent method is shown in Fig. [26]. The obtained ultimate bearing capacities by different methods for group (2) – group of two piles are listed in Table [6].

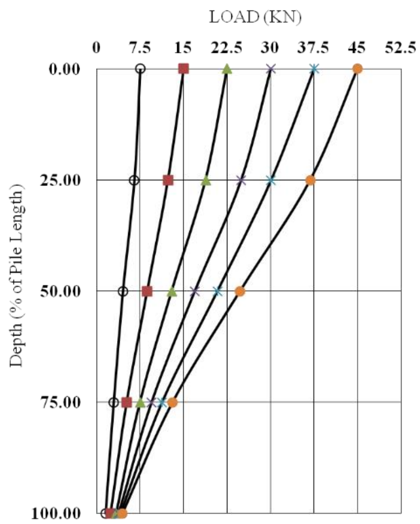

Fig. [20] Distribution of Load at Pile tip From Load Cell and along Pile Shaft Measured from Strain Gauges (Group (1) - Single Pile)

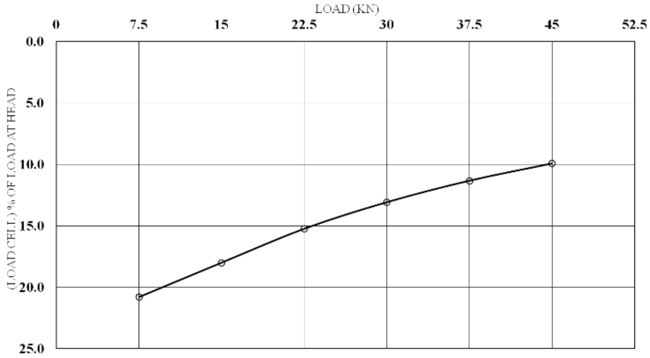

Fig. [21] Percentage of Load Transferred To Pile Tip Compared With Applied Load at Pile Head from Load Cell Unit, Group (1) – Single Pile

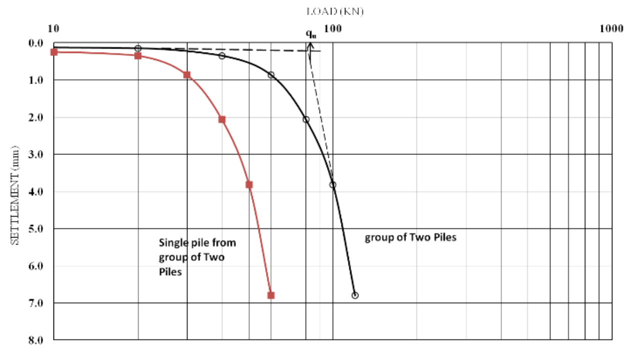

Fig. [22] The Ultimate Load by Tangent Method for Group (2) – Two Piles and Single from Group of Two Piles

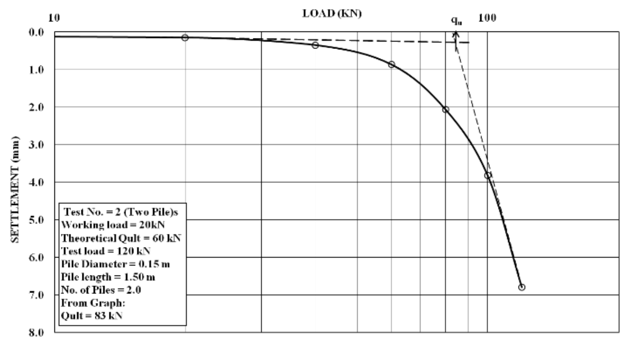

Fig. [23] Determining the Ultimate Load by Tangent method for Group (2) – Two Piles

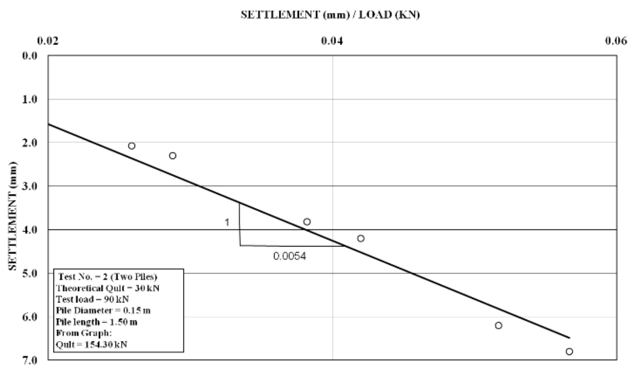

Fig. [24] Determining the Ultimate Load by Modified Chin Method, for Group (2) –Two Piles

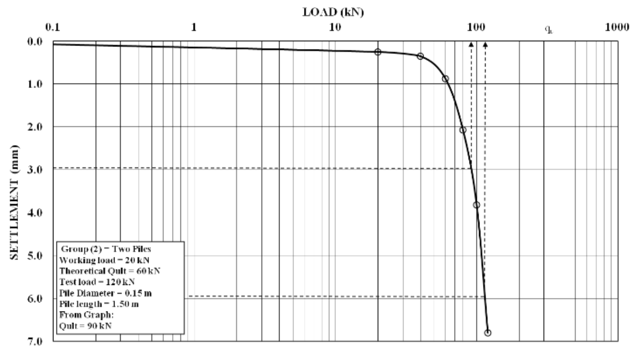

Fig. [25] Determining the Ultimate Load by Brinch Hansen Method (1963) for Group (2) –Two Piles

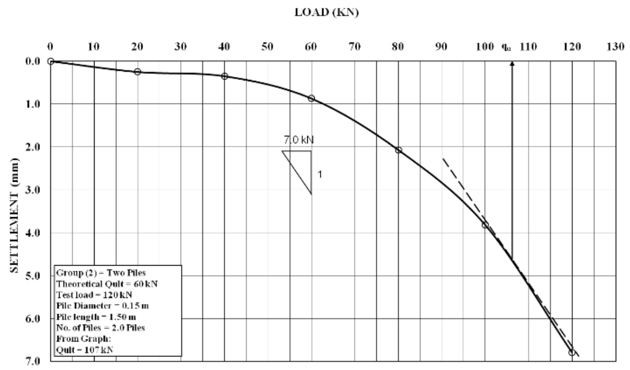

Fig. [26] Determining the Ultimate Load by Butler and Hoy Tangent Method for Group (2) –Two Piles

Table [6] Ultimate Pile Loads Determinated from Load Test by different Method

Design Method	Ultimate load (kN)
Tangent Method	83.00
Modified Chin Method	154.30
Brinch Hansen (1963)	90.00
Buttler and Hoy Method	107.00

iv. For the group of two piles the distribution of load at pile tip from load cell and along pile shaft measured from strain gauges were shown in Fig. [27]. The base resistance measured by load cell at the ultimate load (83.0 kN) was found to be 3.22 kN. This indicates that 96 % of the capacity was transmitted by friction and 4 % was transmitted by base resistance. Fig. [28] shows the relationship between load at pile head and the percentage of load transferred to pile tip measured by load cell.

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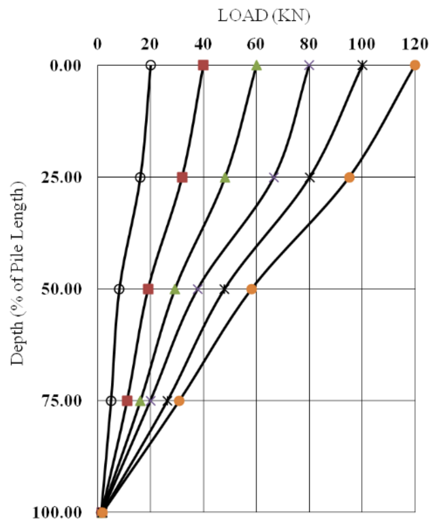

Fig. [27] Distribution of Load at Pile tip From Load Cell and along Pile Shaft Measured from Strain Gauges (Group (2) - Two Piles)

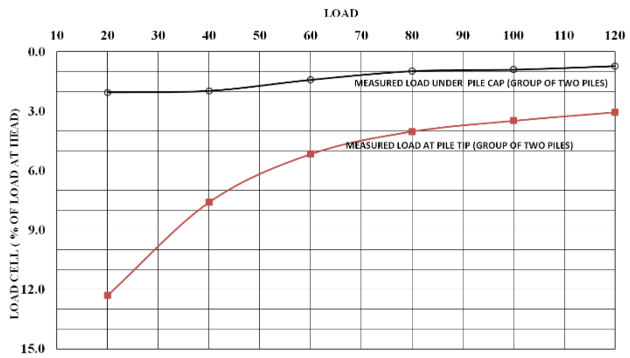

Fig. [28] Percentage of Load Transferred To Piles Tip Compared With Applied Load at Piles Head from Load Cell Unit, Group (2) – Two Piles

v. Fig. [29] shows the relationship between load and settlement for single pile for (group (1)) as well as for group of two piles load. However, the ultimate bearing capacities have been determined by tangent – tangent method.

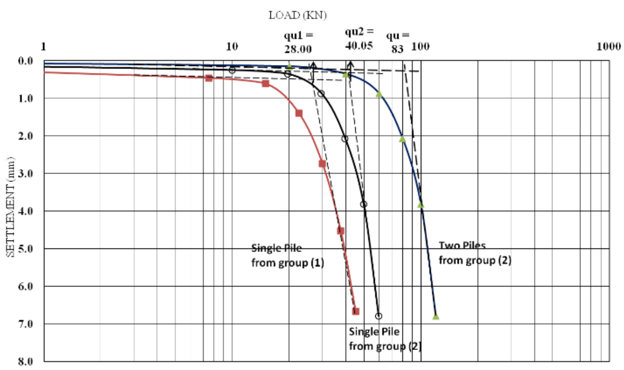

Fig. [29] Comparison between Piles Ultimate Loads for Single Pile from Group (1), Single Pile Load from Group (2) and Total Ultimate Load from Group (2)

vi. For single pile Fig. [30] shows the relationship between the load transmitted by end bearing and side friction as well as the total carrying capacity.

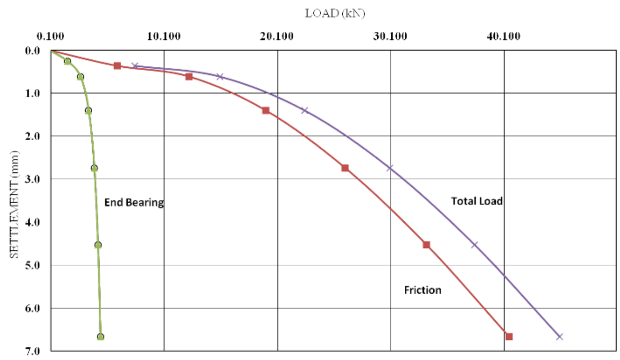

Fig. [30] The Relationship between Total Load Transmitted by Friction, End Bearing and Settlement for Group (1) – Single Pile

vii. For group of two piles Fig. [31] shows the relationship between the load transmitted by end bearing and side friction as well as the total carrying capacity for group of two piles.

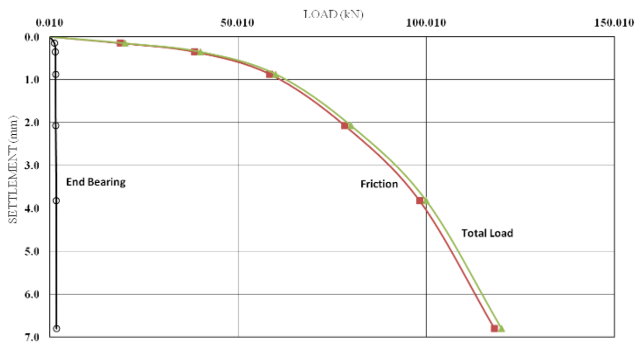

Fig. [31] The Relationship between Total Load Transmitted by Friction, End Bearing and Settlement for Group (2) – Two Piles

viii. Fig. [32] shows the Comparison between Q_{ult} from Pile Load Test with Theoretical values (Group (1) – Single Pile)

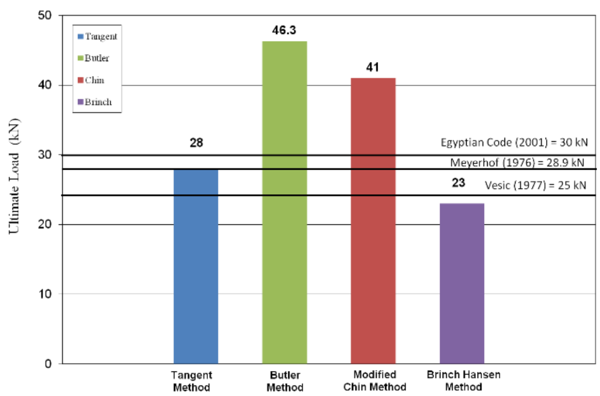

Fig. [32] Comparison between Q_{ult} from Pile Load Test with Theoretical (Group (1) – Single Pile)

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ix. Fig. [33] Shows the Comparison between Q_{ult} from Pile Load Test with Theoretical values (Group of Two Piles)

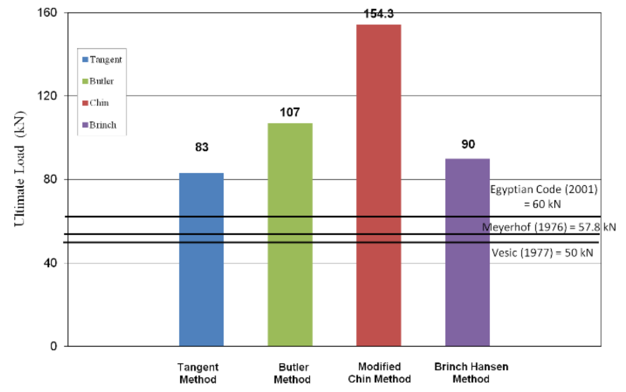

Fig. [33] Comparison between Q_{ult} from Pile Load Test with Theoretical (Group of Two Piles)

6. CONCLUSIONS

From the present study, the followings conclusions are obtained:

i. For single pile, 86 % of the applied load is resisted by side friction and 14 % by tip resistance.
ii. For group of two piles, 96 % of the applied load is resisted by side friction and 4 % by tip resistance.
iii. For the group of two piles at spacing of three times the pile diameters, the group efficiency was found to be 1.43.
iv. The obtained results have fair agreement with Meyerhof (1976) theoretical analysis as well as Egyptian code (2001) static formula.

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