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Alexandria Engineering Journal

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ORIGINAL ARTICLE

Uplift capacity of single piles and pile groups embedded in cohesionless soil

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Received 15 November 2012; revised 1 January 2013; accepted 6 January 2013

Available online 9 February 2013

KEYWORDS

Pile;
Group;
Embedded;
Uplift;
Load;
Displacement;
Cohesionless soil

Abstract Understanding the pile behavior and predicting the capacity of piles under uplift loading are important topics in foundation design. Experimental model tests have been conducted on single piles and pile groups embedded in cohesionless soil and subjected to pure uplift loading. The experimental tests were conducted on straight-shafted vertical steel piles with an outer diameter of 26 mm in a steel soil bin. The tested piles have embedment depth-to-diameter ratios (L/d) of 14, 20, and 26. The sand bed is prepared at three different values of relative density of 75%, 85%, and 95%. Single piles and pile groups containing two, four, and six piles embedded in sandy soil were tested, and the results are presented and discussed in this paper. The influences of pile embedment depth, relative density of soil, and arrangement of piles in a group on the uplift capacity of piles are investigated. The study revealed that the behavior of single piles under uplift loading depends mainly on both the pile embedment depth-to-diameter ratio and the soil properties. An empirical equation is suggested to represent the load–displacement relationships of single piles embedded in sandy soil under uplift loading. When the net uplift load per pile in a group is equal to a single pile load, the upward displacement increased in the pile group due to interaction effects between piles. The obtained group efficiency under uplift loading is illustrated and found to be in a good agreement with previous studies. The uplift group efficiency of a closely spaced pile group decreased with an increase in the number of piles in the group. The group efficiency under uplift loading improved slightly with an increase in the relative density of soil, whereas it decreased with an increase in the pile embedment depth-to-diameter ratio. It is believed that the experimental results presented in this study would be beneficial to the professional understanding of the soil–pile–uplift interaction problem.

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Peer review under responsibility of Faculty of Engineering, Alexandria University.



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1. Introduction

Pile foundations are frequently used to transmit the superstructure loads to deeper strata if the subsurface soil is of inadequate strength. In cohesionless soils, the shaft resistance is an important source of pile capacity under axial loading, especially when the pile is subjected to uplift loading. Uplift forces act on the supporting piles if structures such as dry docks,

basements, and pumping stations are constructed below the water table. Additionally, transmission line towers, tall chimneys, submerged platforms, jetting structures, masts, and similar constructions on pile foundations are usually subjected to overturning moments due to wind effects, seismic events, wave actions or ship impacts. In such structures, the induced overturning moments are transferred to the piles supporting the structure in the form of compression in some piles and pull out on others. Moreover, uplift forces may be exerted on piles due to swelling of the surrounding soils. Therefore, studying the behavior of piles under uplift forces as well as the parameters affecting the uplift capacity of piles is one of the most important and interesting areas of research in geotechnical engineering.

In straight-shafted piles, the applied uplift load is resisted by shaft resistance developed between the pile and the soil. Research on shaft resistance of piles has progressed during the last five decades. Most previous studies were directed toward the shaft capacity of piles subjected to axial compressive loads, while little research was conducted on pile response under uplift forces. Based on soil conditions, the methods for analyzing side resistance of piles are of two types: total stress analysis and effective stress analysis [6]. These analytical methods can be further specified into the alpha (α), beta (β), and lambda (λ) methods. Several studies have concluded that shaft resistance is about the same for uplift and compression loads [14,5]. However, O'Neill and Reese [16] reported that the shaft resistance in tension could be 12–25% smaller than in compression due to Poisson's ratio effects, which would tend to reduce the shaft diameter in uplift. Poulos and Davis [17] recommended estimating the uplift capacity of piles as 2/3 of the downward shaft resistance. Moreover, Ramasamy et al. [18] indicated that the upward shaft resistance is significantly less than the downward shaft resistance. Some studies were conducted on the behavior of a single pile under uplift loads, such as those by Sowa [23], Vesic [25], Das and Seeley [7], Levacher and Sieffert [15], Rao and Venkatesh [19], Chattopadhyay and Pise [4], and Shanker et al. [22].

Model tests were performed by Awad and Ayoub [3] to determine the uplift capacity of vertical and inclined piles. They developed an empirical equation to determine the uplift capacity of inclined piles. Das et al. [8] conducted a model study to test the uplift capacity of single piles and pile groups buried in sand, and they also determined a relationship between the efficiency of a pile group and its spacing. Chattopadhyay and Pise [4] proposed an analytical method for predicting the uplift capacity of piles embedded in sand. Ismael [11] specified the average values of skin friction for driven piles in calcareous sand. Kraft [13] studied various parameters that influence the axial capacity of pipe piles driven in sand. Alawneh et al. [2] studied the significant variables affecting the ultimate uplift resistance of a pile embedded in dry sand. Srivastava et al. [24] presented a numerical procedure for load–displacement behavior of a single pile embedded in sand under uplift loads. Dash and Pise [9] and Joshi and Patra [12] tried to assess the effect of compressive loads on the uplift capacity of single piles. They concluded that the net uplift capacity of piles decreased with an increase in compressive load.

Different theories regarding the behavior of piles under different loading conditions have been developed over the recent three decades. The reliability of the theories can be demonstrated by a comparison of experimental results on model or

field piles with the theoretical predictions. Full-scale field tests are highly desirable, but they are generally expensive and difficult to perform. In the absence of resources, small-scale laboratory model tests conducted on piles embedded in sand under controlled conditions may serve the purpose to some extent. Properly conducted laboratory tests, with known parameters affecting the soil–pile response under uplift loading, would provide information on qualitative contributions of such parameters on the ultimate resistance of piles. At the same time, the increasing use of piles to resist and sustain uplift loads necessitates accurate assessment of uplift resistance to achieve economy and safety. Therefore, it is hoped that the current study may lead to a better understanding of the response of single piles and pile groups under pure uplift loads.

2. Materials and experimental model

2.1. Soil bin

The experimental tests were performed on model piles in a steel soil bin. Fig. 1 illustrates the schematic diagram of the test setup. The cylindrical bin has a 750 mm internal diameter, 900 mm depth, and 10 mm wall thickness. The soil bin was made of three lifts, each 300 mm in height and joined together by steel bolts to produce a container with a total depth of 900 mm. Each lift was stiffened by two angles of 60 × 60 × 6 mm at the top and the bottom ends to facilitate lift attachment. The inner face of the bin was marked at 100 mm intervals to assist accurate formation of

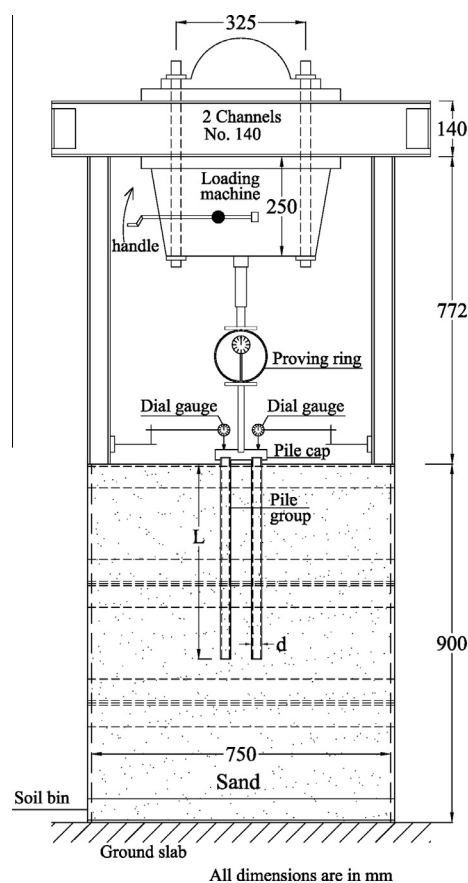


Figure 1 Schematic diagram of the test setup.

sand inside the bin during the tests. It should be born in mind that the boundaries of the soil bin may affect the stress and displacement fields in the soil. Moreover, the vertical stress in the soil may decrease due to friction between the soil and the container walls [13]. To minimize such interference, the inside walls of the soil bin were polished smooth to reduce friction with the soil as much as possible. The zone in which the soil will be affected by the tank boundaries varies with the soil's relative density and the method of pile installation. Robinsky and Morrison [20] reported that the zone of influence is in the range of 3–8 times the pile diameter. In the current study, the dimensions of the bin provided a minimum lateral clearance of 12 times the pile diameter for even the biggest pile group. Although no end bearing stress is anticipated at the pile tip, a vertical clearance of eight times the pile diameter was provided below the pile tips. Therefore, it is believed that the boundaries of the soil bin have no effect on the obtained results of the conducted tests.

2.2. Model piles and pile caps

Model piles were designed and manufactured from smooth mild steel tubes with a 26 mm outside diameter (d) and 3 mm wall thickness. A steel shoe was machined and used to close the end of each pile. The pile lengths (L) considered were 364, 520, and 676 mm, which correspond to (L/d) ratios of 14, 20, and 26 respectively. The top portions of the piles were threaded to fasten them with the pile cap. The pile caps were machined from mild steel plates of 30 mm thick. The pile cap was machined to the designed dimensions within an accuracy of ± 1.0 mm. A thread at the center of the top surface of the pile cap was provided for connection with a proving ring for uplift loading. The piles were fully embedded in the sand during all of the conducted tests. When pile groups were tested, the spacing between the piles-to-diameter ratio (s/d) was kept constant at 2.5.

2.3. Sand

The model piles were embedded in dry siliceous sand of medium to fine particles. Table 1 shows the geotechnical properties of the sand used in the experimental program. All tests were conducted on sand in accordance with the relevant ASTM [1] standard test methods, as shown in the same table. After placing piles with the pile cap in the empty soil bin, sand with

a total height of 900 mm was deposited in the soil bin in nine layers, each 100 mm deep. Sand was formed in the soil bin at selected relative densities of 75%, 85%, and 95%. Controlled pouring of sand and tamping techniques were used to prepare a homogeneous sand layer. The quantity of sand for each layer was estimated and weighed to an accuracy of 0.10 N, placed in the soil bin, and tamped until reaching the required height. The sand layers were placed in the soil bin to achieve the target thickness within an accuracy of ± 1 mm to attain the required relative density. The relative density of the deposited sand was monitored using four wooden boxes of $60 \times 60 \times 25$ mm placed at different locations and different levels in the soil bin. The results of a test were considered in this study when the differences between the measured unit weights of soil inside the wooden boxes and the target unit weight did not differ more than $\pm 1.0\%$ from the target value. Otherwise, some tests were repeated to satisfy the abovementioned condition.

2.4. Experimental model

In each test, the pile or pile group was suspended centrally and vertically in the empty soil bin through the loading machine and the proving ring arrangement, as shown in Fig. 1. The verticality of the pile/pile group was confirmed by using a water level balance with an accuracy of $\pm 0.50^\circ$. Sand was poured uniformly to attain the target relative density as explained above. Before starting the loading, the pile or pile group verticality was rechecked, and the tilt in the pile cap was also checked using the same water level balance. Then, the uplift load was applied incrementally.

The uplift loads were applied using a loading machine via a calibrated proving ring. The proving ring had an accuracy of 1.0 N with a maximum capacity of 1.0 kN. Each increment of the load was kept constant till no significant change occurred in displacement, i.e., the difference between two successive readings was less than 0.01 mm per 5 min for three consecutive readings. The upward displacements were measured using two mechanical magnetic-base dial gauges placed on the pile cap at 180° apart and equidistant from the point of load application. The dial gauges had a sensitivity of ± 0.01 mm with a maximum travel of 50 mm. The uplift load was applied concentrically on the pile cap, and the average value of displacement readings was considered, providing that the difference between the readings of the two dial gauges did not differ more than 5% from the average value. After

Table 1 Geotechnical properties of sand used in the tests.

Parameter	ASTM [1]	Value
Effective size $D_{10\%}$ (mm)	D 422	0.23
Uniformity coefficient, C_u	D 422	2.44
Coefficient of curvature, C_c	D 422	1.32
Percentage of fine material (< 0.075 mm)	D 1140	2.4%
Specific gravity of solids, G_s	D 854	2.65
Minimum dry unit weight (kN/m^3)	D 4254	15.80
Maximum dry unit weight (kN/m^3)	D 1557	18.60
Optimum water content (%)	D 1557	7.6%
California Bearing Ratio, CBR, after soaking 4 days (%)	D 1883	15.6%
Peak angle of internal friction at $Dr = 75\%$ ($^\circ$)	D 3080	39.5
Peak angle of internal friction at $Dr = 85\%$ ($^\circ$)	D 3080	41.3
Peak angle of internal friction at $Dr = 95\%$ ($^\circ$)	D 3080	42.5

completion of each test, the soil was removed from the soil bin and the wooden boxes were recovered for measurement of sand unit weight.

Few replicate tests were performed initially at each relative density to ascertain the variations in the test results. Very close patterns of load–displacement relationship, with a difference in the results of less than 2%, were obtained. Therefore, it is concluded that the used testing procedure and the adopted loading system can produce repeatable and acceptable results.

3. Testing program

A testing program was designed to evaluate the uplift behavior of single piles and pile groups embedded in cohesionless soil with respect to various parameters, such as embedment depth-to-diameter ratio (L/d), relative density of sand (Dr), and arrangement of piles in a group. Embedment depth-to-diameter ratios (L/d) of 14, 20, and 26 were considered. The tests were conducted on sand prepared at three relative densities: 75%, 85%, and 95%. Single piles and pile groups containing two, four, and six piles were tested. It is common practice to arrange the piles in a group with a minimum spacing between their centerlines to limit the dimensions of the pile caps, leading to an economical design. Most codes recommend a minimum center-to-center spacing between piles in a group embedded in cohesionless soil of 2.5 times the pile diameter [10]. Therefore, the spacing between piles in the groups tested in the current study was kept constant at 2.5 times the pile diameter. Table 2 summarizes all the data of the testing program.

The gross uplift load and the corresponding upward displacement were recorded from the readings of the proving ring and the dial gauges. The net uplift load (T) was determined by subtracting the weight of the pile/piles and the pile cap from the gross uplift load. The average measured upward displacement of the pile/piles (Δ) was normalized as (Δ/d) , where (d) is the pile diameter. The net uplift load–displacement relationship was plotted for each loading test. Typical relationships between net uplift load and normalized displacement for single piles are presented in Fig. 2. The net uplift capacity of the pile/piles (T_{ult}) is defined as the value of the net uplift load when the displacement of the pile/piles proceeds unlimitedly, i.e., when the load becomes asymptotic to the displacement axis. The obtained values of (T_{ult}) along with (Δ/d) corresponding to uplift capacities for all of the conducted tests are shown in Table 2.

4. Discussion of results

Test results are grouped in two sets of figures representing the behavior of single piles and pile groups under uplift loading. Results of the pile groups will be compared to the corresponding results of a single pile. The following sections discuss the obtained results in detail.

4.1. Single piles under uplift loading

Three sets of tests were conducted on single piles under uplift loading, where the piles have (L/d) of 14, 20, and 26. Each set

includes three tests at three relative densities of the sand (Dr) of 75%, 85%, and 95% respectively. Fig. 2 demonstrates typical relationships between the applied net uplift load (T) and the corresponding normalized displacement (Δ/d) of single piles embedded in sand of different values of (Dr). In general, the load–displacement responses for all the piles are similar. The obtained load–displacement relationships are fairly similar to those developed by O'Neill and Reese [16]. Fig. 2 and Table 2 indicate that the upward displacements of single piles corresponding to the uplift capacities vary from 1.4% to 2.5% times the pile diameter. It seems that the upward displacement of a single pile at the uplift capacity decreases as the soil becomes denser. If the values of net uplift capacity are divided by a factor of safety of 3, the displacements of single piles corresponding to the allowable loads are typically approximately 0.4% to 0.6% times the pile diameter. This result highlights that very little upward displacement would be required to develop the allowable uplift load of a single pile.

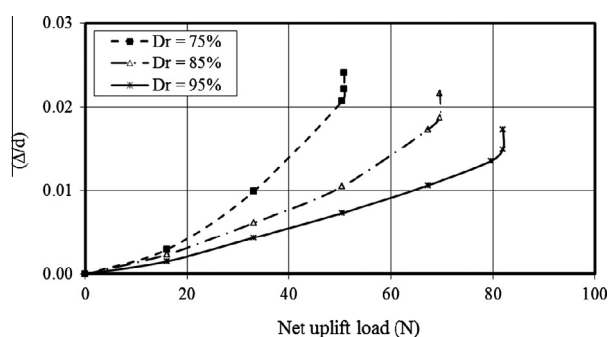
Fig. 2 shows that at a particular upward displacement, the magnitude of the net uplift load of a single pile improves with an increase in the relative density of sand. This can be attributed to the increase in both the effective stress and the friction angle between pile and soil due to the increase in the relative density of soil. The net uplift capacity of a pile increases by a factor of 1.37 as a result of increasing the sand relative density from 75% to 85%, and the increase in relative density from 85% to 95% improves the net uplift capacity by a factor of 1.18. Fig. 3 illustrates the effect of relative density on the uplift capacity of single piles at different (L/d) ratios. As previously mentioned, the increase in the relative density appreciably improves the net uplift capacity for all values of (L/d). Therefore, it can be concluded that the relative density of soil has a significant contribution to both the net uplift capacity and the displacement at the uplift capacity of single piles.

Fig. 3 also shows that the pile embedment depth has a major influence on the net uplift capacity of single piles. It can be clearly observed that for a particular relative density, the net uplift capacity increases significantly with an increase of (L/d) ratio. This effect can be attributed to two different factors. The first one is the improvement in the friction resistance between the soil and the pile. As the pile embedment depth increases, the effective stress at the mid-height of the pile increases, and consequently, an improvement in the shear resistance is achieved. The second factor is the increased contact area between the soil and the pile as the pile embedment depth increases. These two factors lead to the improvement in the net uplift capacity offered by the pile as the pile embedment depth increases. In this situation, it is important to note that the pile embedment depth in offshore structures should be measured from the scour level to the tip level of the pile. In other words, the capacity loss due to scour should not be included in the determination of the axial uplift capacity. In addition, settlement induced downdrag should not be included because it is anticipated that settlement will cease at some point in time.

The results of the tests on single piles were used to obtain a general load–displacement relationship. Fig. 4 shows the relationship between the normalized uplift load ($T/\gamma \cdot d \cdot L^2$) and the normalized upward displacement (Δ/d) of single piles. It is clear that there is a reasonable range of scatter in the results for all of the conducted tests. If the mean of the achieved range

Table 2 Testing program, net uplift capacity, and group efficiency.

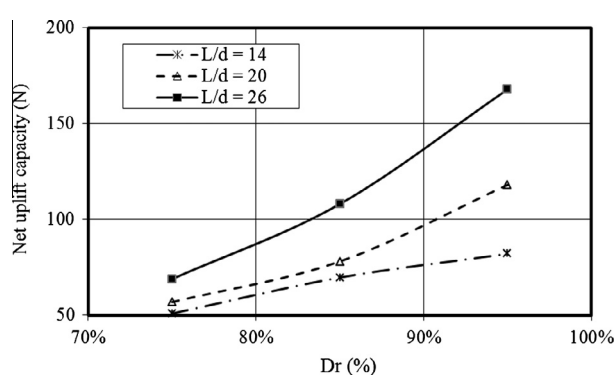
Test no.	No. of piles	L/d	Dr. (%)	T_{ult} (N)	Δ/d (%) at T_{ult}	Group efficiency
1	Single pile (SP)	14	75	50.80	2.50	
2		20	75	56.80	2.30	
3		26	75	68.80	2.25	
4		14	85	69.60	2.20	
5		20	85	78.00	1.70	
6		26	85	108.00	1.60	
7		14	95	82.00	1.80	
8		20	95	118.00	1.50	
9		26	95	167.92	1.40	
10	Two-pile group (2PG)	14	75	70.00	2.15	0.69
11		20	75	72.00	2.05	0.63
12		26	75	74.00	1.90	0.54
13		14	85	100.00	2.10	0.72
14		20	85	102.80	1.85	0.66
15		26	85	167.20	1.75	0.77
16		14	95	136.00	1.80	0.83
17		20	95	149.80	1.70	0.64
18		26	95	167.20	1.65	0.60
19	Four-pile group (4PG)	14	75	96.80	2.04	0.48
20		20	75	99.00	1.90	0.44
21		26	75	103.00	1.75	0.37
22		14	85	135.00	1.85	0.49
23		20	85	145.00	1.74	0.47
24		26	85	175.60	1.62	0.41
25		14	95	180.00	1.83	0.55
26		20	95	196.00	1.71	0.42
27		26	95	220.00	1.52	0.33
28	Six-pile group (6PG)	14	75	99.18	2.00	0.33
29		20	75	155.20	1.80	0.46
30		26	75	162.00	1.62	0.39
31		14	85	140.80	1.75	0.34
32		20	85	184.40	1.61	0.39
33		26	85	286.00	1.53	0.44
34		14	95	196.40	1.72	0.40
35		20	95	225.00	1.56	0.32
36		26	95	380.00	1.42	0.38

**Figure 2** Net uplift load versus normalized displacement for single piles, $L/d = 14$.

is considered, one can define a dimensionless power load–displacement relationship as:

$$T/(\gamma \cdot d \cdot L^2) = 24.1(\Delta/d)^{0.84} \quad (1)$$

The advantage of the proposed equation is that it relates the uplift load to the upward displacement of a single pile as a function of simple parameters, which is a valuable guide for

**Figure 3** Net uplift capacity for single piles versus relative density of soil.

making informed engineering decisions. Thus, it can be used by geotechnical engineers in the preliminary design stage. However, this equation needs to be verified by conducting full-scale uplift-loading tests on single piles with different (L/d) ratios and embedded in sand of different relative densities.

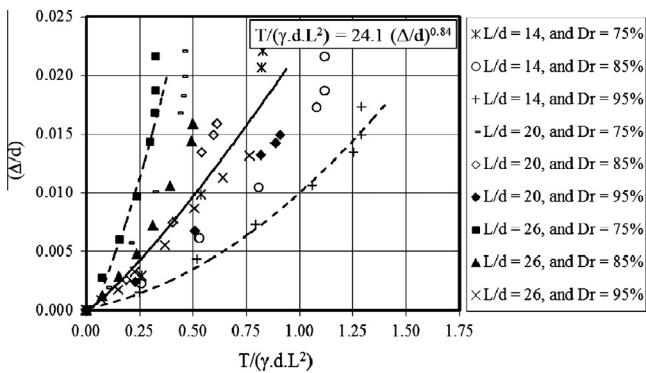


Figure 4 Values of $T/(\gamma \cdot d \cdot L^2)$ versus normalized displacement (Δ/d) for single piles.

4.2. Pile groups under uplift loading

The analysis procedure discussed in the preceding paragraphs is for single piles. For most structures, piles are installed in groups. Therefore, closely spaced pile groups with two, four, and six piles were tested under uplift loading at minimum center-to-center spacing between piles of $2.5d$. To facilitate comparisons between the response of pile groups and a single pile, the net uplift load per pile in a group was computed by dividing the net uplift load of a pile group by the number of piles in that group, as shown in Fig. 5. The determination of the pile load is accurate for two and four-pile groups, but in the six-pile group, the resulting load is the average pile load. The relationships between the net uplift load per pile and the upward displacement for a single pile and pile groups are generally similar in shape. When the net uplift load per pile in a group is equal to a single pile load, the upward displacement increased in the pile group as the number of piles in the group increases due to interaction effects between piles. As a closely spaced pile group moves upward, the stressed areas for individual piles in the group overlap, causing a reduction in the value of net uplift load carried by each pile in the group. Fig. 5 highlights that for the same net uplift load per pile, the upward displacement of a four-pile group is 2–3 times that of a single pile. Table 2 indicates that the upward displacement of pile groups corresponding to the uplift capacity varies from 1.42% to 2.15% times the pile diameter.

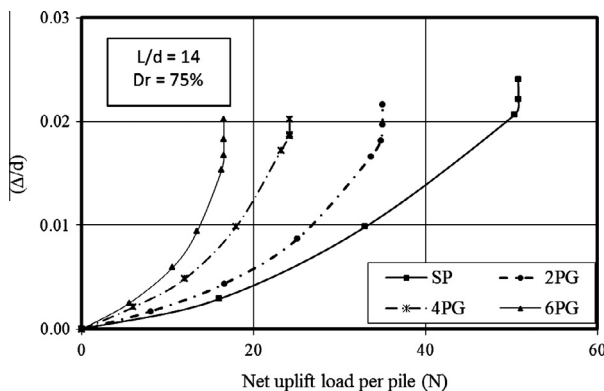


Figure 5 Net uplift load per pile versus normalized displacement (Δ/d) .

To explore the behavior of pile groups under uplift loading, the group efficiency, η , was calculated as:

$$\eta = (T_{ult})_g / [n \cdot (T_{ult})_s] \quad (2)$$

where $(T_{ult})_g$ is the net uplift capacity of the pile group, $(T_{ult})_s$ the net uplift capacity of the single pile in similar conditions as in the pile group, and n is the number of piles in the pile group.

It is important to emphasize that the group efficiency can be used if the boundary conditions of the pile group and the single pile are similar. The net uplift capacity of a pile group was determined from the corresponding load–displacement relationship as the point at which the displacement continuously increases without a further increase in the uplift load. The uplift group efficiencies are computed for all the combinations of the tested pile groups, as shown in Table 2. The table shows that the values of group efficiency range from 0.32 to 0.83 according to the number of piles in the group, the pile embedment depth-to-diameter ratio (L/d), and the relative density of sand (Dr).

Fig. 6 shows the efficiency of different pile groups versus the relative density of sand. It is obvious that at the same relative density, the group efficiency decreases with an increase in the number of piles in a group due to interaction effects between piles, as previously mentioned. The reader should remember that Fig. 6 is drawn for groups with pile spacing of 2.5 times the pile diameter. Joshi and Patra [12] reported an improvement in the group efficiency as the spacing between piles increased, and the efficiency is approximately unity for a spacing of about $6d$. Hence, they suggested $6d$ pile spacing as the isolation spacing for pile groups under uplift loading. Additionally, SCDOT [21] stated that the group efficiency should be taken as 0.65 for pile groups with minimum spacing of $2.5d$ and increased linearly up to 1.0 for pile groups spaced at $4d$. Fig. 6 demonstrates that the group efficiency is slightly increased with an increase in relative density of soil. As the relative density of soil increased, the interaction effects between piles in the group decreased due to the increase in soil stiffness, and as a result, the group efficiency slightly improved.

Fig. 7 illustrates the values of group efficiency versus the pile embedment depth-to-diameter ratio (L/d) for all of the tested pile groups. There is a range of scatter of the obtained values depending on the number of piles in the group and the properties of soil surrounding the piles. If the mean value is considered, the group efficiency exhibits a small decrease

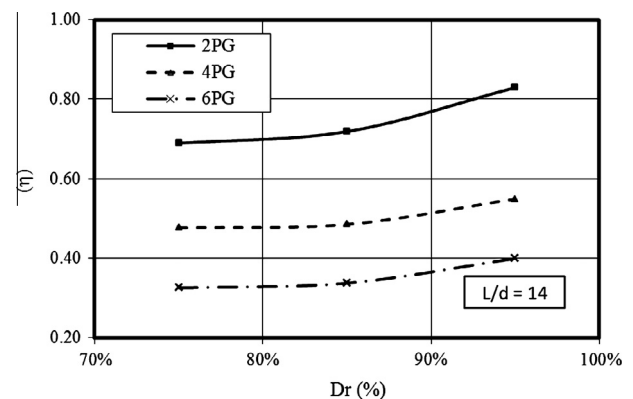


Figure 6 Group efficiency versus relative density of sand.

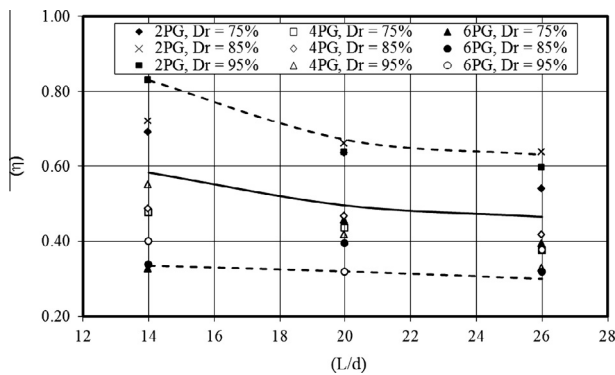


Figure 7 Group efficiency versus pile embedment depth-to-diameter ratio (L/d).

with the increase in pile embedment depth-to-diameter ratio due to an increase in the interaction effects with the increase in pile embedment depth.

5. Conclusions

Experimental tests were conducted on single piles and pile groups containing two, four, and six piles under pure uplift loading. The test results are presented and discussed in this paper. Based on the foregoing study, the following main conclusions are drawn:

1. The behavior of single piles under uplift loading depends mainly on both the pile embedment depth-to-diameter ratio (L/d) and the soil properties. The net uplift capacity of a pile improves significantly with an increase in both the (L/d) ratio and the relative density of soil.
2. An upward displacement of about 1.4–2.5% of the pile diameter is required to attain the net uplift capacity for both single piles and pile groups. A very small upward displacement, 0.4–0.6% times the pile diameter, is required to develop the allowable uplift load.
3. The load–displacement behavior of a single pile embedded in sand under uplift loading can be represented adequately by a power equation that includes simple parameters. This equation needs to be verified by conducting full-scale uplift-loading tests on single piles.
4. For a net uplift load per pile in a group equal to a single pile load, the upward displacement of a closely spaced pile group increases due to interaction effects between piles.
5. The efficiency of the tested pile groups under uplift loading ranges from 0.32 to 0.83 according to the number of piles in the group, the pile embedment depth-to-diameter ratio, and the relative density of sand.
6. The efficiency of a pile group under uplift loading decreases with an increase in the number of piles in the group and with an increase of the pile embedment depth-to-diameter ratio.
7. The efficiency of a pile group under uplift loading increases slightly with an increase in the relative density of soil.

Acknowledgements

The experimental tests reported in this paper were conducted in the Soil Mechanics Laboratory at Faculty of Engineering, Alexandria University. The author would like to express his gratitude to the technicians for their assistance during preparing the tests.

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