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ORIGINAL ARTICLE

Behavior of pile group incorporating dissimilar pile embedded into sand

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KEYWORDS

Friction resistance;
End bearing;
Pile group;
Dissimilar pile;
Deficiency

Abstract Piles are recommended to transfer the superstructure loads safely through soil by friction resistance and end bearing into firm bearing stratum. Piles drive their load via weak soil into competent bearing stratum. Piles in group are designed of similar length, diameter and working load. Except in special cases such as raft on piles which may be attentionally of different lengths. Dissimilarity in piles within a group may result from uncertainties in soil conditions, or imperfection in pile construction. Soil conditions may force the designer to design pile groups in a building having different lengths. Studying the behavior of pile groups incorporating dissimilar piles, in literature is scarce. The paper is devoted to study, through small scale models in laboratory, the behavior of pile groups incorporating one dissimilar pile. The aim of the research work was to emphasize the effect of dissimilar pile on the behavior of pile group through load settlement relationship. The study revealed that the end bearing of the group due to the existence of dissimilar pile, decreases as the number of piles in the group increased. The deficiency of two-pile group containing one dissimilar pile attains 90%, while in a group containing 9-piles it reaches 5%.

1. Introduction

Dissimilarity in Piles may result due to uncertainties in soil condition or imperfection in pile construction. As an example of the former case the sequence of pile driving produce different soil conditions within the soil zone enclosing the pile group, consequently piles of different length may be constructed. This phenomenon is obvious in case of piles driven in sandy soil, the later case was discussed by [6] and [1,3].

Dissimilarity between piles in a group may happen in case of inclined competent stratum on which pile group are seated. Dissimilarity in pile may be attentionally designed such as raft on piles [5]. Rehabilitation of pile foundations using piles of different diameters, material and lengthes may result dissimilar piles in a group [2]. Pile within a pile group is considered dissimilar, if the pile has different length, different diameter and different material. The problem has not attracted the attention of researchers, may be due to that the problem arises during construction, and usually practicians have no time to report and interpret a case study for publication. Consequently the problem is worth investigated [4] and implemented a hybrid approach to analyze pile groups containing dissimilar piles. Piles of different length, different diameter are considered dissimilar in the analysis [7] analyzed the interaction between two-pile group, one pile dissimilar to the another.

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2. Testing equipment

To study the behavior of pile groups, incorporating one dissimilar pile, buried in sand, laboratory tests were conducted on small scale models of aluminum piles. Pile groups containing 2,3,6 and 9 piles were considered. The pile groups are attached to pile cap free standing from soil. The pile caps are machined from aluminum plates. The caps have smooth faces and a notch at the center of the top face for mounting a calibrated proving ring of 2kN maximum capacity and 0.01kN accuracy via ball bearing. Two-dial gauges – of accuracy 0.01 mm – were used to measure the vertical displacements and rotations of the pile group, the dial gauges were attached vertically far apart on the top surface of the pile cap. A total of Nine circular aluminum piles of diameter 12 mm, and 400 mm in length are machined from aluminum rods. For dissimilarity reasons steel, plastic, and timber circular piles of diameter 12 mm and lengths 400, 350, 300, and 200 mm were prepared and used. Aluminum piles of diameter 12 mm and length 350,300 and 200 mm were also prepared. Similar piles of the same material were used but of diameters 8 mm and 6 mm for the same reason. This means that 33 piles are manufactured. Combination of these piles was used to form pile groups with dissimilar piles. The general layout of the equipment used in performing the loading tests is illustrated in Fig. 1. The vertical displacements of the pile group and the rotation of the pile group were obtained from dial gauge readings. The load was applied vertically and concentric on the pile cap model using controlled manually operated loading machine. The soil bin is made out of two steel rings each of 300 mm height and 750 mm diameter. These rings were assembled to form a soil bin of total height 600 mm. The sides of the soil bin were strengthened using circular steel plates at top and bottom of each ring to prevent any lateral deformation of the side walls and to facilitate the erections of the steel rings using steel bolts. The vertical steel ribs are added to each ring and welded to the boundary circular plates of each ring. The soil bin is placed on two rigid steel girders resting on the ground, accurately vertical. Spirit level was used to ensure vertical and horizontal levels of test setup. Reaction frame supporting a loading machine is attached to the soil bin. The dimensions of the soil bin are big enough to overcome the effects of the boundary conditions on the piles response. Table 1 shows the testing program for loading two pile groups, (G1). The arrangement of the piles in the groups was kept one pile in the groups unchanged to be aluminum pile of diameter 12 mm, and length 400 mm the reference pile, and modulus of elasticity, E_p of 70 GPa, that's to say E_p/E_s equals to 1400. The other pile was changed in each experiment creating dissimilarity in the pile group as shown in Table 1. The dissimilarity occurs in pile material, as it is changed to be steel, $E = 200$ GPa, timber, $E = 15$ GPa, and plastic, $E = 3$ GPa, also in piles length to be 350 mm, 300 mm and 200 mm, finally dissimilarity occurs in pile diameter to be 8 mm, and 6 mm as shown in Table 1.

The second group G2 was accomplished on 3-pile groups placed in triangle configuration the properties of dissimilar pile were changed according with Table 2. One dissimilar pile was incorporated in each experiment as the sequence of group G1, and the other two piles were kept unchanged and having the

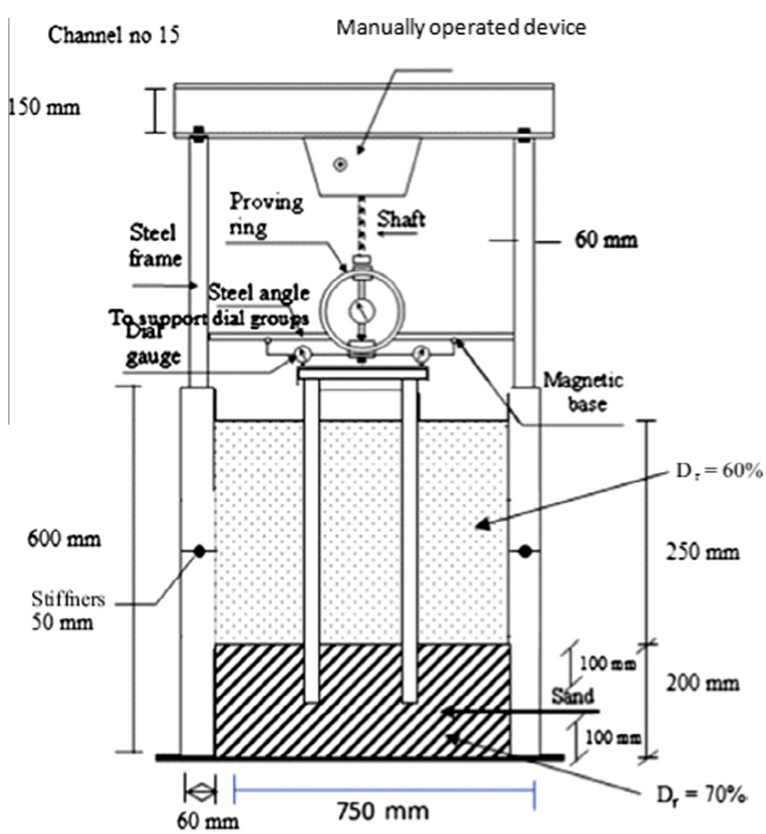

Figure 1 Complete set-up of testing procedures.

Table 1 Testing Program 2-pile group,(G1), properties of dissimilar pile.

Test ID		T2-1	T2-2	T2-3	T2-4	T2-5	T2-6	T2-7	T2-8	T2-9	T2-10	T2-11	T2-12
Material		Aluminum	Plastic	Steel	Timber	Aluminum	Plastic	Steel	Timber	Aluminum	Plastic	Steel	Timber
Modulus of elasticity, *E*, GPa		Al	Pl	St	tm	Al	Pl	St	tm	Al	Pl	St	tm
Length, mm		400	400	400	400	350	350	350	350	300	300	300	300
Diameter, mm		12	12	12	12	12	12	12	12	12	12	12	12
Ultimate Lood (KN) Due to	Displacement, mm	0.11	0.11	0.12	0.113	–	–	–	–	–	–	–	–
	Rotation,$\Delta L/L$	–	–	–	–	0.11	0.01	0.012	0.01	0.01	0.005	0.01	0.01
Test ID		T2-13	T2-14	T2-15	T2-16	T2-17	T2-18	T2-19	T2-20	T2-21	T2-22	T2-23	T2-24
Material		Aluminum	Plastic	Steel	Timber	Aluminum	Plastic	Steel	Timber	Aluminum	Plastic	Steel	Timber
Modulus of elasticity, E, G Pa		Al	Pl	St	tm	Al	Pl	St	tm	Al	Pl	St	tm
Length, mm		200	200	200	200	400	400	400	400	400	400	400	400
Diameter, mm		12	12	12	12	8	8	8	8	6	6	6	6
Ultimate Lood (KN) Due to	Displacement, mm	–	–	–	–	–	–	–	–	–	–	–	–
	Rotation, $\Delta L/L$	0.005	0.004	0.01	0.008	0.02	0.018	0.008	0.02	0.006	0.004	0.005	0.004

Where ΔL difference in dial gauge reading.
Where L distance between dial gauge.

Table 2 Test pump of 3-pile group, properties of dissimilar pile.

Test ID		T3-1	T3-2	T3-3	T3-4	T3-5	T3-6	T3-7	T3-8	T3-9	T3-10	T3-11	T3-12
Material		Aluminum	Plastic	Steel	Timber	Aluminum	Plastic	Steel	Timber	Aluminum	Plastic	Steel	Timber
Modulus of elasticity, *E*, GPa		70	3	200	15	70	3	200	15	70	3	200	15
Length, mm		400	400	400	400	350	350	350	350	300	300	300	300
Diameter, mm		12	12	12	12	12	12	12	12	12	12	12	12
Ultimate Lood (KN) Due to	Displacement, mm	0.29	0.22	0.25	0.18	–	–	–	–	–	–	–	–
	Rotation, $\Delta L/L$	–	–	–	–	0.15	0.11	0.18	0.12	0.12	0.1	0.15	0.11
Test ID		T3-13	T3-14	T3-15	T3-16	T3-17	T3-18	T3-19	T3-20	T3-21	T3-22	T3-23	T3-24
Material		Aluminum	Plastic	Steel	Timber	Aluminum	Plastic	Steel	Timber	Aluminum	Plastic	Steel	Timber
Modulus of elasticity, *E*, GPa		70	3	200	15	70	3	200	15	70	3	200	15
Length, mm		200	200	200	200	400	400	400	400	400	400	400	400
Diameter, mm		12	12	12	12	8	8	8	8	6	6	6	6
Ultimate Lood (KN) Due to	Displacement, mm	–	–	–	–	–	–	–	–	–	–	–	–
	Rotation, $\Delta L/L$	0.08	0.08	0.12	0.085	0.12	0.0858	0.1275	0.06	0.04	0.06	0.1	0.039

properties of the reference pile. Table 3 shows the testing program accomplished on 6-pile group, G3, where 6 piles were arranged in rectangular patter, the corner pile was changed in each experiment to simulate dissimilar pile but all piles are machined from aluminum piles, Length and diameter of the dissimilar pile are changed. Finally the fourth group, G4, was conducted on a square 9 pile group and the sequence of the experiments is shown in Table 4. This means that a total number of sixty laboratory experiments were conducted for studying and investigating the response of dissimilar pile group.

Table 5 Sand properties.

Maximum unit weight Kn/M^3	18.5
Minimum unit weight Kn/M^3	15
Uniformity deficient	5.95
Effective diameter	0.08
Specific gravity, Gs	2.56
Modules of elasticity GPa, E	0.05

3. Experimental procedure

The sand used was medium size sand of minimum dry unit weight 15.0 kN/m^3, maximum dry unit weight of 18.5 kN/m^3, uniformity coefficient of 5.95 the sand properties are shown in Table 5, the grain size distribution curve is shown in Fig. 2. A sand bed was formed in the soil bin in layers each of 100 mm thickness. To ensure homogeneity of sand formation a designed weight of sand with an accuracy of 0.001 kN, was formed by raining into a certain volume of the soil bin. The sand was compacted to achieve a relative density of 70% for 100 mm under the pile tip, that is to say 8.3 times the largest pile diameter incorporated in pile groups prepared for laboratory tests. The top surface of the formed sand was leveled using sharpened straight steel plate and the model pile/piles which are attached to pile cap accurately in their positions are then placed on the surface of the compacted sand. Sand was then added to give a height of almost eight times the pile diameter above the pile tip, 100 mm and compacted in the same sequence as the previous sand giving the same relative density of 70%. Compaction was carried out manually on each 100 mm thickness of sand using a circular steel rammer weighing 40.0 N and of 200 mm diameter.

The uncompacted sand was used to surround the pile/piles shaft for a height of 250 mm, the sand relative density was 60%, this relative density was attained by adding a designed weight into a designed height of the soil bin. The relative density of the formed sand was assured by putting 2 aluminum boxes of dimensions $50\,mm \times 50\,mm \times 30\,mm$ to assess the actual relative density. The unit weight of the formed sand was revised, if need it this means that the total height of sand surrounding the pile shaft is 350 mm, the pile cap is free standing above the ground surface. The max angle of internal friction between the pile shaft materials and the sand, $Ø^\backslash$, was experimentally determined using direct shear test apparatus, Fig. 3. The direct shear tests were performed between sand and manufactured 60 cm * 60 mm square piece of aluminum, steel, timber, and plastic.

The angles of internal friction, $Ø^\backslash$, are 18, 17, 16, and 9 degrees for aluminum, steel, timber, and plastic respectively. The direct shear test results are shown in Fig. 3. The load was applied using a manually operated loading device that gives an axial concentric load. The load was measured using a calibrated proving ring. The load was applied incrementally. Each increment was kept constant till no significant change occurs in pile settlement, that is to say the difference between two successive readings is less than 0.01 mm per 5 min for three consecutive readings under the same load. The corresponding pile group displacements were measured using two-dial gauges. The average displacement is calculated from dial gauges readings and used to draw pile group, Load–displacement relationship for each experiment. Rotation was calculated for each load increment and plotted against the applied load, where the rotation, $\Delta L/L$ is calculated as the difference in readings between dial gauges, ΔL over the horizontal distance L between the two dial guages, The ultimate pile group load was determined at a displacement equal to 5% of the

Table 3 Test m program for 6-pile group (G3), properties of dissimilar pile.

Test ID	T6-1	T6-2	T6-3	T6-4	T6-5	T6-6
Material	Aluminum	Aluminum	Aluminum	Aluminum	Aluminum	Aluminum
Modulus of elasticity, E, GPa	70	70	70	70	70	70
Length, mm	400	350	300	200	400	400
Diameter, mm	12	12	12	12	8	6
Average Displacement, mm	0.86	0.34	0.31	0.25	0.32	0.288
Rotation, $\Delta L/L$	–	–	–	–	–	–

Table 4 Test m program for 9-pile group (G4), properties of dissimilar pile.

Test ID	T9-1	9 T9-2	9 T9-3	9 T9-4	T9-5	T9-6
Material	Aluminum	Aluminum	Aluminum	Aluminum	Aluminum	Aluminum
Modulus of elasticity, E, G Pa	70	70	70	70	70	70
Length, mm	400	350	300	200	400	400
Diameter, mm	12	12	12	12	8	6
Average Displacement, mm	0.74	0.7	0.69	0.67	–	–
Rotation, $\Delta L/L$	–	–	–	–	0.725	0.71

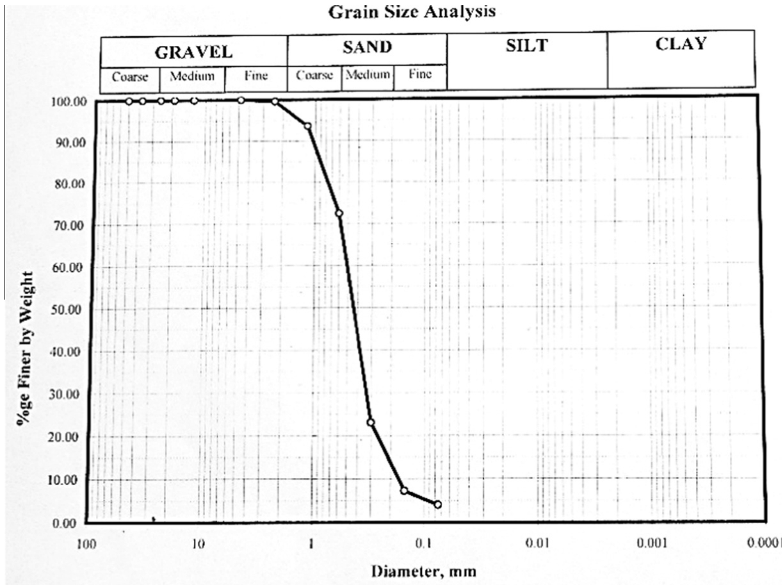

Figure 2 Grain size distribution curve for sand.

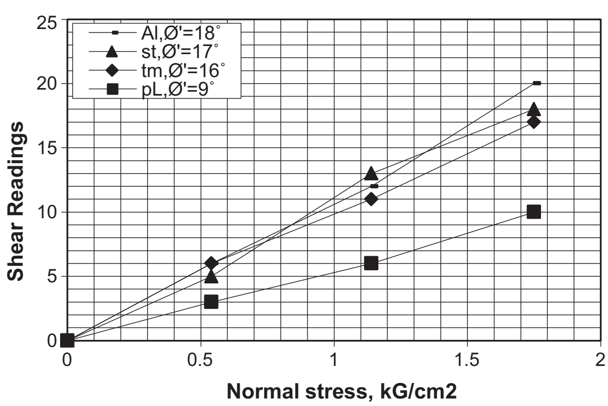

Figure 3 Angles of internal friction between the pile shaft materials and the sand.

reference pile diameter, 12 mm, and at rotation of pile cap equal to 1:500 whatever the less. The deficiency, η_o, can be defined as the ultimate load of pile group attained when dissimilar pile is incorporated in the group subtracted from the ultimate load of pile group having similar piles and dividing the resulting value by the ultimate load of group having similar piles as shown in Eq. (1). Reference tests were carried out on groups having similar pile to study the deficiency due to the presence of dissimilar pile within the group, the deficiency was plotted against the length ratio, and diameter ratio of the dissimilar pile related to reference pile. It is worth mentioning that no rotation was allowed in the reference tests on pile groups. This was assured by the difference in readings of the two dial gauges. The pile groups are not considered to exhibit rotation, as long as, the recorded rotation angle is less than 1/1000.

Obviously, the designed testing program and the test facilities are very simple and less costly, but the disadvantage of these tests is that the obtained results are affected by scale factor.

$$\eta_0 = \frac{Q_{\text{u dissimilar}} - Q_{\text{u similer}}}{Q_{\text{u similar}}} \tag{1}$$

4. Test results and discussion

4.1. 2-pile group

Fig. 4-a and b presents the effect of pile length ratio (L_{Dis}/L_{Sim}) and the diameter ratio (D_{Dis}/D_{sim}) on the response of 2-pile group. L_{Dis} is the length of dissimilar pile, L_{sim} is the length of similar pile, (reference length), D_{Dis} is the diameter of dissimilar pile and D_{sim} is the diameter of similar pile (reference diameter).

Fig. 4a confirms that as the ratio (L_{Dis}/L_{Sim}) decreased, that is to say the length of dissimilar pile decreased, the settlement of pile group and rotation increased and consequently the ultimate load of the pile group decreased. Consequently the deficiency of pile group increased substantially up to L_{Dis}/L_{sim} becomes 0.9. Beyond this limit the deficiency increased, but with smaller rate. This may be attributed to that the control of assessing the ultimate load of pile group, Where L_{Dis}/L_{Sim} bigger than 0.9, is the pile group displacement. For L_{Dis}/L_{Sim} smaller than 0.92. The control of assigning the ultimate load is the rotation of pile group. The rotation of pile group is mainly due to rotation of the reference pile, and the dissimilar pile becomes dummy pile, that is to say ineffective pile in the group.

It is interesting to notice that there is no appreciable effect of E_p/E_s in the initial range of pile group deficiencies shown in Fig. 4-A. This may be attributed to that E_p/E_s has no appreciable influence on the pile group vertical displacement compared by pile group rotation.

Fig. 4b indicated to that as the diameter of dissimilar pile decreased the deficiency of pile group increased, due to increase in pile group displacement and rotation. The single

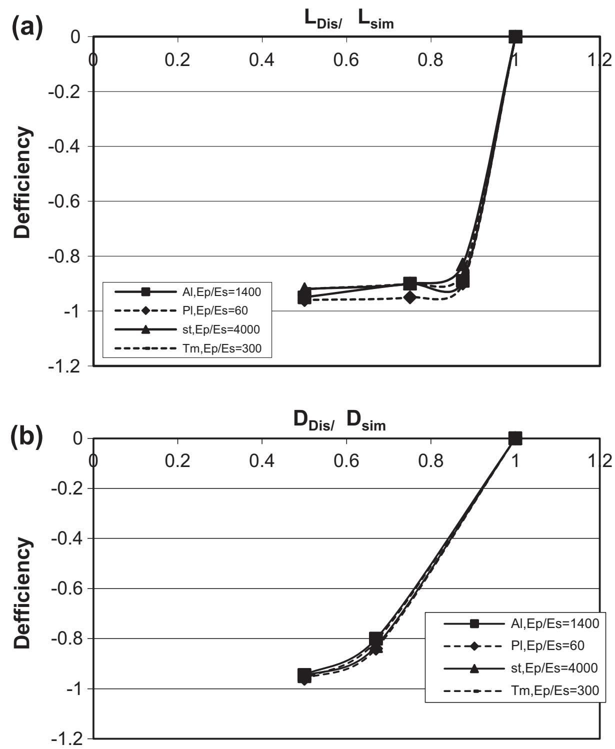

Figure 4 (a) Length ratio versus deficiency for different E_p/E_s for 2-pile group. (b) Diameter ratio versus deficiency for different E_p/E_s for 2-pile group.

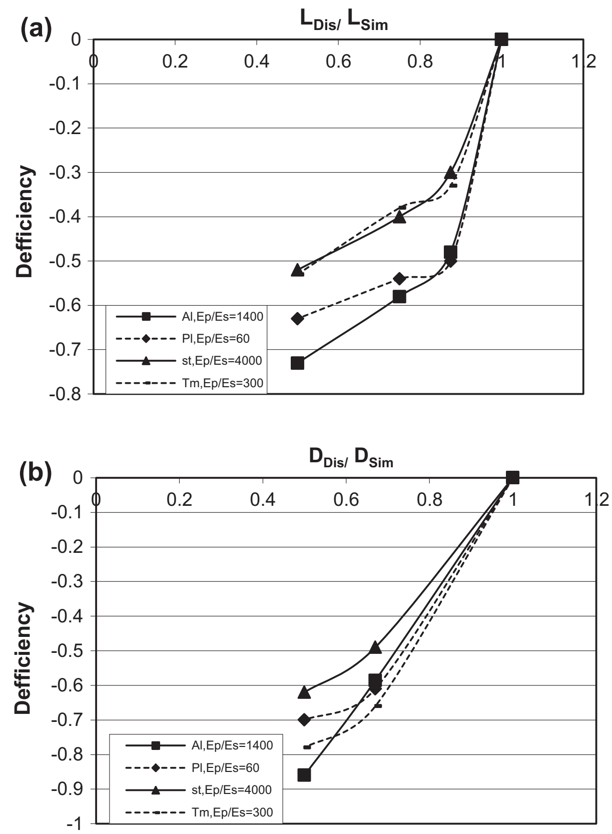

Figure 5 (a) Length ratio versus deficiency for different E_p/E_s for 3-pile group. (b) Diameter ratio versus deficiency for different E_p/E_s for 3-pile group.

pile displacement and also pile group displacement increases as L/D ratio of the pile increased. So the contribution of dissimilar pile in the displacement of pile group increases with the decrease in the pile diameter D_{Dis} Also pile group rotation increases as the pile diameter decreased. Fig. 4b indicated that the ultimate load of pile group is controlled by pile group displacement up to D_{Dis}/D_{Sim} equal to 0.65. Values of D_{Dis}/D_{Sim} less than 0.65, the ultimate pile group is controlled by pile group rotation. Again, the figure indicates that there is no appreciable difference of E_p/E_s on the deficiency of the pile group.

It is interesting to note that the deficiency of 2-pile group approach to unity when D_{Dis}/D_{Sim} is approaching 0.55. This means that the ultimate load of pile group having deficient pile vanished. In order to manipulate this finding in practice, and to keep deficiency value of the four pile groups at 0.2 the difference between pile lengths and pile diameters should not vary by more than 0.95 and 0.90 respectively in the group.

4.2. Three Pile group

The deficiency of 3-pile group arranged in triangular pattern was investigated when one pile of the three piles is shorter than the other two piles, Fig. 5a and also when the diameter of one pile is smaller than other two piles, Fig. 5b.

The figures indicated that the deficiency of the 3-pile group increases as the length of dissimilar pile decreased and also as the diameter of dissimilar pile decreased, the increase is linearly up to the length of dissimilar pile becomes 90% of the length of the reference pile. Beyond this limit of the pile length, L_{Dis}/L_{Sim} smaller than 0.9, deficiency increased with smaller rate. This may be attributed to the change of the mode of failure from pile group displacement to pile group rotation.

When the diameter of the dissimilar pile get smaller the contribution of dissimilar pile to pile group settlement increased and consequently the ultimate load of the pile group with dissimilar pile decreased as a result of that, the deficiency of pile group increased.

Fig. 5a and b indicates inconsistent effects of E_p/E_s this may be attributed to that the relative stiffness of dissimilar pile is expressed as EA/L_{Dis}. Where, E: is the modulus of elasticity of pile, A: is the cross sectional area, L_{Dis} is the dissimilar pile length. The relative stiffness of the dissimilar pile is different form relative stiffness of similar pile. Consequently, the results reflect a combination effect of pile length ratio and relative stiffness.

The implication of the achieved results in practice is useful in a way that pile of length equal to 92% from the length of the reference pile in a 3-pile group can reduce the efficiency of 3-pile group to about 93%. Also reduction of pile diameter to 90% can reduce the efficiency of 3-pile group to 80%, compared by pile group having similar piles.

Ten percent reduction in 3-pile group efficiency may be attained at 95% reduction in pile diameter. Ultimate load of 3-pile group having one pile with smaller diameter than the diameter of other piles by a ratio up to 40% is controlled by pile group displacement rather than pile group rotation. It is worth that the ultimate load of 3-pile group is controlled by pile group displacement as long as L_{Dis}/L_{Sim} is less that.

4.3. 6-pile group

One corner pile in 6-pile group was installed with different pile length to explore the effect of pile length dissimilarity on the response of the pile group.

Also corner pile of different diameters has been installed to explore the effect of dissimilarity of pile diameter on pile group response, Fig. 6a and b.

Fig. 6a indicates that the deficiency of pile group increased linearly as the dissimilar pile length decreases. It is worth noting that the deficiency of pile group attains 0.3 when the pile length of dissimilar pile decreased to 0.5 of the reference pile length.

However 10% deficiency attains when the pile length of dissimilar pile becomes 82% of the reference pile length. The figure indicates that the ultimate load of the pile group is due to excessive displacement of the group. Fig. 6b indicates that the deficiency of 6-pile group increased as the diameter of dissimilar pile decreased.

The displacement of single pile and pile groups increased as the length of the pile decreased at constant pile diameter, and as the diameter of the pile decreased at constant pile length. Also the figures indicate that the response of pile group, with dissimilar pile of length pile of length equal to 0.5 the length of the reference pile, or dissimilar pile of diameter equal to 0.5 the diameter of the reference pile, is not affected by the rotation of pile group.

This may explain the response of pile group as presented in drawing (6a) and (6b).

Fig. 6a and b presents that the effect of dissimilarity in pile diameter is less than the effect of dissimilarity in pile length.

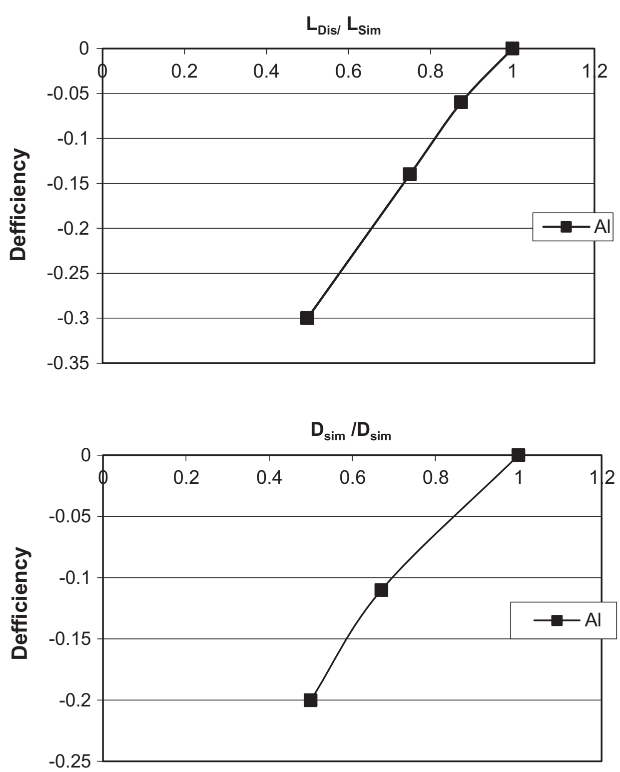

Figure 6 (a) Defficiency versus Length variation for 6-pile group, $E_p/E_s = 1400$. (b) Defficiency versus diameter variation for 6 pile group, $E_p/E_s = 1400$.

4.4. 9-pile group

The corner pile in 9-pile group was installed with different pile length to explore the effect of dissimilarity in pile length on the response of pile group.

Also piles of different diameter were installed to explore the effect of dissimilarity of pile diameter on the response of the group. The corner pile was chosen to be dissimilar in order to magnify the effect of the response of 9-pile group having dissimilar pile. The dissimilarity increases if corner pile is adopted compared by dissimilar edge or center piles.

Fig. 7a and b indicated the effects of, dissimilar corner pile on the response of pile group. The deficiency attained to 9% as the dissimilar pile length decreased to 50% of the reference pile length. The deficiency also decreased to 4% as the diameter of the pile decreased to 50%.

The dissimilarity in the configuration of pile group decreases as the number of similar pile in the group increased. The study was based on one dissimilar pile in a group. So it is anticipated that as the number of similar piles in a group increased the effect of dissimilar pile on the response of the group decreased and the deficiency of the group decreased.

The study revealed that dissimilar pile in two pile group is not recommend such group need remedy if the situation happened during construction.

If deficiency of the ultimate load of pile group is limited by 10%, the pile length of the deficient pile may attain 50%, 80%, 90% of the reference pile length in 9,6 and 3 pile group respectively Fig. 8a.

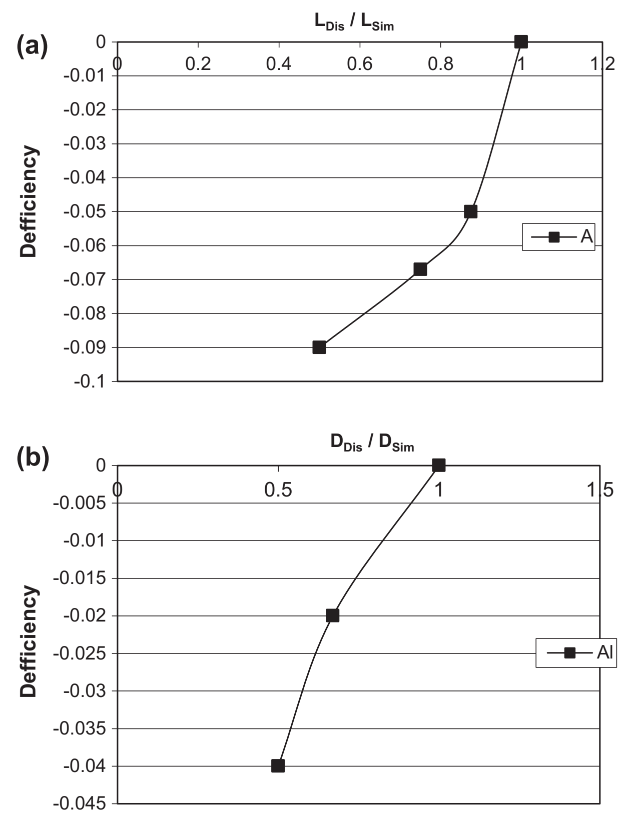

Figure 7 (a) Defficiency versus Length variation for 9 pile group, $E_p/E_s = 14000$. (b) Defficiency versus diameter variation for 9 pile group, $E_p/E_s = 1400$.

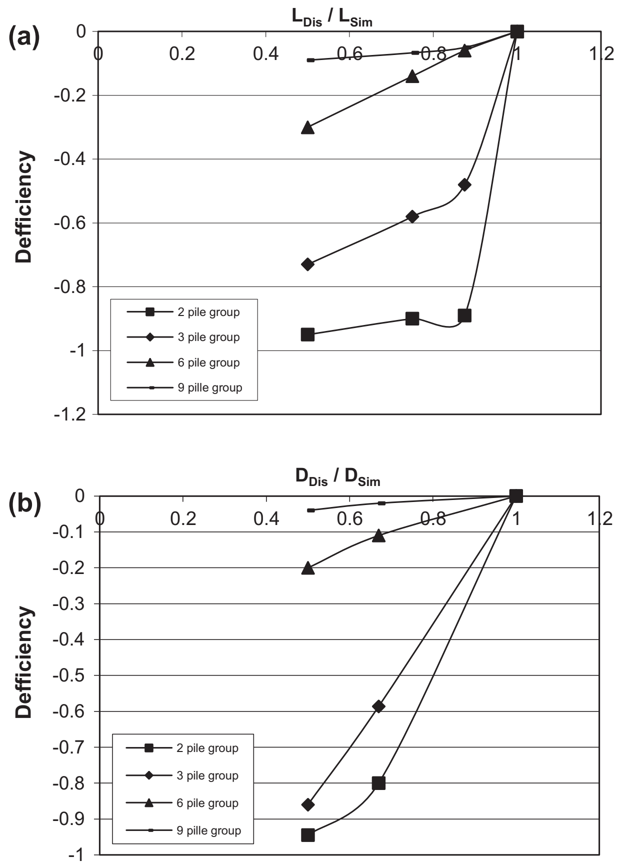

Figure 8 (a) Comparison between the deficiencies for different aluminum pile groups versus length ratio. (b) Deficiencies versus Diameter ratio for different aluminum pile groups, $E/E_s = 1400$.

The dissimilarity in pile diameter has less pronounced effects on the response of pile group. If the deficiency of pile group is limited to 10% the pile diameter of dissimilar pile in 9-pile group can be less than 50% while in 6 pile group 70% and 95% in three pile group as shown in Fig. 8b. But the structure design of dissimilar pile may limit the decrease in the diameter of the pile.

5. Conclusions

The course of investigation takes a practical problem may be arise during pile construction. Therefore, the achieved results may be practically implemented, at least qualitatively, due to scale effects of laboratory model. The course of study revealed the following conclusion.

1. It is advisable to form two pile groups of similar piles, Similar in length and similar in diameter, to avoid deficiency in the response of the group.
2. If the deficiency in ultimate load of 3-pile group is limited to 10%, the length of dissimilar pile having the same diameter as piles in the group shall not be less than 98% of other two pile length, and the diameter of the pile of the same length shall not be less than 95% of the pile diameter of the other two piles.
3. In case of 6-pile group, and for a limited deficiency of 10%, one corner pile out of the 6-piles shall have length not less than 80% of the other 5-pile length, with the same pile diameter. To limit the levels of deficiency at 10% the pile diameter should not be less than 70% of other 5-pile diameter, but with similar pile length.
4. Dissimilar corner pile in case of 9-pile group of length equal to 50% of similar pile, and having the same pile diameter causes deficiency of 9% of the ultimate load of pile group. However corner pile of diameter equal to 50% of similar pile diameter causes deficiency of 4% of the ultimate pile group.

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