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Experimental Investigation on Efficiency Factor of Pile Groups Regarding Distance of Piles

Mojtaba Pashayan [a*], Gholam Moradi [b]

[a] *Master, Civil Engineering Department, Tabriz University, 29 Bahman Blvd., Tabriz, Iran.*

[b] *Professor, Civil Engineering Department, Tabriz University, 29 Bahman Blvd., Tabriz, Iran.*

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Abstract

There are a lot of the parameters which affect pile group behavior in soil. One of these factors is the distance of piles from each other. The impact of distance on pile groups in sand has been investigated through some researches, whereas most of them have not represented an exact estimation according to the continuous change of the distance in sand. Moreover, most of previous investigations have considered two piles as a perfect group. Since two-pile group has the least interaction effect among piles, it cannot suitably demonstrate the influence of spacing. In this lecture, several 4-pile groups modeled with different spacing were subjected to axial loading in laboratory. The pile groups were free-head with length to diameter ratio of 13.5. The piles are designed in a way which the shaft resistance of piles can be completely mobilized through the test. Then, the bearing capacities of pile groups are measured and compared with the single pile's resistance in order to calculate the efficiency coefficient of the groups. It is revealed that the distance is noticeably effective in efficiency factor and this effectiveness, non-linearly decreases by increase of spacing. The results show that the efficiency coefficient is changing between almost 1 and 1.4.

Keywords: Pile Group; Spacing; Distance; Efficiency; Axial Loading.

1. Introduction

Since the computational formulas are too conservative, designers take the advantages of practical experiment, satisfied with concepts such as the efficiency coefficient and the ratio of the pile group settlement. These two factors are properly able to represent the performance of the group. Nevertheless, due to the cost of the real size test, the laboratory models are more reasonable.

The influence of distance on group piles' behaviour has been investigated through some researches and it is clear that the increase of piles' spacing declines the effect of piles on each other in most aspects [1, 2], but most of them have not represented an exact estimation according to the continuous change of distance in sand. Moreover, most of previous investigations have considered two piles group as a perfect group. Because the interaction between piles enhances with increasing of the number of piles in group, in this lecture, 4-pile groups are investigated to better show the influence of spacing. In groups with more piles the loads are not distributed equally among piles. Therefore, four piles are suitable.

In one of the previous works, Vesić (1969) declared that the efficiency of the pile group in sandy soil is higher than 1 only if the density of sand or the distance between the piles is not high .Moreover, in the distance ratio of 2 to 3 times of the diameter, the efficiency reaches maximum state (1.3 to 2, respectively) [3]. Poulos and Davis (1980) have obtained

* Corresponding author: mojtabapashayan@yahoo.com

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the interaction factors for the bivalent pile groups in two modes of friction (floatation) and end bearing. These factors, which are used to estimate settlements, display how piles influence each other. The interaction factor decreases with the increase of distance-diameter ratio. As a result, their influence declines [4].

Robinsky and Morrison (1964) investigated the amount of compactness and relative density around the pile using radiographic technique. It was found that in relatively loose sand ($D_r = 17\%$), soil movement proceeds in range of 3 to 4 times the diameter of the pile from the sides and 2.5 to 3.5 times of diameter, below the pile point. In a relatively dense sand ($D_r = 35\%$), the amount of motion is slightly larger and equals 4.5 to 5.5 times the diameter of the pile from the sides and 3 to 4.5 times below the pile point [5]. Ismael (2001) conducted some experiments on sand in real size. He concluded that pile group with distance-diameter ratio of 2 and 3 has the efficiency coefficient of 1.22 and 1.93, respectively [6]. Basile (2003) declared that the two parameters are effective in the behaviour of pile group and load distribution. First: the interaction of adjacent piles. Second: the hardened soil which is enclosed among pile groups [7].

Le Kouby et al. (2016) demonstrated that efficiency coefficient based on the pile spacing ratio, in the tip resistance, increases or stabilizes by values always smaller than one. The efficiency coefficient exhibits a decrease with an increasing pile spacing ratio when considering shaft friction [8].

2. Materials and Testing

The experiments were conducted in the laboratory of the Faculty of Civil Engineering, Tabriz University. In these experiments, 5 different modes were tested. Four of which were pile groups with different spacing, and the fifth one was a single-pile which was used to obtain an efficiency coefficient.

2.1. Properties of Soil

0.4 cubic meters of sieved sand (sieve no.20) used in the experiments. Three experiments were conducted to determine properties of the soil. The soil profile obtained from the graining curve is presented in Table 1 and **Figure 1**.

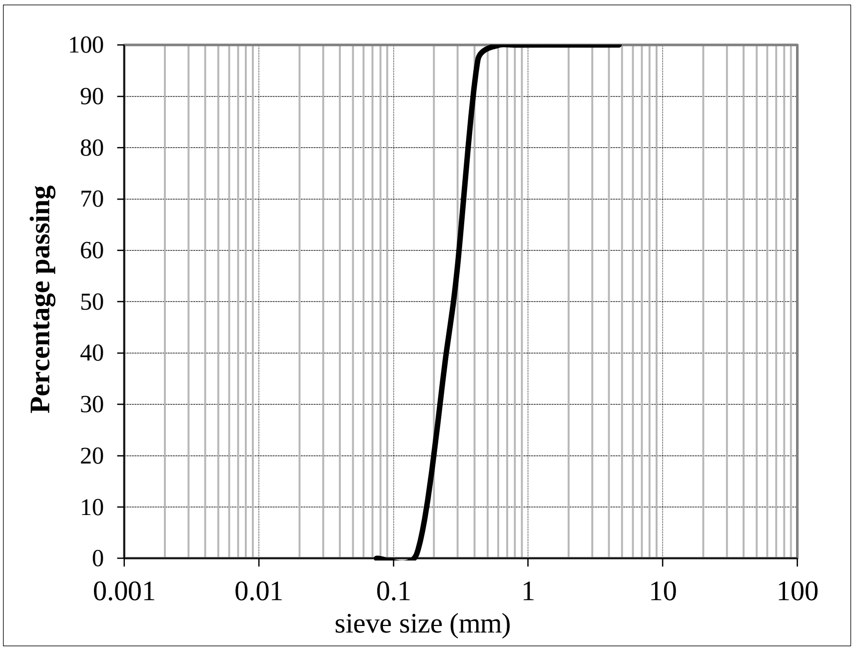

Figure 1. Grain-size distribution

Table 1. Properties of soil

C_c	C_u	D_{50}	D_{10}	D_{30}	D_{60}
1.04	20.6	0.27	0.15	0.22	0.31

As it is obvious, the soil type is SP. In addition, the results of relative density test revealed that the maximum and minimum dry soil density was 1.75 and 1.49 grams per cubic centimetre, respectively. The density of the soil in the tank, which was poured from the raining sand machine, was measured to be 1.65 grams per cubic centimetre. Accordingly, relative density is obtained at about 65%. This relative density is suitable for our test because in very dense or very loose sand the change of distance does not have an impressive effect [9].

$$\gamma_{d(average)} = 1.65 \frac{gr}{cm^2} \quad (1)$$

Direct shear test was performed to determine the internal friction angle of the soil which was φ =38.

Figure 2. Equipment of experiments

The internal friction angle of the sand is directly related to the relative density. Bowles (1996) converted the relative density to $\emptyset'$ using the suggested following equation. The obtained friction angle and the relative density seem to be correct since they match Equation 2 [10].

$$\emptyset' = 28 + 15\, D_r \quad (2)$$

2.2. Testing Equipment

The testing set consists of two separate parts. One part is a tank which contains the soil of experiment is connected to the loading arm. The dimensions of the tank are 800 × 800 and 600 mm in depth. The other part is deployed for sand raining located above the main tank. As shown in Figure 2, a hydraulic piston is responsible for providing the reciprocating movement of the second case. The reason for using a sand pluvial/raining method is to create homogeneous circumstances for tests. The relative density of the sand in the raining operation system is essentially dependent on the height of the pouring and the rate of sand discharge. The height of the sand raining in the tests is constant and the rate of the sand discharge is controlled by the opening of valves of the case. As mentioned, the density of the soil in the tank was 1.65 grams per cubic centimetre.

The wall of the tank could be influential in the stress and settlement of the pile group. Friction between the soil and container wall can reduce the vertical stress in the sand. This friction can result in the vertical stress being transferred to the wall [11]. In fact, the effect zone of the wall varies depending on the soil density and the instalment method of the piles [12]. According to the testing dimensions, the distance between the wall and the piles is 13 times bigger than the diameter of the piles, which is satisfying.

2.3. Model piles

The piles used in experiments are equal. These piles are steel and with the intention of reducing their weight, hollow ones have been used. The outer diameter of the piles is 22.2 mm, the inside diameter is 16 mm with the useful length of 30 cm. Based on the dimensions presented, the ratio of length to diameter of the piles is evaluated to be 13.5.

Figure 3. Model piles

The top part of the piles (4 cm length) is used to fix them to the cap and the grip set. Since the roughness of the piles significantly influences the shaft resistance and confining pressure of soil around the pile [13, 14], the outer part of the pile is covered with sandpapers as shown in **Error! Reference source not found.**, in order to mobilize the shaft resistance [14, 15]. Even though, the dimensions of test are not equal with real size in practice, the behaviour and mechanism of the reactions between piles and pile-soil are the same. The tests are designed in the biggest possible size and the soil and shaft material have been chosen from materials that can behave like a real size in practice.

It is demonstrated that in 4-pile groups, all of the piles endured the identical force and the maximum difference was between 3% and 7% in piles. There was a significant difference in the 9-pile group and the central pile tolerated 36% more force than the average bearing [3, 16]. Therefore, the arrangement of the piles in all cases was 2 × 2, so that the load is spread homogenously between the piles and the possibility of interruption by other factors was eliminated.

In these experiments similar caps have been designed for four modes. Caps thickness was 5 mm, and their size 20 to 20 cm. To have a uniform settlement, the cap should have rigid behaviour. In this regard, using the SAP2000 program, cap behaviour was modelled at the worst possible mode and the deformation rate was less than 0.01 mm. Therefore, it can be said that the cap behaviour was rigid.

The free standing mode is considered in these experiments since Lee and Chung (2005) proved that the interaction among piles is severely affected by the cap in comparison to a free standing group. Indeed, he showed the pile group capacity with cap remarkably increased at narrow pile spacing of 2d and 3d and then dramatically decreased at widening pile spacing [17].

2.4. Test procedure

The loading of the experiment has continued with consecutive imposing of weights which were 1 kg, till reaching 20 mm settlement. In regard that loading speed is effective in the bearing capacity, the loading speed during all experiments was constant and slow [18]. A load cell was set to record and send pressure of loading to the pc prepared for these experiments. In the same way, the settlement was recorded by a LVDT (Figure 2). All the data were saved in the pc in a special program to analyze.

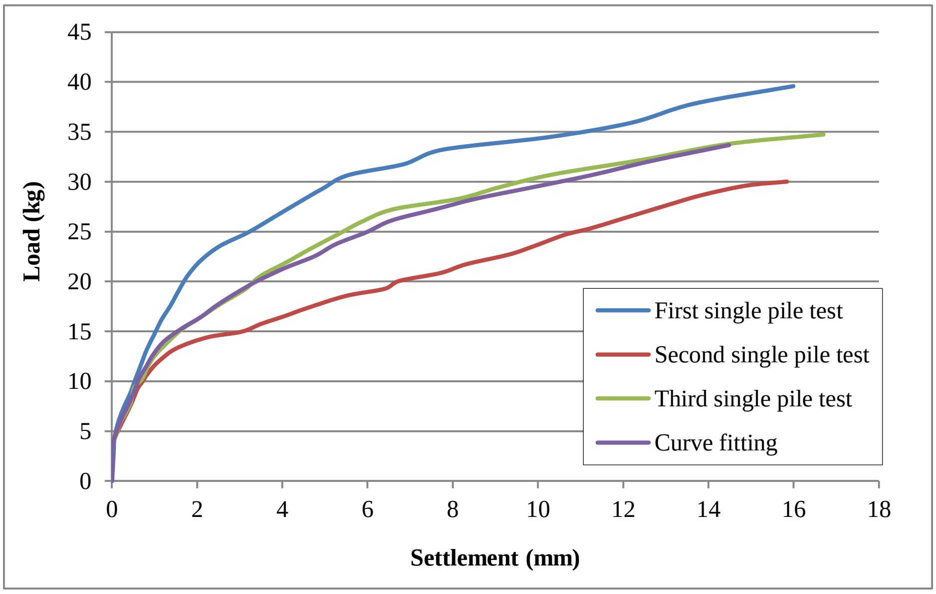

Figure 4. Load – settlement of single pile

The loading of the experiment has continued with consecutive imposing of weights which were 1 kg, till reaching 20 mm settlement. In regard that loading speed is effective in the bearing capacity, the loading speed during all experiments was constant and slow [18]. A load cell was set to record and send pressure of loading to the pc prepared for these experiments. In the same way, the settlement was recorded by a LVDT (Figure 2). All the data were saved in the pc in a special program to analyze.

In order to investigate the effect of distance in the behaviour of the pile group, experiments were carried out in 4 different spacing including 3, 4, 5 and 6 times the diameter of the pile. It is worthwhile mentioning that the maximum value was considered 6 times pile diameter because from this point on, piles start to take the form of the single-pile. In addition, further spacing may cause interference of the tank-wall. It is noticeable that the distance should not be less than 2 times the diameter of the pile too since the soil loses its integrity and there would not be the desired interaction between soil and pile.

Each of these experiments was repeated 2 times. Sometimes, when it seems that the existing errors had a significant impact on the test results, the experiment was repeated and the test result which was more different from others is omitted. Single-pile experiments have been repeated 3 times. The intention of the experiment repetitions was reducing the error effect and reaching the most actual response. Although it is done to reduce the error to the lowest possible extent, the results are not error-free. The grip set, used to hold piles, causes inconsistency in pouring of sand, among the piles, which could reduce soil density of that area.

3. Results and Discussion

Single-pile tests continued to 1.5 cm settlement since single piles were ruptured in this settlement. As deduced from the figures, when the pile settles 1.5 centimetres, it comes close to the full- failure and loses its resistance against the load. The bearing capacity of the pile is about 20 kg and settlement is almost 3.2 mm. It should be noted that the bearing capacity is approximately evaluated through the fitting curve by Double Tangent method.

As it is obvious, the results of the tests of the pile group show less fluctuation than the single-pile. It can be stated that due to the high bearing capacity of the pile group compared to a single-pile, the effect of the errors is insignificant. The load-settlement curve of pile groups are shown in Figures 4 to 7.

The results show that in the spacing of 6 times the diameter, the efficiency coefficient reaches less than 1, but considering the error factors, it can be stated that the efficiency coefficient in the spacing of 6 times the diameter is also approximately 1. In fact the grip set in pile group is bigger causing some inconsistencies in soil which make the soil around the shaft looser than the single ones. Therefore the coefficient efficiency is smaller than 1.The efficiency of pile groups is more than single pile and this increase maximizes at closer distances. These results are similar to the results which previous researchers have achieved such as Vesić (1969) [3], Sales et al. (2017) [19], Lee and Chung (2005) [17]. In groups with distance of 3d, piles have interaction to each other. This interaction is a function of density and friction angle. In practice, the driven pile raises the soil density, and consequently increases the bearing capacity of the pile group. On the contrary, in situ pile is accompanied with well digging, resulting in looseness and decreasing the soil density. In addition, the materials used in this method like bentonite intensify the looseness. These two methods of installation have different effects on interaction factor [19-20]. In these experiments, none of these conditions was exactly dominated since piles initially were set. Then the soil was poured in the tank. In other words, the soil around piles is not sensibly disturbed.

The previous researches show that shaft resistance is not influenced by the installation method. Le Kouby et al. (2013) proved that the maximum resistance of pile tip in jacking installation is remarkably higher than non-displacement pile. However, in terms of shaft friction, despite the first phase of non-displacement loading test showing a stiffer response, the maximum values are similar [21].

As mentioned the tip resistance in pouring system is not so sensible. Consequently, it seems that shaft resistance is the most important item in groups in sand. In fact, the simultaneous presence of all piles in the soil mass increases the hardness of the enclosed soil, and as a result, more friction forces are mobilized. The small distances more intensively enclose the soil so it has no place to escape. The trapped soil under imposed loading settles and the density of it increases, which results in higher lateral earth pressure, so that the resistance of shaft would increase [22]. In other words, interaction between piles helps each other to endure more. With increasing of spacing, interaction between piles decreases and therefore the bearing capacity of the soil containing the pile group also declines. In spacing of 6 times pile's diameter, the efficiency coefficient decreases to the point that piles turn out to be single piles which perform separately. In that case the efficiency factor is almost one. It is also noticeable that the rate of the efficiency change is interesting. As seen the difference of efficiency coefficient between groups with distance to diameter ratio of 3 and 4 is 19% whereas the its difference, between groups with spacing-diameter 5 and 6 is 11%. This shows that interaction factor is more effective in closer distances and the change of distance impresses the bearing capacity more intense in small spacing.it seems that shear stress in shaft is mobilized more so the resistance increases intensively.

Moreover, it seems that with increase of the distance, the amount of settlement is declining. Actually the pile group has desire to show more settlement than single pile due to larger width that the pile group has. In lower spacing, the pressure bulbs produced by every pile overlap each other and cause a higher stress imposed to soil which result in higher settlement. In larger distances, the amount of settlement is restricted to constant amount.

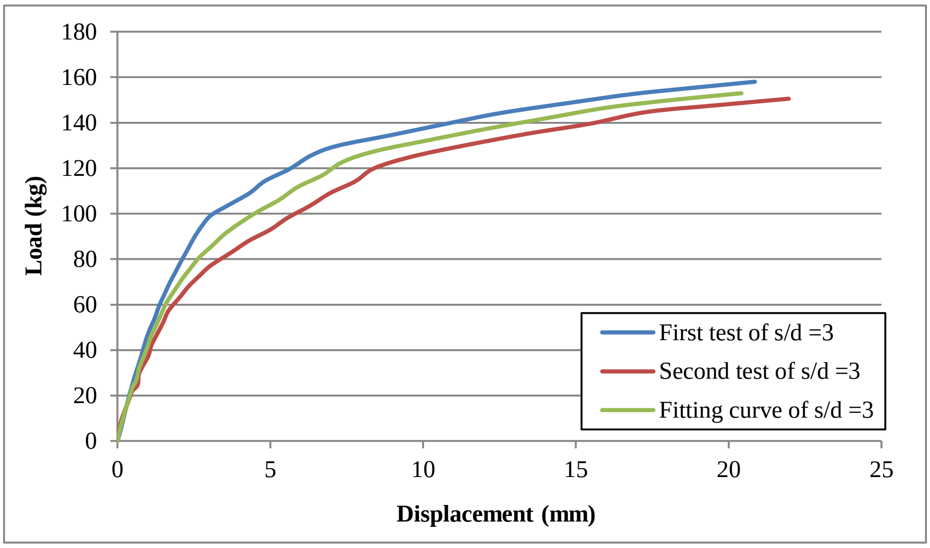

Figure 5. Load-settlement of $s/d = 3$

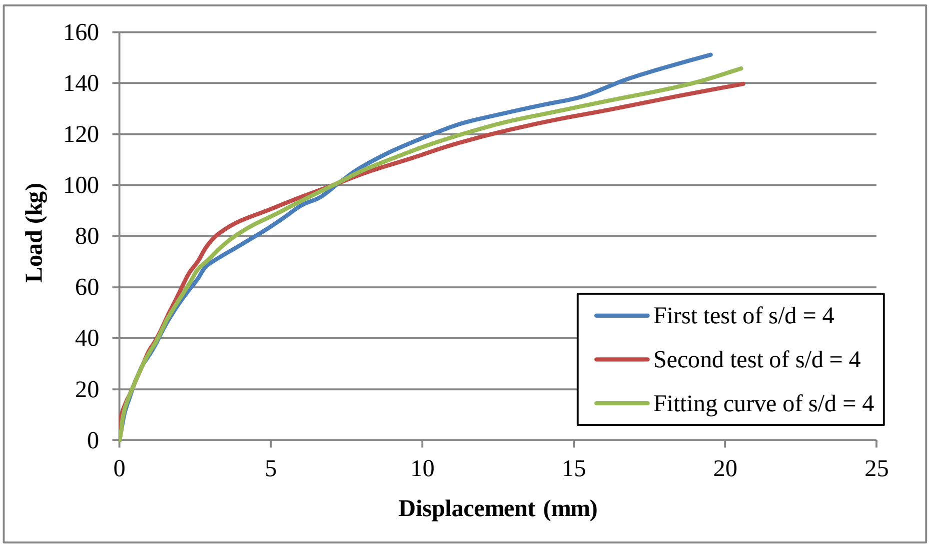

Figure 6. Load-settlement of $s/d = 4$

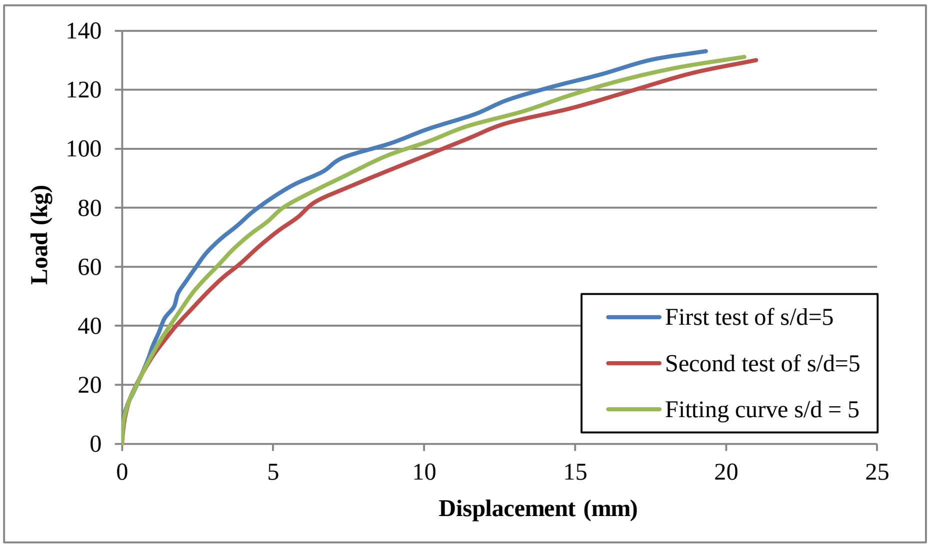

Figure 7. Load-settlement of $s/d = 5$

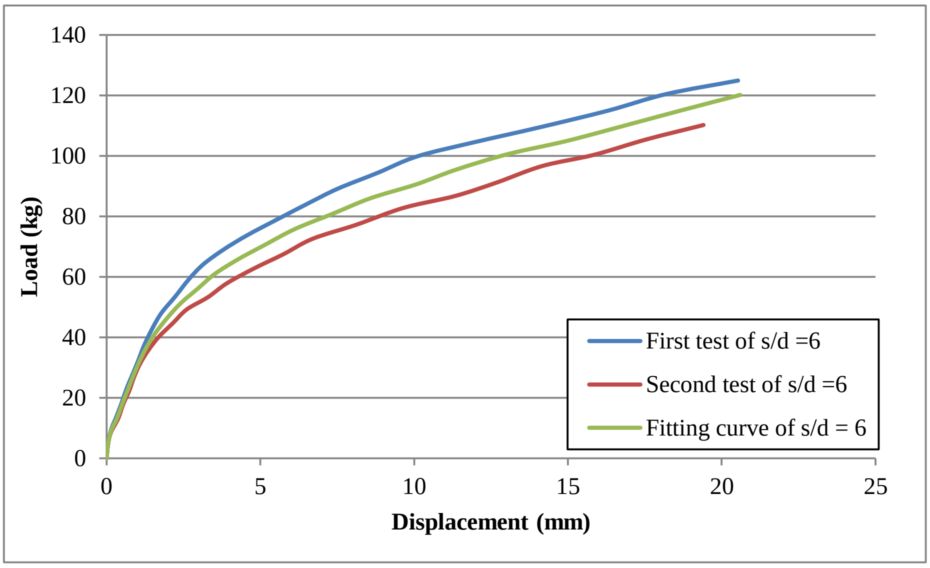

Figure 8. Load-settlement of $s/d = 6$

Table 2. Efficiency coefficient at different spanning

	Force (kg)	Settlement (mm)	Efficiency coefficient
Pile group with $s/d = 3$	112	7.31	1.40
Pile group with $s/d = 4$	97	6.9	1.21
Pile group with $s/d = 5$	84	6.2	1.06
Pile group with $s/d = 6$	76	6.2	0.95

4. Conclusions

Based on the findings of the current study it can be concluded that:

- The spacing between the piles has a significant effect on the efficiency coefficient of the pile group.
- In general, the behaviour of the pile group embedded in sand is such that the efficiency coefficient would be greater than one.
- As the spacing of the piles increases, the efficiency coefficient of the pile group decreases. This value is equal to 1.4 for a spacing of 3 times the diameter of a pile. As the distance-diameter ratio increases, this value reaches 0.9 in the spacing of 6 times the diameter of the pile, which is close to 1.
- The change in distances in closer spacing is more effective on bearing capacity than n case of far spacing.
- With increase of spacing, the settlement decreases since interaction between piles decline which always is higher than single pile.

5. Acknowledgement

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6. Conflicts of Interest

The authors declare no conflict of interest.

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