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Behavior of closely spaced square and circular footings on reinforced sand

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Abstract

This paper describes an experimental investigation conducted to evaluate the ultimate bearing capacity, the settlement and the tilt of two types closely spaced footings, one having square shapes and the other having circular shapes, on unreinforced and reinforced soil. To decrease the objectionable influence of interference on the performance of the closely spaced footings, the foundation soil is reinforced by geogrid layers. The results of this reinforcement show both positive and negative effects, namely, a positive effect because there is a considerable increase in the ultimate bearing capacity, and a negative effect because there is an increase in settlement and tilt. Regarding the experimental results, the negative effect of interference can be decreased considerably through the use of soil reinforcements. The ultimate bearing capacity of the interfering footings increased by about 25–40%, whereas the settlement of the interfering footings at the ultimate load increased in the range of 60–100%. However, the closely spaced footings tilted by approximately 45% and 75% for reinforced sand with one and two layers of geogrid, respectively.

Keywords: Sand; Ultimate bearing capacity; Settlement; Tilt; Interfering footing; Geogrid

1. Introduction

Interference occurs when a number of closely spaced footings are constructed. This occurrence has a significant effect on the ultimate bearing capacity, the settlement, the tilt and the failure mechanism of the footings. The influence of the interference on the above-mentioned factors is directly related to the distance between adjacent footings. Most prior studies have focused on the ultimate bearing capacity of interfering strip footings on unreinforced soil (Stuart, 1962; Das and Larbi-Cherif, 1983; Wang and Jao, 2002, Kumar and Ghosh, 2007; Mabrouki et al., 2010). The results of these research works have indicated a significant increase in the ultimate bearing capacity of neighboring footings.

Due to advances in soil reinforcement, numerous investigations have been carried out to describe the ultimate bearing capacity of single shallow foundations on reinforced sand with geogrids (e.g., Guido et al., 1986; Yetimoglu et al., 1994; Omar et al., 1993; Adams and Collin, 1997; Boushehrian and Hataf, 2003; Huang and Hong, 2000). All these researchers have revealed that reinforcing the foundation soil can significantly increase the ultimate bearing capacity, which is maximized at a particular critical size and resting location for the geogrid layers. This has encouraged investigators to study the performance of interfering footings on soil reinforced with

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geosynthetics (Khing et al., 1992; Kumar and Saran, 2003; Ghazavi and Lavasan, 2008). These studies were focused on the bearing capacity of the interfering strip and square footings on reinforced earth. Although the settlement of interfering footings on reinforced soil was not considered in the existing studies, the tilt of two identical adjacent square and strip foundations was investigated by Kumar and Saran (2003); however, Ghazavi and Lavasan (2008) revealed some ambiguities in their results. Therefore, studies on the objectionable influence of interference, settlement and tilt in particular, have received little or no attention. In addition, the influence of the footing shape (especially for round foundations) on interference merits a thorough investigation. Hence, the bearing capacity, the settlement and the tilt of interfering square and round shaped footings on unreinforced and reinforced soil are herein presented.

In the present study, a total number of 20 large-scale model tests were performed on sets of closely spaced square and circular footings placed on unreinforced and reinforced sand with one and two layers of geogrid. To control the reproducibility of the experimental results, four extra tests for single and interfering square and circular footings were randomly replicated and the obtained values were compared. These comparisons resulted in an encouraging agreement. The variation in ultimate bearing capacity, settlement and tilt of the interfering square and circular footings were evaluated on the basis of the test results.

2. Experimental test procedure

A series of large-scale model tests was conducted in a rectangular test box, 4 m in length, 3 m in width and 1.2 m in depth. The size of the test box was in conformity with those reported by Ueno et al. (1998) for large-scale circular and square surface footings. The footings considered in this experimental study were assumed to be square and circular with a width and a diameter both equal to 40 cm. The footings were made from steel plates with a thickness of 30 mm. The bottoms of the rigid footing plates were made to be rough by attaching coarse sandpaper to them with glue. The footings were placed at a soil surface having no embedment depth. The footings were loaded at a constant loading rate of 10 mm/min until a settlement of 10 cm was reached. Therefore, the tests were performed under displacement-controlled conditions. In order to measure the tilt of the footings during the tests, a skullcap groove was scraped in the center of the footings. The loading shafts were tipped to a half-sphere shape sitting in the skullcap zone at the center of the footing plates. This zone was completely lubricated with grease to decrease the friction on the surface. Accordingly, the loads applied on the footings remained vertical throughout the tests and the footings were allowed to tilt conveniently during the loading process without the undesirable effects of inclined loading (Saran et al., 1971). To apply equal loads to the footings, two identical hydraulic jacks, charged by a single hydraulic unit at the same pressure for each step of loading, were rigidly connected to the stiff reaction beam. To measure the magnitudes of tilt and settlement of the footings, four Linear Variable Differential Transformers (LVDTs) were connected to the centers of the footing sides in machine and cross machine directions, as presented in Fig. 2. Therefore, the tilt of the foundation was calculated by considering the difference between the two opposite LVDTs in each direction.

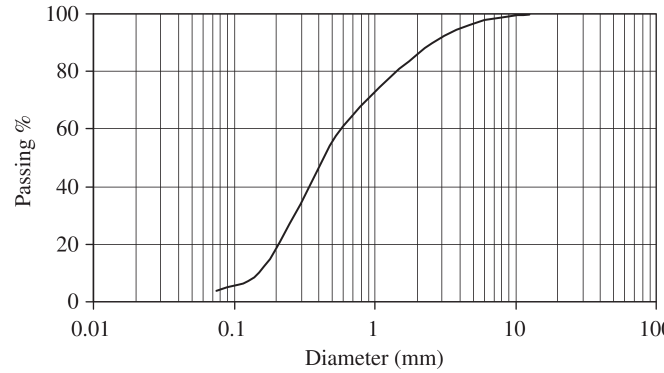

Fig. 1. Average curve of grain size distribution for 4 samples of sand used in present study.

Table 1
Physical properties of soil in present study.

Parameter	Value
D_{10}	0.15 mm
D_{30}	0.26 mm
D_{60}	0.54 mm
U_c	3.6
C_c	0.83
ω	7%

The soil considered in the entire test study was round-shaped silica sand classified into SP according to the Unified Soil Classification system. The average result of the grain size distribution test for the four samples is presented in Fig. 1. The physical properties of the soil used in the experimental study are indicated in Table 1.

For each test, the sand was initially filled in the test box in 20-cm-thick layers. To obtain uniform compaction, five blows of a 10-kg steel hammer, dropping from a height of 53 cm, were tamped on a 40×40 cm^2 steel plate 5 mm in thickness. With this method, the compaction energy exerted on the sand soil in the test box was approximately equal to 8200 N m/m^3. The obtained relative density of the sand was about 40% and the corresponding unit weight was 15.1 kN/m^3. The angle of internal friction of the sand, estimated through drained triaxial shear tests at a relative density of 40%, was 34°.

A commercially available biaxial geogrid, made from high-tenacity polyester yarn and coated with a polymeric covering, was used as the reinforcement element. The geogrid was Miragrid GX 20/20, which was produced by Tencate Polyfelt. The tensile strength of the geogrid was reported to be about 5.5 kN/m at a strain of 3%. The geogrid had 3.5 cm and 2.0 cm openings in the machine and cross machine directions, respectively.

3. Test results and discussion

The geometry of the two closely spaced reinforced square and circular foundations and the contributing parameters are presented in Fig. 2. All the geometrical parameters of the interfering footings (i.e., Δ, B and D) and of the reinforced soil (i.e., u, d, b, h and N) are explained in this figure.

Regarding prior studies, the performance of a single footing on reinforced sand was optimized when the critical size and the location of the geogrid were approximately equal to $b=4B$, u and $h=0.3$–$0.5B$ for square foundations and $d=4D$, u and $h=0.3$–$0.5D$ for circular footings. Therefore, these critical values were considered for reinforcing the soil in this present study.

In the present study, in order to evaluate the influence of interference on the ultimate bearing capacity of the closely spaced footings, the interference factors on the ultimate bearing capacity, I_f and I'_f, are defined as

$$I_f = \frac{q_{u\text{-}int\text{-}N}}{q_{u\text{-}single}} \quad (1)$$

$$I'_f = \frac{q_{u\text{-}int\text{-}N}}{q_{u\text{-}single\text{-}N}} \quad (2)$$

where $q_{u\text{-}int\text{-}N}$ is the ultimate bearing capacity of the interfering footing on the reinforced soil with N layers of geogrid, and $q_{u\text{-}single}$ and $q_{u\text{-}single\text{-}N}$ represent the ultimate bearing capacities of the same single footing on unreinforced and reinforced soil with N layers of geogrid, respectively.

To control the consistency of the test preparation, the reproducibility of the single and interfering square and circular footings on unreinforced sand was checked by replicating the test. The difference between the bearing pressures obtained from the first and second tests was about 3% (for the single square footing), 7% (for the interfering square footing $\Delta=1.5B$), 5% (for the circular footing) and 4% (for the interfering circular footing $\Delta=1.5D$) at the settlement ratio (δ/B or δ/D) of 10%. These fairly excellent agreements proved the reliability of the experimentally obtained results.

To reinforce the soil beneath the interfering square footings, two separate square shaped geogrid layers, with a width of 1.6 m ($b=4B$), are placed at a depth of 20 cm for the footing bottom ($u=0.5B$). The soil beneath the interfering round-shaped footings is reinforced with circular geogrid layers with a diameter of 1.6 m ($d=4D$) and layered at a depth of 20 cm for the footing bottom ($u=0.5D$). On account of the considerable interrelation between the value of the ultimate bearing capacity obtained from the experiments and the test scale, the soil type, the material parameters, the reinforcement location, the loading rate and the magnitudes of the interference factors, the settlements and the tilts reported in this experiment correspond to the conditions considered in the present testing procedure. However, it is expected that the nature of the variation in the above-mentioned factors remains similar to that obtained from the present study.

To investigate the behavior of the interfering circular and square footings, the typical load–settlement curves for single and interfering foundations ($\Delta/D=1$ and $\Delta/B=1$) are shown in Fig. 3.

3.1. Ultimate bearing capacity of interfering footings

The variations in interference factor I_f at different spacing ratios for the interfering square and circular footings obtained from the experimental study are expressed in Fig. 4. In the present study, the ultimate bearing capacity of each footing is determined using De Beer's (1970) method. De Beer (1970) defined the ultimate bearing capacity as the load corresponding to the intersecting tangents of two linear portions of the load–displacement curve on the log–log scale. Acquiring this criterion to investigate the ultimate bearing capacity of

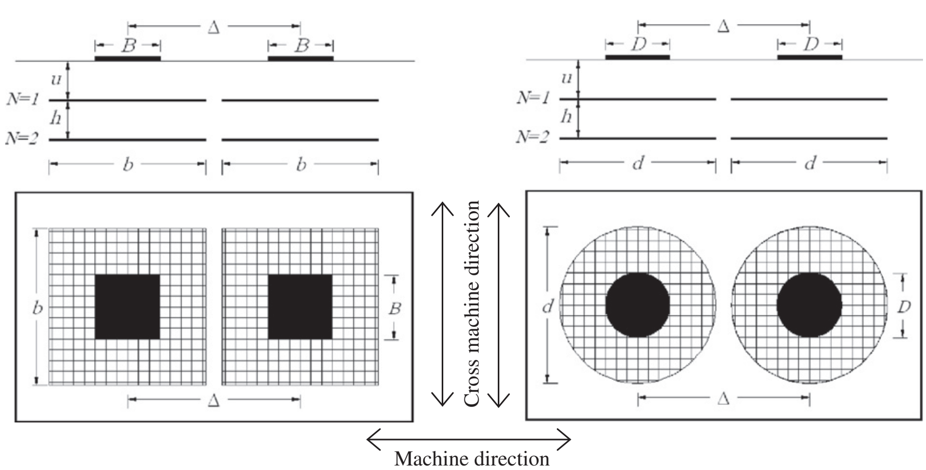

Fig. 2. Geometrical scheme and contributing parameters for interfering square and circular footings on reinforced soil.

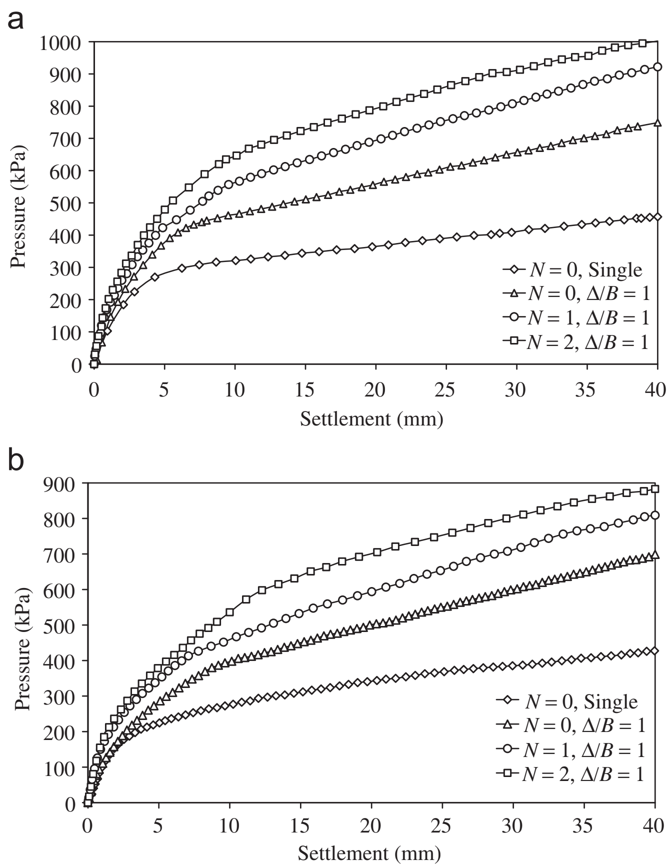

Fig. 3. Typical load–settlement curves for single and interfering footings in present study. (a) Square footing and (b) circular footing.

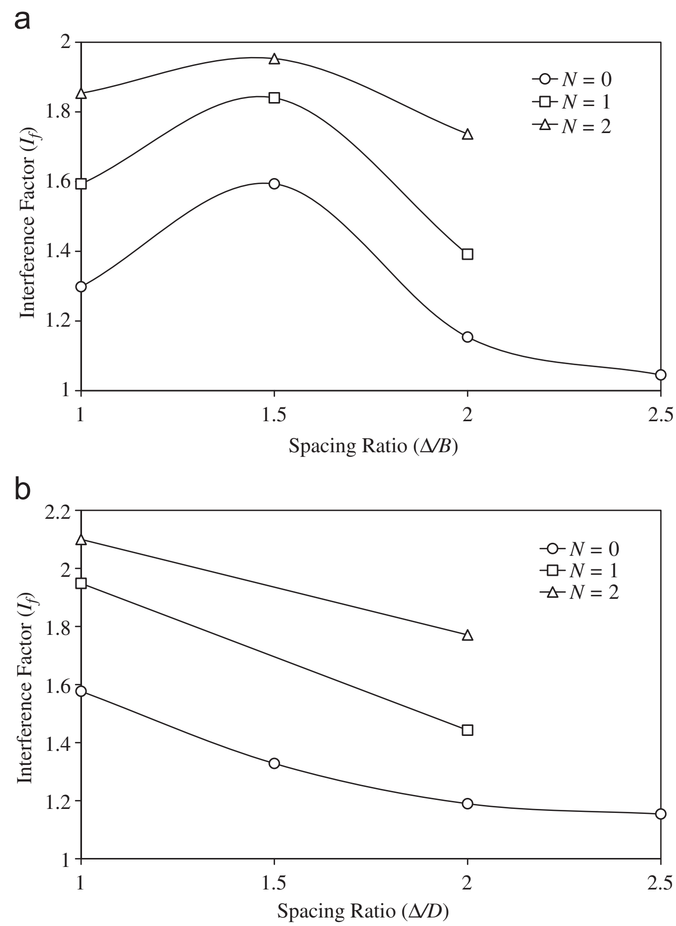

Fig. 4. Variation in I_f versus spacing ratio for interfering square and circular footings on unreinforced and reinforced sand: (a) Interfering square footings (for reinforced sand: $b/B=4$, $u/B=0.5$, $h/B=0.5$) and (b) Interfering circularle footings (for reinforced sand: $d=4D$, $u=0.5D$, $h/B=0.5$).

footings is appropriate when the load–settlement curve does not approach a constant value.

According to Fig. 4, the bearing capacity of the closely spaced footings is significantly influenced by the occurrence of interference. The ultimate bearing capacity of the footings increases with close spacing ratios. In addition, the interference factor for either square or circular footings is increased due to the use of reinforcements. According to Fig. 4(a), for two neighboring square footings, the ultimate bearing capacity increases with an increasing spacing between footings in the range of $\Delta/B \leq 1.5$. A further increase in distance between closely spaced square footings results in a decrease in the interference factor. Obviously, the ultimate bearing capacity is maximized when two adjacent square footings stand at a center-to-center spacing equal to 1.5B. Stuart (1962) related this event to the formation of an inverted arch beneath closely spaced strip footings, which is called ‘‘blocking’’. The results of tests performed in this study indicated that the soil between two square units at $\Delta/B=1.5$ traveled down with the footings, while the applied settlement was less than 20 mm. Therefore, the two individual footings acted as a single unit due to occurrence of blocking. When the settlement exceeded 20 mm, the soil between the footings heaved rapidly. According to Fig. 4(a), blocking occurs for interfering square footings on unreinforced and reinforced sand as well. As shown in Fig. 4(b), the ultimate bearing capacity of closely spaced circular footings tends to perpetually decrease with an increasing spacing between neighboring footings. Therefore, the interference factor is maximized when two adjacent footings are placed exactly beside each other ($\Delta/D=1$). Furthermore, blocking does not happen in the soil beneath two closely spaced circular footings. Lee and Eun (2009) also observed the same variation pattern for the interference factor versus Δ/D for interfering circular footings. This may be due to the rounded shape of circular foundations in which stress can flow in the soil around footings without any limitation or confinement. Obviously, when two square (or strip) footings are located at close spacing, the soil between them is locked between neighboring edges of the close foundations. Thus, the level of soil stress is increased in this zone by an increase in the load applied to the foundations. Since the stress cannot flow around square footings, the stress is concentrated at the edges of the footings and a block is formed in the confined soil between the foundations. This phenomenon results in the formation of a rigid confined block in the space between the square and the strip footings. However, the concentration of stress in the blocked zone is decreased by an increase in the distance between adjacent footings. Thus, the soil between two footings acts in an identical manner to the soil at the outer sides of the foundations and the blocking disappears in such a situation.

The maximum interference factor is about 1.6 for both interfering square and circular footings on unreinforced sand. According to the nature of the variation in I_f, it seems that the influence of the interference on the ultimate bearing capacity vanished for spacing ratios greater than 3.5–4 for the sand used in the present study.

There are different approaches for determining the ultimate bearing capacity of a shallow foundation from experimentally obtained load–settlement curves. According to the full-scaled tests conducted in the Laboratoires des Ponts et Chaussees (LPC) on a shallow foundation (Amar et al., 1994), the bearing capacity was consistently defined as the load corresponding to a settlement of 10% of the foundation width ($s/B=0.1$). On the other hand, some studies determined the bearing capacity from the point of the maximum curvature in the load–settlement curve. Therefore, the values for the ultimate bearing capacity obtained from the present study are compared with the existing analytical solutions and conventional codes. The results of this comparison are indicated in Table 2. As seen in the table, the bearing capacities obtained from De Beer's method are appropriately close to those calculated considering classical and recommended approaches. The difference between the experimental and the analytical values for the ultimate bearing capacity is firmly related to the simplifying assumptions which are made in the analytical calculations. This becomes more significant when a three-dimensional problem is considered. It also should be noted that in all the theoretical methods presented in Table 2, the formulations are based on a strip foundation and that different empirical coefficients are regarded in the estimation of the ultimate bearing capacity of non-strip shaped foundations.

Table 2
Comparison of bearing capacity for isolated footings from different methods.

Footing shape	Present experiments			Theoretical methods							
	LPC ($\delta/B=10\%$)	De Beer (1970)	Max. curvature	Euro[a] code	Hansen (1970)	Terzaghi (1943)	API[b] Rec	Chen (1975)	Feda (1961)	Meyerhof (1963)	Dewiakar and Mohapatra (2003)
Square	458	237	281	81	52	87	74	140	89	127	97
Circle	418	153	195	72	46	65	66	124	79	112	83

[a]Euro code (1993).
[b]API Recommendation (1984) and Norwegian Rules (1980).

Table 3
Comparison of interference factor I_f for closely spaced identical footings.

Footing shape	Reference	N	Δ/B				Description
			1	1.5	2	2.5	
Strip	Stuart (1962)	0	2	2.6	2.0	1.7	Theoretical, $\phi=35°$
	Das and Larbi-Cherif (1983)	0	1.8	2	1.7	1.6	Test, $\gamma=15.88$ kN/m^3, $D_r=54\%$, $\phi=38°$
	Kumar and Ghosh (2007)	0	2	1.7	1.4	1.2	Theoretical, mechanism I, $\phi=35°$
			2	2.5	1.9	1.4	Theoretical, mechanism II, $\phi=35°$
	Kumar and Saran (2003)	0	2	1.8	1.3	1.2	Test, $D_r=60\%$, $\phi=37°$, SP (continues geogrid, $b/B=3+\Delta/B$)
		1	1.4[a]	2.6[a]	2.3[a]	2.1[a]	
	Mabrouki et al. (2010)	0	2	1.7	1.2	1	Numerical, $\phi=35°$
Square	Ghazavi and Lavasan (2008)	0	1.5	1.7	1.9	1.6	Numerical, $\phi=34°$
		1	2.1	2.4	2.7	2.2	
		2	2.9	3.3	3.6	3.2	
	Present study	0	1.3	1.6	1.2	1.1	Test, $\gamma=15.1$ kN/m^3, $D_r=40\%$, $\phi=34°$ SP
		1	1.6	1.8	1.4	–	
		2	1.9	2	1.8	–	
	Kumar and Saran (2003)	0	1.4	1.9	1.4	1.2	Test, $D_r=60\%$, $\phi=37°$, SP (continues geogrid, $b/B=3+\Delta/B$)
		1	1.1[a]	1.2[a]	1.1[a]	1.1[a]	
Circular	Present study	0	1.6	1.3	1.2	1.2	Test, $\gamma=15.1$ kN/m^3, $D_r=40\%$, $\phi=34°$ SP
		1	1.9	–	1.4	–	
		2	2.1	–	1.9	–	
	Lee and Eun (2009)	0	1.8	1.7	1.3	1.2	Test, $\phi=35°$, SP-SM

[a]Values correspond to I_f' (Eq. (2)).

These coefficients are called shape factors. Such consideration can lead to a significant decrease in the accuracy of the results obtained from the analytical methods. In addition, De Beer's method of calculating the bearing capacity is recommended for cases in which the load–settlement curve does not approach a constant value (Amar et al., 1994; De Beer, 1970). The values of interference factor I_f, for two closely spaced identical footings, are presented in Table 3. As observed in the table, the interference factor of the strip footings is almost greater than that of the other shaped footings. This may be due to the plain strain condition of such foundations. A comparison of the results indicated in Table 3 demonstrates that the theoretical and the numerical solutions lead to considerably higher magnitudes of interference factors than the experimental test results. Obviously, the interference factors and the foundation soil properties are directly interrelated. This means that the values of the interference factor increase due to an increase in the strength of the soil beneath adjacent footings. Almost all of the research works show that blocking occurs for interfering square and strip footings. Thus, the ultimate bearing capacities of such footings are maximized at the critical spacing. This is in contrast to that which occurs for round-shaped closely spaced foundations where the maximum ultimate bearing capacity was observed when two footings were placed exactly beside each other.

3.2. Settlement of interfering footings

The influence of interference on the settlement of adjacent footings at the ultimate bearing pressure is investigated. The magnitude of the settlement (s) was normalized by dividing it by the width (B) or the diameter (D) of the interfering footings, which is called the settlement ratio (s/B or s/D). The variation in dimensionless settlement ratios for closely spaced square and circular footings on unreinforced and reinforced sand is presented in Fig. 5.

According to Fig. 5, the settlement of the square and circular footings at the ultimate bearing capacity is increased due to the occurrence of interference. According to Fig. 5(a), the ultimate settlement of the interfering square footings increased, on the average, by about 45–80% by an increase in the number of geogrid layers from 1 to 2, respectively. Since the failure in the reinforced soil foundation occurred at greater values of settlements, it may be concluded that the flexibility of soil is increased by an increase in the number of reinforcements. This means it is possible for the soil to bear more pressure and settlement without reaching the failure limit. As seen in Fig. 5(a), blocking affects the ultimate settlement of closely spaced square footings. Regarding the previously mentioned postulate on soil blocking, the formation of a single unit beneath two adjacent foundations increased the width of the footing system and led to a significant increase in the ultimate settlement in that situation. Therefore, the settlement of interfering square footings was maximized at $\Delta/B=1.5$. By eliminating the blocking from further spacings, the ultimate settlement tended to decrease. With respect to Fig. 5(b), the ultimate settlement of the interfering circular footings on unreinforced and reinforced soil was maximized when two foundations were attached. This happening was due to the absence of blocking where the maximum width of the foundation system occurred at $\Delta/D=1$. The settlement of the interfering circular footings is increased, on average, about 60–100% for reinforced sand with 1 and 2 layers of geogrid layers, respectively. Regarding Fig. 5(a) and (b), although reinforcing the soil increases the ultimate bearing capacity, as an encouraging aspect, the magnitude of the settlement at the ultimate load is discouragingly increased as well. However, the magnitude of the footing settlement at a given load is decreased by reinforcing the soil. According to Table 2, the ultimate bearing capacities of single square and circular footings considered in the present study are 237 and 153 kPa, respectively. For instance, at a given load equal to the ultimate bearing capacity of a single identical footing, the settlement ratio decreases, on the average, by about 18% and 29% for square interfering footings and 11% and 19% for circular interfering footings on reinforced sand with 1 and 2 layers of geogrid ($N=1$, 2), respectively.

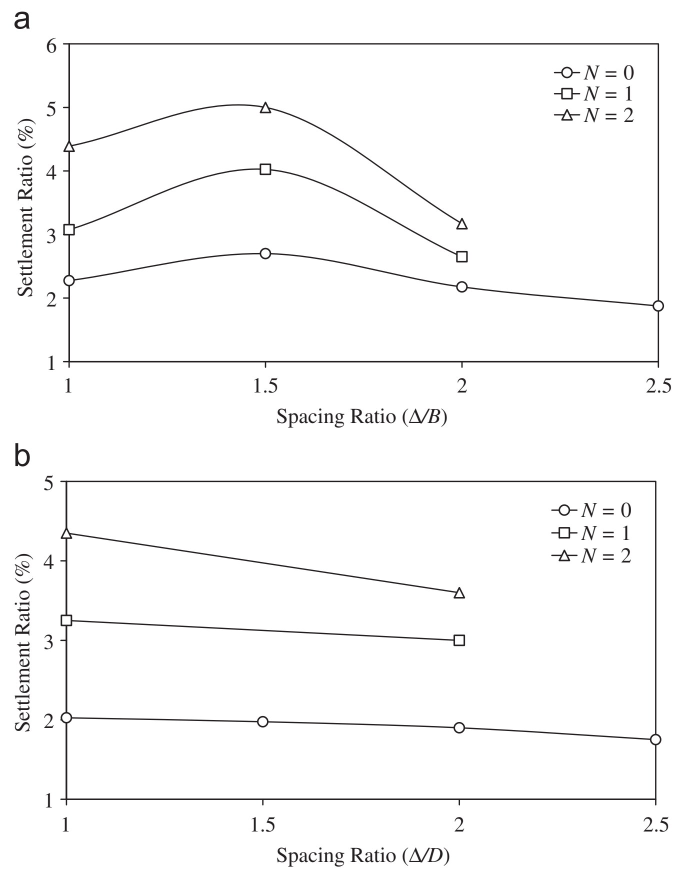

Fig. 5. Variation in settlement ratio versus spacing ratio for interfering square and circular footings on unreinforced and reinforced sand: (a) Interfering square footings (for reinforced sand: $b/B=4$, $u/B=0.5$, $h/B=0.5$) and (b) Interfering circular footings (for reinforced sand: $d=4D$, $u=0.5D$, $h/B=0.5$).

Fig. 5 shows that the ultimate settlement ratio is less than 5% for the soil used in present study. Therefore, using the LPC method does not lead to accurate results for the ultimate load and the settlement in the present experiments.

3.3. Tilt of interfering footings

In this section, the influence of interference on the tilt of two closely spaced footings under a centric vertical ultimate load is investigated on the basis of performed tests.

The variations in footing tilt at various spacing ratios for interfering square and circular footings at the ultimate load are presented in Fig. 6.

As shown in Fig. 6, the occurrence of interfering leads to the tilt of the footings subjected to a vertical centric load. The magnitude of the tilt is less than about 1° for unreinforced soil. However, such tilts may considerably affect the performance of the foundations of superstructures (i.e., silos, cooling towers, tall tanks, etc.). According to Fig. 6(a), blocking has a considerable effect on the tilt as well as on the bearing capacity and the settlement of adjacent footings. This means that the maximum tilt of neighboring square footings takes place with the greatest width of blocking ($\Delta/B = 1.5$). As shown in Fig. 6(b), the maximum tilt of interfering circular footings occurs when two foundations are exactly beside each other. Furthermore, the tilt of circular footings is perpetually decreased by increasing the spacing between the footings. By comparing Fig. 6(a) and (b), it is seen that reinforcing soil causes a significant decrease in the magnitude of the footing tilt. The tilt direction of the footings is reversed for reinforced soil. The stress applied to soil is concentrated between two footings when two closely spaced footings are placed on unreinforced sand. Therefore, the settlement is increased at the inner edges of the footings; hence, the footings tilt inwardly. With respect to the large diameter of the reinforcement layers, geogrids overlap in the zone between two adjacent footings. Therefore, the tensile strength and the shear strength of the reinforcements are significantly increased in this region due to the stress applied to the soil from the footings. This aspect leads to a smaller settlement at the inner edges of the footings rather than at the outer edges. Thus, the tilt direction alters from an inward direction to an outward direction when interfering footings are constructed on reinforced sand. According to Fig. 6, reinforcing soil with 1 and 2 layers of geogrid decreases the tilt of the interfering footings by about 35% and 80% for square foundations and 50% and 75% for interfering circular footings, respectively.

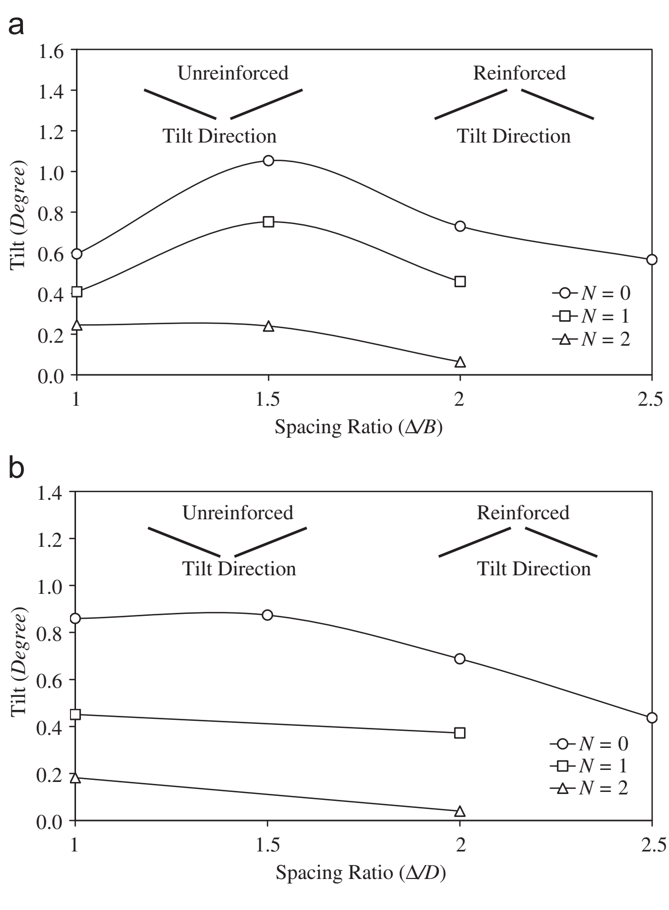

Fig. 6. Variation in footing tilt versus spacing ratio for interfering square and circular footings on unreinforced and reinforced sand: (a) Interfering square footings (for reinforced sand: $b/B=4$, $u/B=0.5$, $h/B=0.5$) and (b) Interfering circular footings (for reinforced sand: $d/D=4$, $u/D=0.5$, $h/D=0.5$).

4. Conclusion

A number of large-scale model tests were performed on two types of closely spaced footings, square and circular, on unreinforced and reinforced sand. The influence of interference on the ultimate bearing capacity, the settlement and the tilt of the interfering footings under vertical centric loads were investigated at various spacing ratios between foundations. Based on the test results, the following conclusions can be drawn:

(1) Due to the occurrence of blocking, the ultimate bearing capacity, the settlement and the tilt of the interfering square footings are maximized when the spacing between neighboring footings is about $1.5B$.
(2) The maximum ultimate bearing capacity, the settlement and the tilt of the interfering circular footings are observed when two footings stand exactly beside one another.
(3) Interference and reinforcement are two factors which increase the settlements of the footings at the ultimate load. The influence of the interference on the settlement of closely spaced footings at a given load can be decreased by increasing the number of geogrid layers.
(4) The closely spaced footings tilt under vertical centric loads; this effect can be decreased by increasing the number of reinforcement layers.
(5) The direction of the tilt of the footings can be reversed by reinforcing the soil beneath the foundations.
(6) The behavior of two identical adjacent foundations and the efficiency of soil reinforcement on the improvement of the interfering footings depend on the shape of the footings and the spacing between them.

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