INFLUENCE OF INTERFERENCE ON FAILURE MECHANISM OF CLOSELY CONSTRUCTED RING FOOTINGS ON REINFORCED SAND

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Abstract: Influence of reinforcement on failure mechanism and displacement fields of soil for spread and interfering ring footings on cohessionless granular soil has been studied in this paper. The analyses have been carried out using finite difference method based on commercially available code, *FLAC*^{3D} (Fast Lagrangian Analysis of continua). The behaviour of the soil has been considered according to the Mohr-coulomb criterion with non-associated flow rule. To ensure the reliability of the numerical simulation for the prediction of results, the obtained numerical data for spread unreinforced and reinforced ring footing were compared with former experimental and theoretical data on the same soil. This comparison showed appropriate conformation between numerical and experimental results. The results show that the footing interference causes some directional differences in soil displacement fields and failure mechanism of closely spaced footings subjected to vertical loads. The paper focuses on the distribution of plastic zones in the soil for both reinforced and unreinforced closely spaced footings.

Keywords: failure mechanism, geogrid, numerical, sand, interaction.

INTRODUCTION

The behaviour of two closely constructed footings is strongly affected by the spacing between each other in comparison with the otherwise identical but isolated footing. In the case of two adjacent footings, settlement, bearing capacity, deformation patterns of soil and failure mechanisms would be influenced due to interference effects. According to these variations, design criteria should be modified respecting to changes of abovementioned factors.

The soil reinforcing techniques are significantly improved by development of science. Some different materials were used, for instance, metal strips (Binquet & Lee 1975, Fragaszy & Lawton 1984, Huang & Tatsuka 1988), metal bars (Huang & Tatsuka 1990), rope fibers (Akinmusuru & Akinboladeh 1981), geotextiles (Guido *et al,* 1986), and geogrids (Guido *et al.* 1986, Yetimoglu *et al.* 1994, Omar *et al.* 1993a,b, Adams & Collin 1997, Das & Shin 1999). All these studies have shown that the use of reinforcements in granular soils has led to increase in the footing bearing capacity and significant decrease in settlement by an identical loading condition. A dimensionless parameter that named BCR has been issued to identify the effect of soil reinforcement on the bearing capacity of an isolated foundation. This is defined as:

$$BCR=q_{u(reinforced)}/q_{u(unreinforced)}$$

where $q_{u(reinforced)}$ and $q_{u(unreinforced)}$ represent ultimate bearing capacity of reinforced and unreinforced identical footing, respectively.

Stuart (1962) was the first who analytically considered the effect of spacing between two neighbouring footing on bearing capacity. He assumed an identical failure mechanism beneath two close footings. Results of this study showed a significant increase in bearing capacity of strip footing. Hanna (1962) conducted an experimental study on bearing capacity and failure mechanism of interfering strip footings. He showed that the failure mechanism is not symmetric for the system of two footings and adjacent foundations were not failed at the same time. He also concluded that interference causes a significant tilt in adjacent footings subjected to axial vertical loads. Das and Larbi-Cherif (1983 a,b) performed an experimental research on bearing capacity and settlement of interfering strip footings. According to their results, settlement of foundations is increased by a decrease in spacing between footings. Khing *et al.* (1992) conducted a study on effect of soil reinforcing on ultimate bearing capacity of interfering strip footings. They showed a decrease in influence of interference by reinforcing soil. Kumar and Saran (2003) pursued a study about interference effects on interfering strip and square footings on unreinforced and reinforced sand. They revealed an appreciable decrease in tilt and settlement of interfering footings by reinforcing soil. However, Ghazavi and Lavasan (2008) indicated that results of Kumar and Saran (2003) for ultimate bearing capacity of interfering reinforced footings were involved some discrepancies. Ghazavi and Lavasan (2007), Ghazavi and Lavasan (2008), Lavasan and Ghazavi (2008) numerically examined the optimum values of the dimension, location, orientation and number of reinforcement layers which maximize the ultimate bearing capacities of strip, square, and circular interfering footing on reinforced sand with geogrid. Results of these studies showed that by the use of reinforcement layers in the appropriate size, location and orientation, the ultimate bearing capacity could be maximized conveniently. Figure 1 shows the two interfering shallow ring foundations supported by a soil reinforced with layers of geogrid. According to Figure 1, characters d, u, h, D_o, D_i, Δ, and N represent diameter of geogrid layer, depth of the first reinforcing layer from ground level, vertical distance between reinforcement layers, outer diameter of ring footing, inner diameter of ring footing, horizontal spacing between centres of two neighbouring footings, and the number of reinforcement layers, respectively.

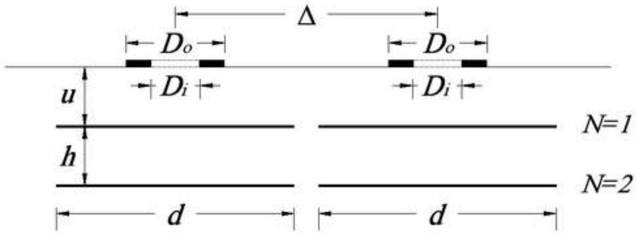


Figure 1. Geometry of two interfering ring footings supported by geogrid-reinforced soils

In the present study, to evaluate the bearing capacity of interfering footings on reinforced soil, the interference factor (I_f) is defined as follows:

$$I_f = q_{u\text{-}N(interfering)}/q_{u(single)}$$

where $q_{u\text{-}N(interfering)}$ and $q_{u(single)}$ describe ultimate bearing capacity of interfering footing reinforced with *N* layers of geogrid and single unreinforced footing, respectively. As shown in the literature, there is no study on failure mechanism and ultimate bearing capacity of interfering ring footings. Therefore, a number of numerical analyses conducted to investigate the failure mechanism, soil deformation patterns and ultimate bearing capacity of interfering ring footings. Then an attempt was devoted to determine the influence of soil reinforcing on mentioned factors.

NUMERICAL ANALYSIS PROCEDURE

In the performed numerical modelling, a commercially available finite difference code, *FLAC^{3D}* (Itasca Group 2001) was used to simulate two interfering ring footings placed on unreinforced and reinforced sand. A Mohr-Coulomb elastic-plastic failure envelop was used corresponds to a shear yield function criterion which was controlled by a non-associated flow rule ($0 \le \psi < \phi$). With respect to the symmetry of the soil-footing system and to decrease the required time for each analysis, only a quarter part of the system domain was simulated. The footings were assumed to be fully rigid and rough-base in numerical studies. It is also assumed the ring footings have outer and inner diameter equal to 15 cm and 6 cm, respectively. The dimensions of numerical model were regarded to extend about $7D_o$ around and beneath footings system to ensure that the influence of boundaries on the results was completely disappeared. With respect to the small scale of simulated footings, a maximum settlement of s=50%D_o was applied to all models with a constant velocity of 5×10^{-7} m/step. In all numerical analyses, the domain was divided into 19,425 grid-points that correspond to 16,800 hexahedral zones.

Soil properties

Previous numerical studies on behaviour of granular soil showed that more accurate results would be accomplished by the use of non-associated flow rule. Zienkiewicz *et al.* (1975) indicated the difference between ϕ and ψ represents a non associated plastic flow rule which means the plastic potential surface is not identical to the yield surface. A number of numerical studies reported that the dilation angle has a significant influence on the numerical estimation of the footing bearing capacity (Yin *et al.* 2001, Erickson & Drescher 2002, Frydman & Burd 1997, De Borst & Vermeer 1984). They concluded that more accurate numerical results for ultimate bearing capacity and failure patterns can be obtained by considering dilation angle of soil between 1/2 and 2/3 friction angle. Therefore, to ensure the reliability of numerical analyses, a number of verifying simulations were performed considering results presented by Boushehrian and Hataf (2003) for single ring footing on unreinforced sand. Mechanical parameters of the soil, which were obtained from mentioned verification study and were used in numerical modelling, are presented in Table 1.

Table 1. Mechanical properties of soil and reinforcement

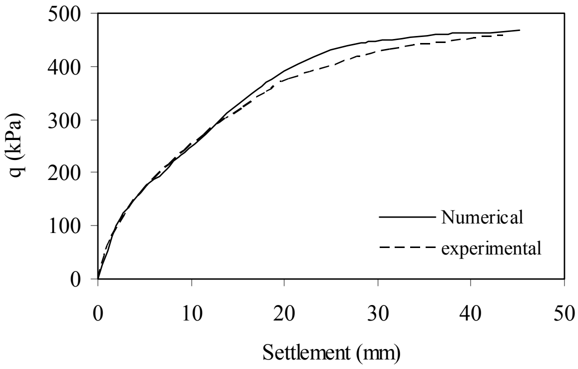
Soil parameters		Geogrid parameters	
Bulk modulus	8×10^3 kPa	Elasticity modulus	26×10^6 kPa
Shear modulus	4×10^3 kPa	Poisson ratio	0.3
cohesion	0.1 kPa	**Interface parameters**	
friction	38°	Stiffness per unit area	2.3×10^3 kN/m^3
Dilation	25°	Cohesion	0
		friction	28°

Reinforcement properties

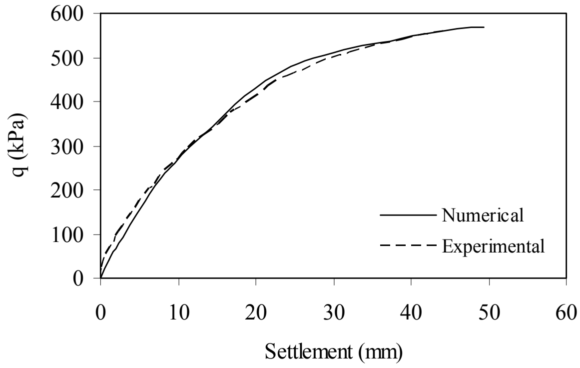
The numerical behaviour of geogrid simulated considering in-built geogrid structural element which involved in *FLAC^{3D}* as an isotropic linear elastic material. A shear directed (in the tangent plane to the geogrid surface) frictional interaction occurs between the geogrid and the soil grids, and the geogrid is slaved to the grid motion in the normal direction. To permit sliding between soil and geogrid, an interface element was used on both sides of reinforcement layers. The shape of geogrid layers was assumed to be circular. The shear behaviour of the geogrid-soil interface is cohesive and frictional in nature and is controlled by the coupling spring properties of: (1) stiffness per unit area; (2) cohesive strength; and (3) friction angle. The total shear stress that develops on geogrid was calculated by balancing the effective confining stress "σ_m" that acts equally on both sides of geogrid surfaces (Itasca group 2001). Thus, at the first of each run, a gravity analysis was performed to determine the vertical and horizontal stresses that acting at each level due to weight of system. Mechanical properties of geogrid and soil-geogrid interface are shown in Table 1.

VERIFICATION OF NUMERICAL SIMULATION

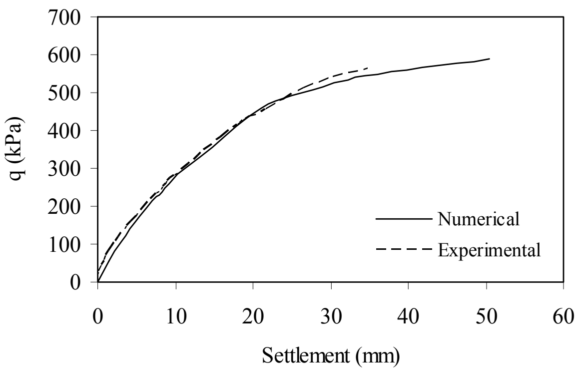
To evaluate the reliability and admissibility of the numerical simulations, experimental tests of Boushehrian and Hataf (2003) on bearing capacity of ring footing on unreinforced and reinforced sand with geogrid were simulated numerically and the results were compared. They used a cylindrical steel tank with 1.0 m diameter and 1.0 m height with sand which classified as SW in the Unified Soil Classification System. The relative density of sand was reported about 40±5%. The average unit weight of the soil was 17 kN/m^3. The rigid rough ring model footing had an outer and inner diameter of 15 and 6cm, respectively. These were kept the same in all tests. The peak friction angle of the sand was 39°. A biaxial polypropylene (PE) polymer geogrid with nominal thickness of 2 mm was used for reinforcement. A comparison of numerical and experimental results is presented in Figure 2. As seen, a good agreement between numerical and experimental results exists and this indicates the capability of numerical modelling to predict the behaviour of reinforced soil.



(a) unreinforced sand



(b) reinforced sand with 1 layer of geogrid (N=1)



(c) reinforced sand with 2 layers of geogrid (N=2)

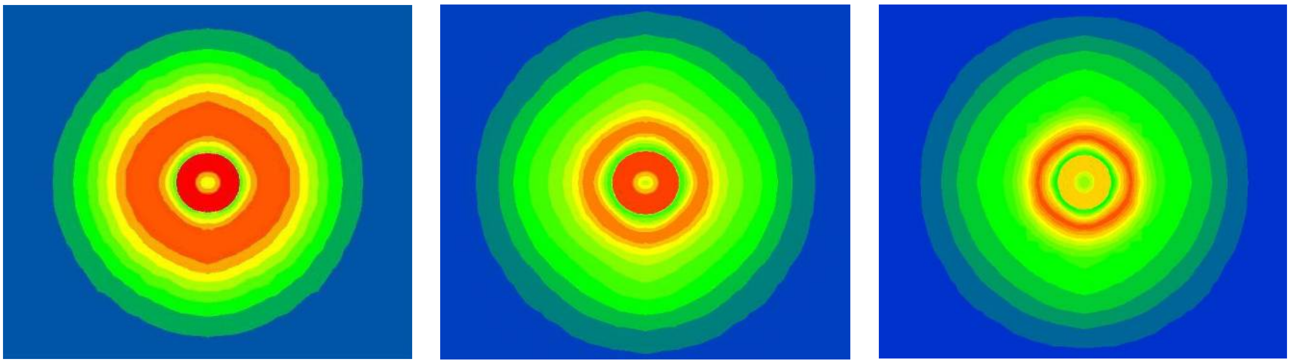
Figure 2. Results comparison of numerical and experimental methods

ANALYSIS RESULTS AND DISCUSSIONS

In this section, variations of surficial soil deformation patterns for interfering ring footings are considered. Then, influence of soil reinforcing on deformation patterns and failure mechanisms is considered. On the other hand, to clarify the results, results of displacement field for single ring footing are presented.

Single ring footing on unreinforced and reinforced sand

Soil displacement fields at surface of a single ring footing on unreinforced and reinforced sand are presented in Figure 3. As seen, soil displacement contours are completely symmetric around the ring footing. According to Figure 3, it seems a general shear failure took place for the ring footing on simulated soil. Light contours of soil displacement at footing holes represent low value of soil deformation at middle of footing. It might be correspond to increase in soil density at that region due to footing loading. With regard to Figure 3, the size of highly deformed (plastic) zones which is showed by red contours, decreases significantly by an increase in number of geogrid layers. Therefore, reinforcing soil causes a substantial decrease in magnitude of deformations, size of displacement contours and also area of plastic zones. Decrease in soil deformation causes a considerable decrease in soil shear strains correspond to footing at identical settlements.

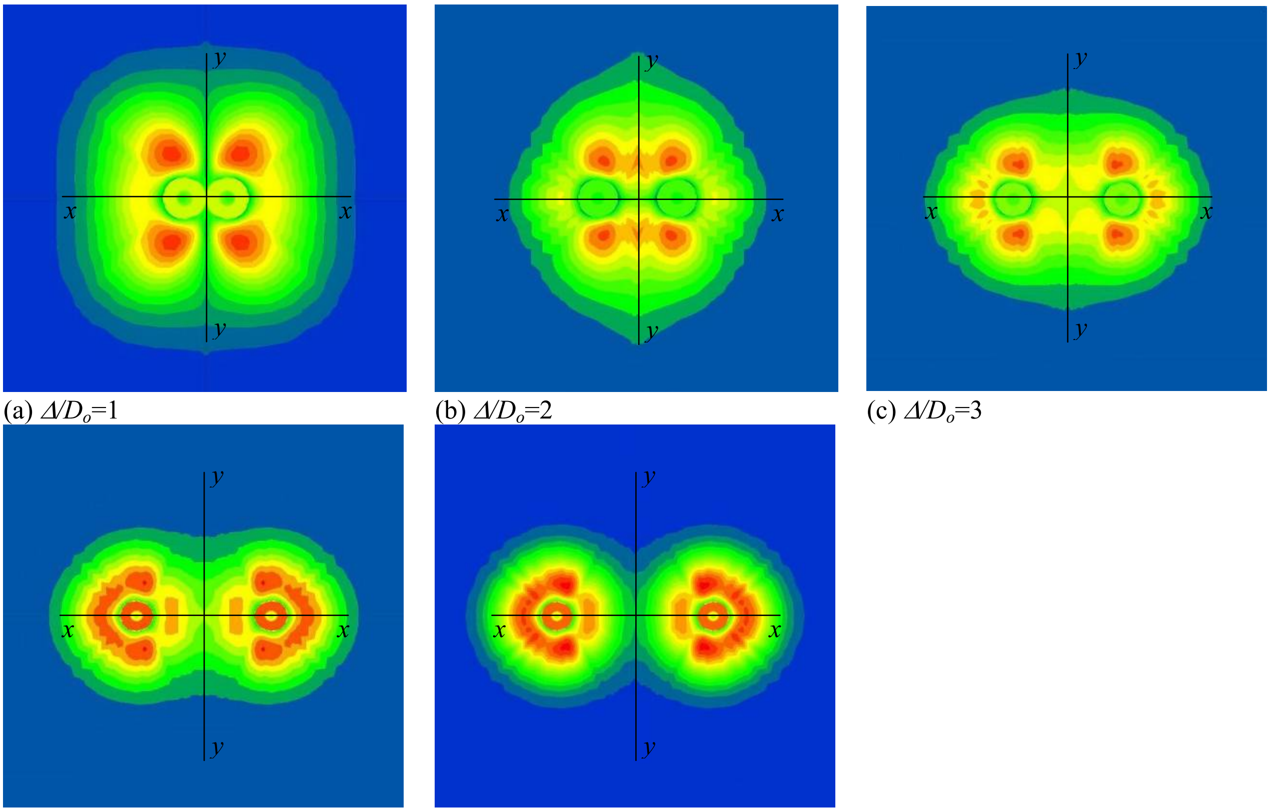


(a) N=0 (b) N=1 (c) N=2

Figure 3. Surficial displacement field of isolated unreinforced ring footing

Interfering ring footings on unreinforced sand

The second group of numerical analysis was conducted on unreinforced sand. Variations of soil deformation patterns at different spacing for model ring interfering footings were shown in Figure 4. As shown, when two neighbouring footings were placed close to each other ($\Delta/D_o \geq 3$), the critical path of failure occurrence stands nearly on bisector of x-y axes.



(a) Δ/D_o=1 (b) Δ/D_o=2 (c) Δ/D_o=3

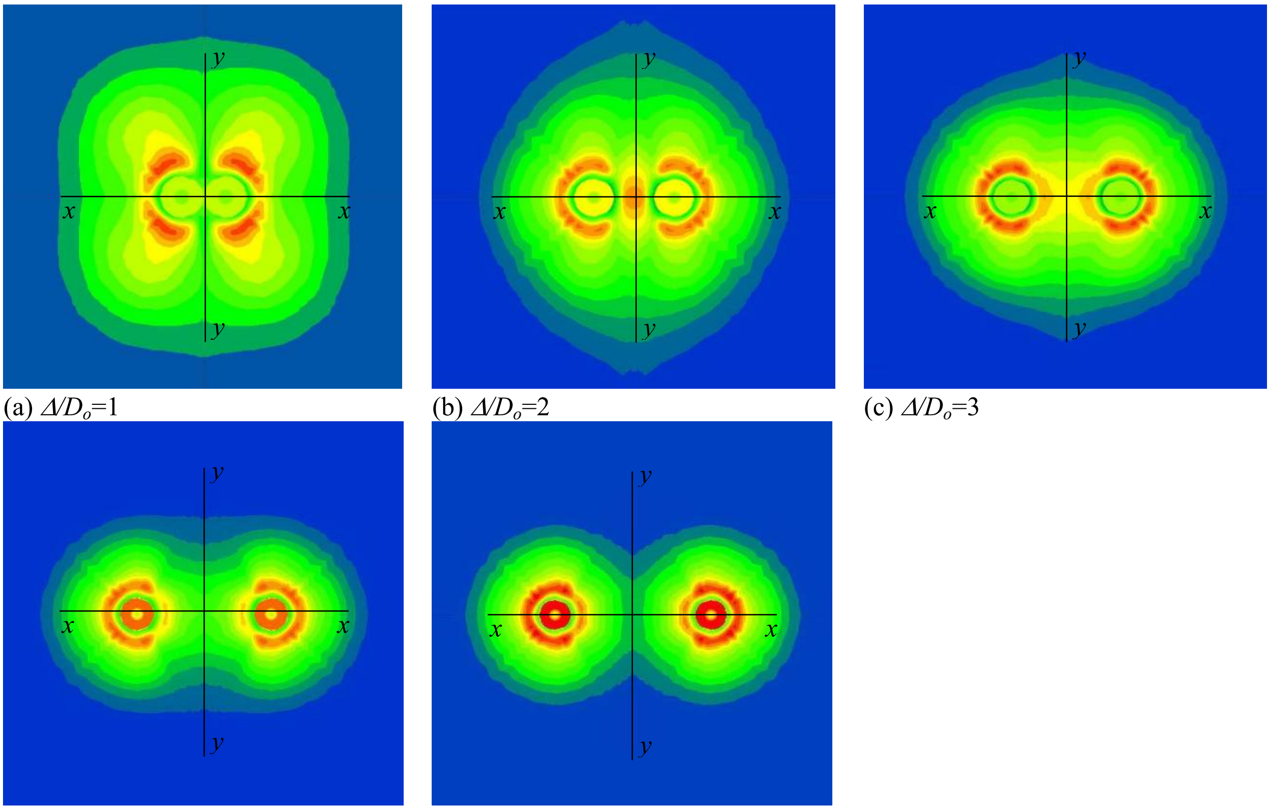
(d) Δ/D_o=4 (e) Δ/D_o=5

Figure 4. Displacement field at soil surface of interfering unreinforced ring footings

According to Figure 4(a), by situating two ring footings completely close together (Δ/D_o=1), the system of two footings acts as a single unit semi-rectangular foundation and deformation pattern forms in a large zone around mentioned system. This event causes a significant in ultimate bearing capacity and stability of each footing. By increasing the spacing ratio between footings, failure mechanism of footings tends to form like a single ring footing. The effect of interference on deformation pattern and failure mechanism of footing disappears almost when the spacing ratio is equal to 5. Although the footings were assumed to be rigid and rotationally fixed but difference and asymmetry of displacement contours around footings may cause a significant differential settlements or tilts particularly in the case of non-rigid or rotationally free ring footings, respectively.

Interfering ring footings on reinforced sand

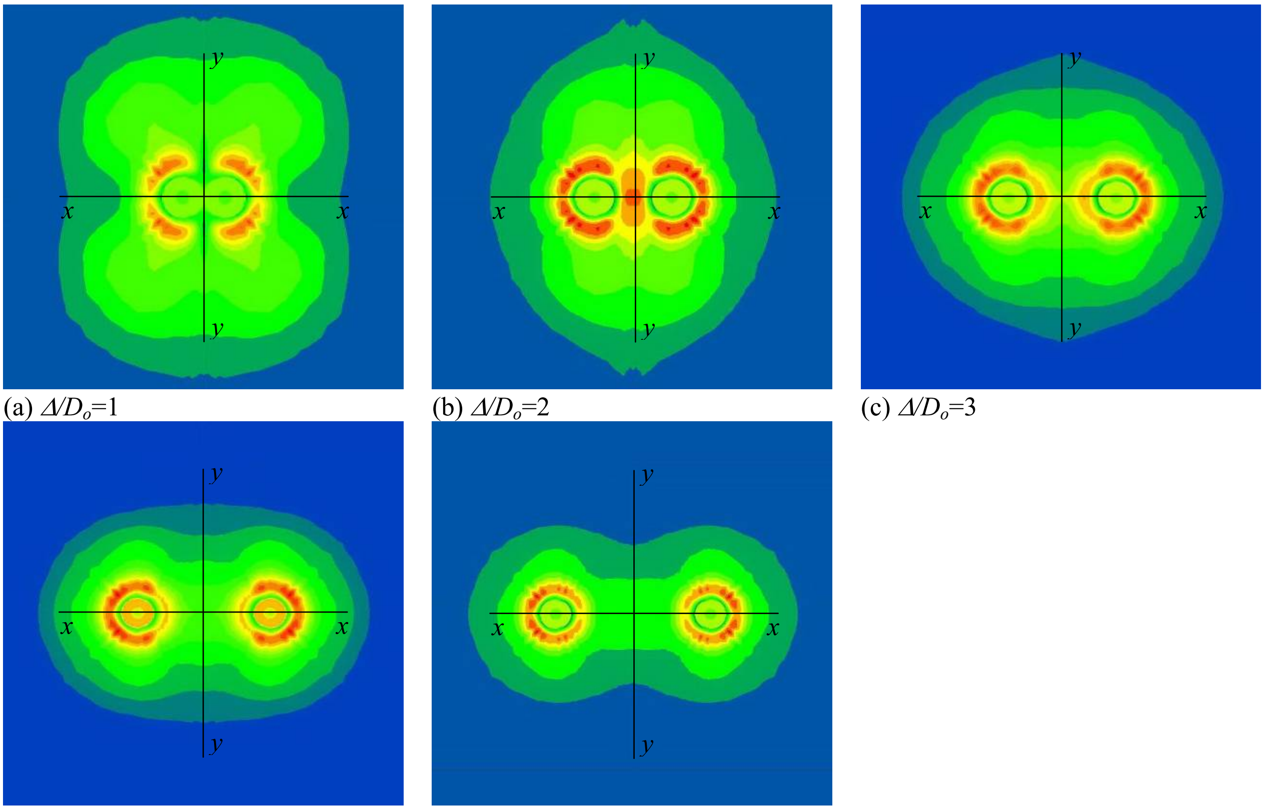
The third group of analyses was conducted on influence of soil reinforcing on soil deformation patterns of two adjacent ring footings at different spacing ratios. Variations of soil displacement fields for reinforced sand with 1 and 2 layers of geogrid are presented in Figures 5 and 6, respectively.



(a) Δ/D_o=1 (b) Δ/D_o=2 (c) Δ/D_o=3

(d) Δ/D_o=4 (e) Δ/D_o=5

Figure 5. Displacement field at soil surface of interfering reinforced ring footings (N=1, d/D_o=3, u/D_o=0.3)



(a) Δ/D_o=1 (b) Δ/D_o=2 (c) Δ/D_o=3

(d) Δ/D_o=4 (e) Δ/D_o=5

Figure 6. Displacement field at soil surface of interfering reinforced ring footings (N=2 d/D_o=3, u/D_o=0.3, h/D_o=0.2)

According to Figures 5 and 6, the distribution of displacement contours changes to be more symmetric around system of two footing by the use of geogrid layers. It could be concluded that the balance in displacement contours causes an appropriate decrease in differential settlement and tilt of closely spaced ring footings. Figures 5 and 6 also show that the effect of interference on failure mechanism of reinforced interfering footings almost disappears at Δ/D_o=4. Achievement to balance in displacement contours owes to collaboration between soil and reinforcement in distributing strains steadily in the soil. By a comparison between results of unreinforced and reinforced sand, it seems the balance of soil displacement increasing with an increase in number of reinforcement layers. Therefore, bad effects of interference on behaviour of close ring footing decrease considerably by an increase in geogrid number. As shown in Figures 5 and 6, the magnitude of soil displacements decrease significantly for reinforced sand with 2 layers of geogrid. Therefore, replacing soil with hard reinforced sand is a practical solution for constructing close ring footings on weak soils. It is obviously seen that by the use of reinforcement, soil behaves more isotropic and deformation of soil would be steady in soil surface.

Influence of interference on ultimate bearing capacity

Variation of interference factor at different spacing between two neighbouring ring footings on reinforced and unreinforced sand is presented in Figure 7. As seen, the ultimate bearing capacity increases due to interference occurrence. The interference factor is maximized when two adjacent ring footings placed completely close to each other. This significant increase in ultimate bearing capacity at Δ/D_o=1 is related to acting the system of two close footings like a single unit as showed in previous sections. According to Figure 7, the ultimate bearing capacity of footings increases by an increase in the number of reinforcement layers. Effect of interference on ultimate bearing capacity of interfering ring footings disappears by increasing spacing ratio more than 5.

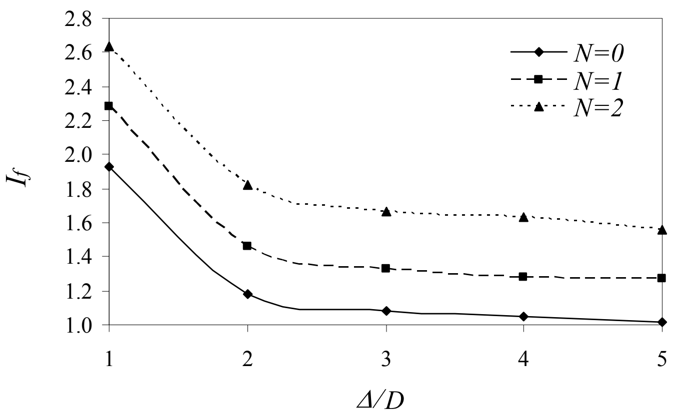


Figure 7. Variation of I_f versus Δ/D_o for interfering ring footing (d/D_o=3, u/D_o=0.3, h/D_o=0.2)

CONCLUSION

The results of a number of numerical analyses on surface rough ring foundations on both unreinforced and reinforced sand were presented. Based on the performed analyses, the following general conclusions may be pointed out:

- By placing two ring footings completely close together, the system of two adjacent ring footings acts as a single semi-rectangular unit.
- Effect of interference on failure mechanism of unreinforced ring footings disappears for $\Delta/D_o \geq 5$.
- Interference causes a significant asymmetry in deformation of soil surface around each footing and this could be an important reason for differential settlement or tilt in footings.
- Reinforcing soil cause an appreciable decrease in influence of interference on failure mechanism and displacement counters.
- By the use of Reinforcement the area of highly deformed region in soil decreases and it causes an increase the capability of footing to suffer more loads.
- The dimension of plastic zones decreases significantly by an increase in the number of reinforcement at identical settlements.
- Ultimate bearing capacity of interfering ring footings increases by increasing the number of geogrid layers.
- Placing two neighbouring footings completely close together (Δ/D_o=1) makes the ultimate bearing capacity to be maximum.

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