INTERFERENCE EFFECT ON BEARING CAPACITY OF SHALLOW FOUNDATIONS ON GEOSYNTHETIC-REINFORCED SAND

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ABSTRACT

Bearing capacity of foundations always has been considered as one of main subjects by geotechnical researchers. Applying heavy loads on shallow foundations built with low distance, cause interference phenomenon in behavior of foundations, that its main effects is varying in bearing capacity of foundation. Soil reinforcing with geosynthetic reinforcements such as geogrid and geotextile is a new method which is used in various projects. According to additive usage of geosynthetics as tensile element in soil reinforcing, it is needed that problems of reinforced soil be studied to enlighten its different aspects. In this study, bearing capacity of multiple strip shallow foundations over geogrid-reinforced sand has been investigated. Numerical models have been analyzed and model accuracy has been controlled by comparing experimental results. Results showed that bearing capacity of multiple shallow foundations increases using geosynthetic layers.

Keywords: Bearing capacity, shallow foundation, geosynthetic, interfering, reinforced soil

INTRODUCTION

In many cases, foundations encountered in practice are not isolated and they interfere with each other on account of their close spacing. Due to close spacing, the behavior of interfering footings becomes different from that of a single isolated footing and failure mechanism would be varied due to interference effects.

The bearing capacity of interfering footings on unreinforced soil was investigated repetitiously. For example, Stuart (1962), Das and Larbi-Cherif (1983a,b), Graham et al. (1984), and Wang and Jao (2002) studied the interference effects on closely spaced footings on unreinforced soil. Kumar and Saran (2003) studied interfering square footings. Almost all these studies have shown an increase in the bearing capacity of interfering footings that depends on distance between two close footings.

Dimensionless parameter that named BCR have been used to identify the effect of soil reinforcement on the bearing capacity of an isolated foundation. This is defined as:

$$BCR = q_{u(reinforced)} / q_{u(unreinforced)} \quad (1)$$

where $q_{u(reinforced)}$ and $q_{u(unreinforced)}$ state the ultimate bearing capacity of reinforced and unreinforced footings, respectively.

Interference effect on bearing capacity of two closely spaced footing on unreinforced soil was considered for first time by Stuart (1962). Results of this study showed increase in interference coefficient at low spacing, and values of these coefficients decrease by increasing distance between two neighboring footings. Thereafter, Das and Larbi-Cherif (1983a,b), Kumar and Ghosh (2007a,b) and Kumar and Bhoi (2009) presented same results.

In recent years, the beneficial use of reinforcement materials like metal strips and geosynthetics to increase the bearing capacity of sand has been clearly established.

Khing et al. (1992), and Kumar and Saran (2003) performed studies on interfering strip and square footings on reinforced sand. These studies indicated that reinforcing soil causes a significant increase in the bearing capacity of interfering footings. They identified a dimensionless coefficient that called I_f as below:

$$I_f = q_{u(interference\text{-}reinforced)} / q_{u(single\text{-}unreinforced)} \quad (2)$$

where $q_{u(interference\text{-}reinforced)}$ and $q_{u(single\text{-}unreinforced)}$ are the ultimate bearing capacity of interfering footing supported by geogrid reinforced and unreinforced sand respectively.

In this paper, bearing capacity of interfering shallow strip footings on reinforced sand have been investigated. Geometrical definition of the model and parameters used is shown in Fig. 1.

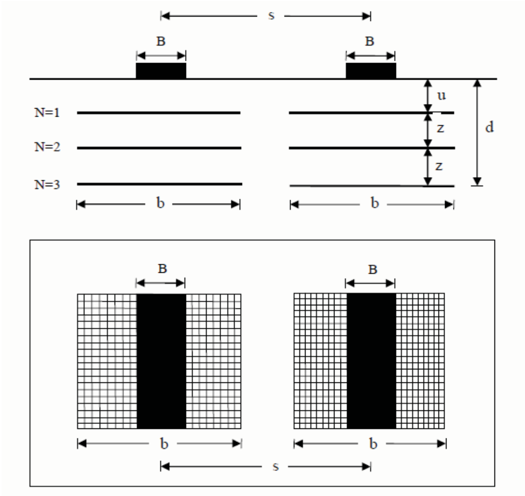

Fig. 1 Geometrical definition of the model and parameters

In this research the effective parameters are: depth of the first reinforcing layer from the footing bottom (*u*), distance between the reinforcement layers (*z*), number of reinforcement layers (*N*), total depth which has been reinforced (d), and width of reinforcement layers (*b*). The reinforced depth can be defined as following equation:

$$d = u + (N-1)\, z \tag{3}$$

EXPERIMENTAL STUDIES

A large and extensive experimental research was undertaken in order to investigate the bearing capacity of interfering strip shallow foundations supported by geogrid reinforced sand.

Material Properties

The soil tested was granular soil provided by Iran north. Grain-size distribution curve of the used materials is shown in Fig. 2. Based on Unified Classification System, the tested soil was classified as well graded sand (SW). Table 1 shows the employed material properties.

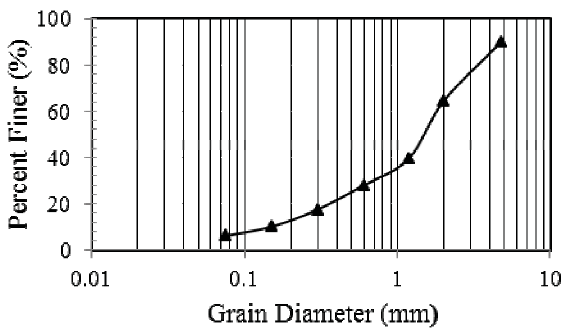

Fig. 2 Grain size distribution curve for tested material

Table 1 Employed material properties

Parameter	Sand
Specific gravity	2.45
Coefficient of uniformity	11.60
Coefficient of concavity	2.40
Mean grain size	1.70 mm
Relative density	65.8 %
Internal friction angle	37.5º
Dry density	16.2 kN/m^3

The CE 131 geogrid used in the test samples was made of high-density polyethylene (HDPE) which could be used at temperatures between -50˚C to 85˚C and was supplied by the representative of Polyfelt Company located in Gilan Province, north part of Iran. The geogrid used were slender materials with normal stiffness but with no bending stiffness which could only sustain tensile forces and no compression. The geogrid tensile strength, thickness, and mesh aperture size was 7kN/m, 5.2mm, and 27mm×27mm, respectively.

Test Apparatus

Test box was a cubical metal box with dimensions of 1m×0.7m×0.6 m and anchored with braces to prevent lateral deflection during loading. Loading system consisted of reaction frame and a hydraulic jack. The frame connected to a strong horizontal reaction beam was designed for the reaction of hydraulic jack for measurements of the load and settlement values, a sensitive proving ring with capacity of 35kN and two sensitive dial gauges with resolution of 0.005mm were used. The proving ring was located between the hydraulic jack and the footing. The gauges mounted on a piece of steel attached to the top of the test box and the average readings of the gauges were reported as the footing settlement. The footings provided were steel footings with width, length and thickness of 5.8cm, 25cm, and 3.7cm, respectively. For all tests, the loadings applied were vertical and the performances of all footings were fully rigid. Jaggy bottom surfaces were provided for all footing models to simulate the roughness of the footings. The loading was applied at the center of both footings at the same time.

Experimental Program

The experimental program is summarized in Table 2. A-0-0 and A-x-y indicate the tests carried out on a single strip footing on unreinforced and reinforced sand using x-layer of reinforcement with ratio of s/B = y.

Table 2 Summarized testing program
(B = 58mm, b/B = 5, $u/B = z/B \approx 0.3$)

Test number	N	s/B
A-0-0	---	---
A-0-1	---	1
A-0-2	---	2
A-0-3	---	3
A-0-4	---	4
A-0-5	---	5
A-1-1	1	1
A-1-2	1	2
A-1-3	1	3
A-1-4	1	4
A-1-5	1	5
A-2-1	2	1
A-2-2	2	2
A-2-3	2	3
A-2-4	2	4
A-2-5	2	5
A-3-1	3	1
A-3-2	3	2
A-3-3	3	3
A-3-4	3	4
A-3-5	3	5

Test Procedure

To prepare test specimens, the required depth of soil sample in the box was achieved by pouring sand layers in 50mm thicknesses. The compaction of each layer was initiated by using a tamping device, with a compaction foot having a diameter of 170mm. The constant compaction effort of each layer was achieved using 1.5kg rammer and 12-in. (304.8-mm) drop, and 20 blows per layer. By reaching the sand level to predicted desired depth, the reinforcement geogrid was laid and a similar method was continued for placement of other reinforcement layers.

Experimental Results

For each test the pressure-settlement curve is plotted for various values of s/B and N. The bearing capacity is obtained by tangent method. In this method, two tangents are plotted along the initial and latter portions of the curve and the pressure corresponding to the intersection point of these two lines is taken as ultimate bearing capacity of the footing. For example Fig. 3 shows the results of these tests for one layer of geogrid. Fig. 4 depicts the calculated values of interference factor.

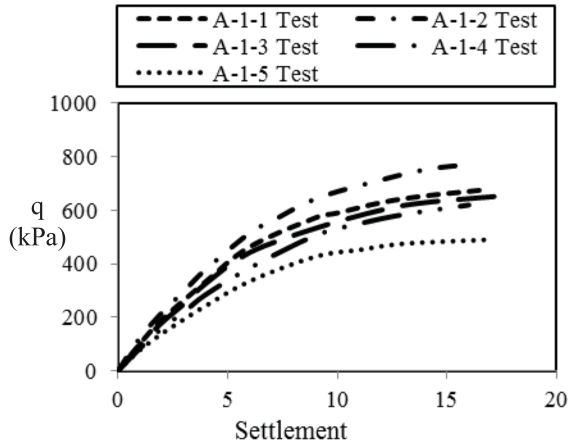

Fig. 3 Pressure-settlement curves for interfering footings on reinforced sand (N = 1)

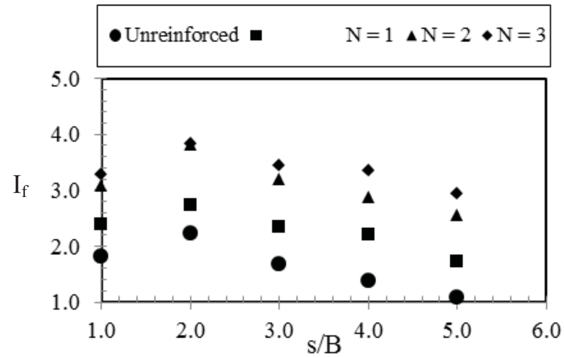

Fig. 4 Variation of I_f versus s/B for reinforced and unreinforced sand

NUMERICAL ANALYSIS

To model strip interfering shallow foundations supported by geogrid-reinforced sand the PLAXIS program was used. The finite element program, PLAXIS, is one of the most powerful numerical programs for analyzing the behavior, deformation, and stability studies in geotechnical engineering projects. The Mohr-Coulomb model and plane strain condition with 15-node triangular elements and 12 stress points were used for the analysis and evaluation of the soil behavior. The soil-reinforcement interaction was modeled by interface elements and was simulated as special tension elements.

Table 3 shows the material parameters used for the analysis. To evaluate the effects of various parameters, the parameter values are varied and their effects are observed by the interference factor (I_f).

Geometrical parameters consist of the depth of the first geogrid layer from the footing bottom (u), width of the layers (b), vertical distance between the layers (z), and the number of layers (N). These parameters play vital roles in behavior of foundation supported by reinforced soil.

Table 3 The material specifications

Soil	Cohesion	1 kPa
	Friction	37.5°
	Dilation	7.5°
	Poison ratio	0.30
	Elastic modulus	35000 kPa
	Density	16.2 kN/m^3
Strip footing	Depth	0 m
	Width	1.5 m
Geogrid	Tensile strength	100 kN/m

ANALYSIS RESULTS AND DISCUTION

Depth of First Geogrid Layer (u)

Variations of interference factor I_f versus interfering strip foundation distance ratio of (s/B), with change in depth ratio (u/B), for one and two layers of reinforcements are shown in Figs. 5 and 6. The results show that, if the reinforcement layer is located near the foundation, the mass of top soil is light and very thin; however, it cannot produce enough friction force to prevent the pulling out of reinforcement. Therefore, the possibility of cutting of the reinforcement can be predicted in practice when wedge failure is produced underneath the footings. Also, the normal force applied on the surface of geogrid which is the effective parameter for correct performance of reinforcement layer is not enough to produce considerable confining pressure.

The results show that for $(u/B)_{opt}$ = 0.3, the reinforcement layer is able to distribute the load on a broader area underneath the foundation. In this condition the best mechanism exists for load transmission. Fig. 6 shows that for two reinforcement layers with (u/B)≈ 0.3 the interference factor I_f is increased considerably due to the closeness of second reinforcement layer to the failure zone.

Width of Geogrid Layers (b)

Variation of interference factor I_f versus ratio of distance between the footings, s/B, with change in width ratio of geogrid, b/B, for one reinforcement layer is shown in Fig. 7. The results show that with an increase in width ratio the value of I_f increases. In fact, a part of geogrid which is not placed in failure zone must have enough pull out resistance as an anchorage. Bearing capacity improvement continues up to $(b/B)_{opt}$= 5 whereas, for $(b/B)_{opt}$ greater than 5, the bearing capacity remains constant. The reason for an increase in bearing capacity with an increase in b/B is the delay in geogrid slippage. The slippage of reinforcement layer prevents the bearing capacity reaching to its maximum value.

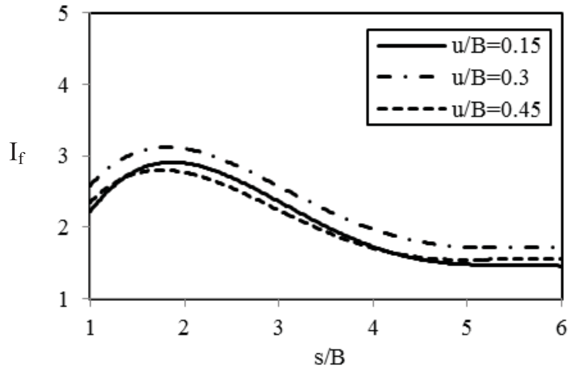

Fig. 5 Variation of I_f versus s/B with change in u/B (N = 1, b/B = 5)

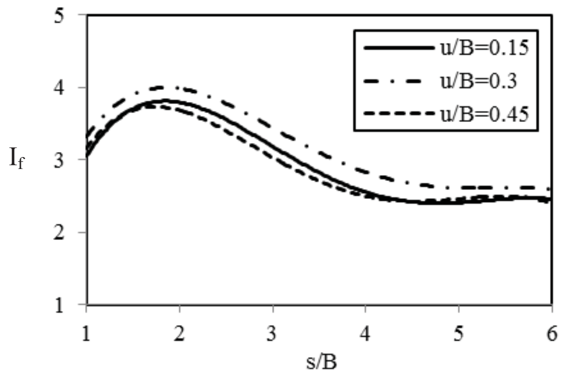

Fig. 6 Variation of I_f versus s/B with change in u/B (N = 2, b/B = 5, z/B = 0.3)

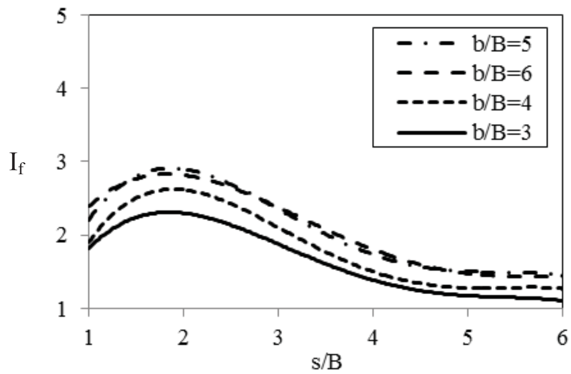

Fig. 7 Variation of I_f versus s/B with change in b/B (N = 1, u/B = 0.3)

Vertical Distance between Layers (z)

Figure 8 shows the variation of I_f versus s/B with change in vertical distance ratio, z/B, between the geogrid layers. The results show that the highest improvement in I_f value is observed when z/B = 0.3. Beyond this value a decrease in interference factor is monitored. This founding coincides with results obtained by other researchers that an increase in distance between the reinforcement layers beyond a certain value could not increase I_f. Suitable reinforcement arrangement in failure zone may disturb distribution of stresses and cause more incitement of reinforcement and lead to an increase in the bearing capacity.

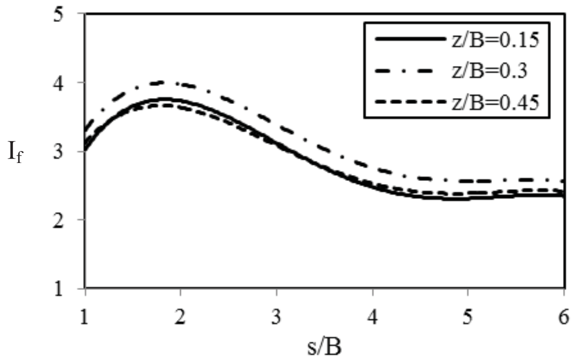

Fig. 8 Variation of I_f versus s/B with change in z/B (N = 2, b/B = 5, u/B = 0.3)

Number of Geogrid Layers (N)

The results show that the number of reinforcement layers has the most effect on improvement of bearing capacity in respect to the other parameters. In this respect Fig. 9 show the variation of interference factor versus s/B and pressure-settlement with change in number of reinforcement layers respectively. The results indicate that the interference factor increases with an increase in the number of reinforcement layers up to N = 3. Also the results obtained in Fig. 10 show that the pressure-settlement curves for N = 3 and N = 4 are very close to each other. This contribution coincides with researches performed by Akinmusuru and Akinbolade (1981), and Guido et al (1985) reported that the increase in bearing capacity for single reinforced footing is not much tangible when the number of reinforcement layers is greater than 3. However, Das and Omar (1994), and Boushehrian and Hataf (2003) reported that for a single reinforced footing the optimized N is 4.

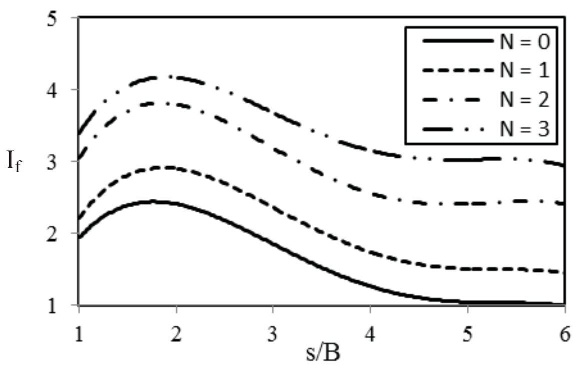

Fig. 9 Variation of I_f versus s/B with change in N (*b/B = 5, u/B = 0.15, z/B = 0.3*)

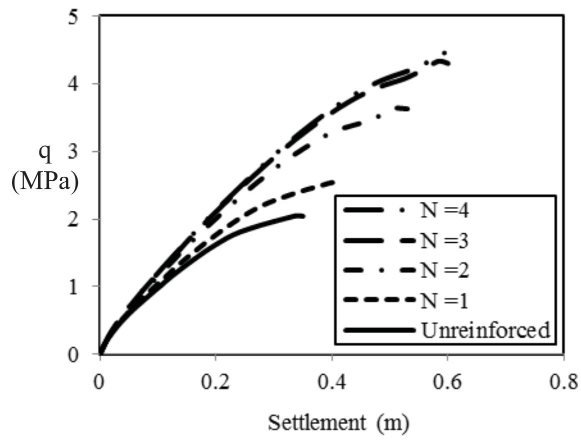

Fig. 10 Pressure-settlement curves for reinforced and unreinforced footings (s/B = 3, b/B = 5, u/B = 0.15, z/B = 0.3)

ESTIMATION OF I_f FOR PRACTICAL CONDITIONS

By inserting the interference factor (I_f) in the general conventional bearing capacity equation, a new modified bearing capacity equation is suggested for determination of bearing capacity of shallow footings supported by sandy soil as follows:

$$q_u = 0.5.\gamma.B.N_\gamma.I_{\gamma s}.I_{\gamma d}.I_{\gamma i}.I_f \quad (4)$$

where B = footing width, N_γ = coefficient of bearing capacity, $I_{\gamma s}$ = correction factor for footing shape, $I_{\gamma d}$ = correction factor for footing depth, $I_{\gamma i}$ = correction factor for load inclination, and I_f = interference factor.

Based on finite element analysis, the results show that for $1 \leq s/B \leq 1.6$, the bearing capacity of interfering strip footings increases and for $1.6<s/B\leq5$ its value decreases. However, at a distance of $s/B>5$, there is no interference between the footings. The maximum bearing capacity is achieved when $s/B\approx1.6$; thus, an increase or decrease in this ratio leads to decrease in bearing capacity.

Based on optimization of the reinforcement location and analysis carried out, the results show that the main parameters that affect the values of the interference factor are the footing distance (s/B) and the number of reinforcement layers (N). Therefore, a new relation is suggested for sandy soils with and without reinforcement as follows:

$$I_f = a.e^{-b(s/B)} - c.e^{-d(s/B)} \quad (5)$$

where a, b, c and d are correlation parameters shown in Table 4.

Table 4 Correlation parameters used in Eq. 5

Reinforcement layers	a	b	c	d
N = 0 (Unreinforced)	3.351	0.193	7.335	2.169
N = 1	3.968	0.142	9.382	2.319
N = 2	5.005	0.121	22.11	2.941
N = 3	4.709	0.076	31.92	3.589

VERIFICATION OF INTERFERENCE FACTOR MODEL

To verify certainty in the accuracy of suggested interference factor model, the results obtained were compared with other experimental and theoretical findings carried out in present and other researchers works performed on shallow strip footings supported by unreinforced sandy soils. Figure 11 shows the experimental findings of the present study and other experimental results carried out by some researchers.

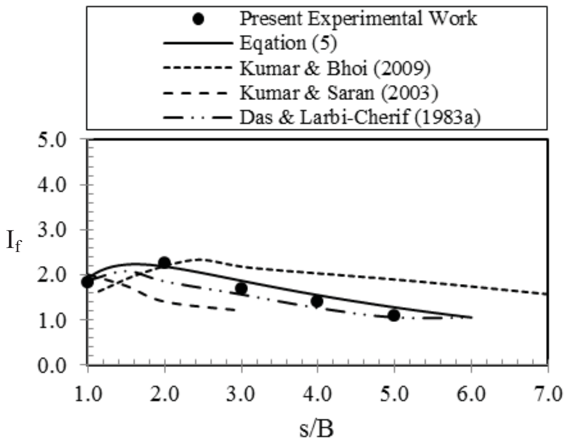

Fig. 11 Verification of I_f model with other experimental results for unreinforced soil

Figure 12 shows verification of the interference factor model with other theoretical results for shallow strip footings supported by unreinforced sandy soils. Stuart (1962) was the first who examined the effect of interference factor on ultimate bearing capacity of two closely spaced strip footings using limit equilibrium method. In researches carried out by Kumar and Kouzer (2007), they used upper bound limit analysis in conjunction with finite element programming. Kumar and Ghosh (2007a,b) carried out theoretical researches by stress characteristics method.

The results obtained in the present work indicate that not only are they correlated with each other but also they have similar trend with the results obtained by other researchers.

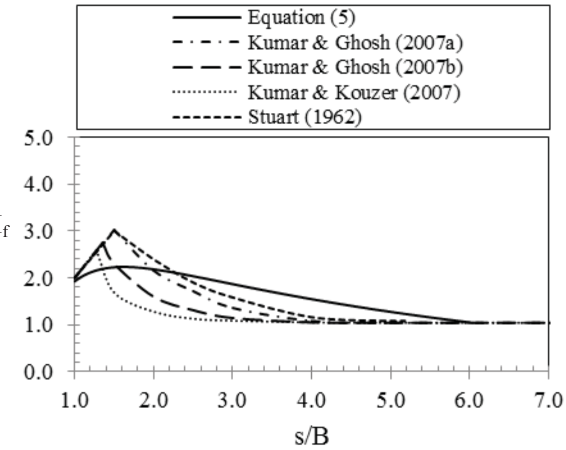

Fig. 12 Verification of I_f model with other theoretical results for unreinforced soil

To verify the correlation between the suggested interference factor model and experimental works carried out for 1, 2, and 3 layers of reinforcement, the I_f versus s/B is drawn in Fig. 13.

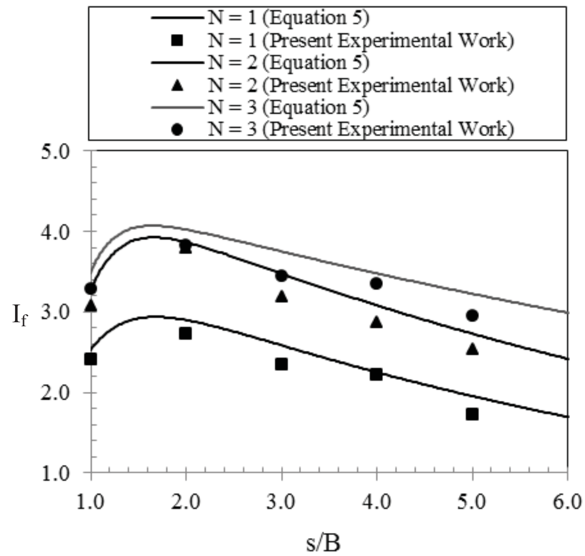

Fig. 13 Verification of I_f model with present experimental results for reinforced soil

As seen, a good agreement between results exists. Both theoretical and experimental findings correlate with each other and have similar trend. These indicate the capability of suggested interference factor model to reflection the effect of interfering on the bearing capacity of footings.

CONCLUSIONS

In the present research a series of tests was carried out to measure the bearing capacity of interference shallow strip footings supported by geogrid-reinforced sand, and it was evaluated using a numerical method. Accordingly, the following conclusions can be drawn:

1. For one and two layer of reinforcement, by placement of the first reinforcement layer at $u/B \approx 0.3$ maximum bearing capacity is achieved. In this condition the best mechanism exists for load transmission.

2. Bearing capacity improvement continues up to $(b/B)_{opt}= 5$ whereas for $(b/B)_{opt}$ greater than 5, the bearing capacity remains constant.

3. At $z/B \approx 0.3$, the improvement in I_f value is the highest.

4. The number of reinforcement layers has the most effect on the improvement of the bearing capacity in respect to the other parameters. However, using reinforcement layers more than $N = 3$ would not increase the bearing capacity or the efficiency considerably.

5. For $1 \leq s/B \leq 1.6$, the bearing capacity of interfering strip footings increases and for $1.6 < s/B \leq 5$ its value decreases. However, at a distance of $s/B > 5$, there is no interference between the footings.

6. Both theoretical and experimental findings correlate with each other and have a similar trend.

7. The suggested interference factor model has an effective reflection on the calculated bearing capacities of the footings.

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