

Effect of Interference on Ultimate Bearing Capacity of Strip Footings Resting on Reinforced Clay Overlying Sand



Chandra Sekhar Jonnagiri, Venkata Balaiah Kami
and Rabi Narayan Behera

Abstract The prevailing studies on the bearing capacity of shallow foundations show the tendency of relying on a hypothesis of an isolated footing resting in a homogeneous soil mass. In practice, the soil is seldom homogeneous, and heterogeneity increases with the area of consideration. In addition to the non-homogeneous nature of the soil, the footing also may not be isolated due to various reasons like very rare availability of good construction sites and rapid urbanization coupled with the shortage of land. However, these studies are ineffective when the closely placed footings encountered at shallow depths of a multi-layered soil mass. In the present study, a numerical investigation is carried out to evaluate the effect of interference on the ultimate bearing capacity of two closely placed identical surface strip footings resting over two-layered soil (weak soil overlying on a strong soil) mass subjected to a vertical concentric load using the finite element package, PLAXIS 3D. The granular soil (sand with relatively higher stiffness) is considered as strong soil, whereas the soft soil is considered as a weak soil. The analysis is carried out for various ratios of clear spacing to the footing width (s/B) ranging from 0.5 to 6 by varying first layer thickness (H) as $B-5B @ B$. Based on the analyses of results, the critical spacing (s_{cr}) and significant depths (H_s) were observed as $3B$ and $2B$. The increment in ultimate bearing capacity ceases after these spacing and depth for weak soil overlying strong soil mass system. Also, with the inclusion of reinforcement, the critical spacing (s_{cr}) was observed as $1.5B$.

Keywords Interference · Strip footings · Ultimate bearing capacity · Multi-layered soil · Reinforcement · Numerical analysis

C. S. Jonnagiri · V. B. Kami · R. N. Behera (✉)
Department of Civil Engineering, National Institute of Technology Rourkela, Rourkela, India
e-mail: rnbehera82@gmail.com

C. S. Jonnagiri
e-mail: chandra.2052@gmail.com

V. B. Kami
e-mail: balu.k1200@gmail.com

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1 Introduction

The interference concept is observed when two or more number of footings are placed closely. The interference phenomenon was first coined by Stuart [1]. Stuart [1] examined the closely spaced strip footings laying on the surface. Stuart [1] observed a difference in the ultimate bearing capacity and settlement of isolated footings when they placed close. Finally, Stuart [1] concluded that the overlapping of pressure bulbs has a significant impact on the bearing capacity and settlement behavior of the isolated footings. Numerous researches have been carried out to determine the interference effect on the ultimate bearing capacity of various types of footings resting over homogeneous soil mass. Stuart [1] reported that the bearing capacity of interfering footings increases as the spacing between the footings decreases and it attains a peak magnitude at a spacing known as *critical spacing* (s_{cr}). The similar findings were observed by Ghazavi and Lavasan [2], Srinivasan and Ghosh [3], Elthohamy and Zidan [4], Pusadkar et al. [5]. From the literature, the critical spacing is observed in the range of $0.6B$ [4] to $2B$ [2]. It is also noted that the interference effect becomes insignificant after a certain spacing. This spacing is reported in the range of $3B$ [6] to $6B$ [7] for two identical square footings resting over sandy soil. West and Stuart [8] observed the increase in bearing capacity of parallel spaced strip footing considering the effect of eccentricity and inclination of soil reaction. Kumar and Saran [9] reported non dimensional charts for pressure ratio calculation of adjacent rectangular footing. The interference effect of strip footing on single layer uniaxial sand bed was presented by [10]. The response of a number of identically spaced multiple strip footing was presented in [11]. A Fast Lagrangian Analysis of Continua algorithm for studying the effect of interference was presented by [12]. Daud [13] reported that, response of multiple strip footing is similar to that of single footing for distance greater than four times the width of footing. Noorzad and Manavirad [14] found that increasing the number of reinforcement layer does not have significant effect beyond the threshold value. Interference of strip footing was presented, using Hoek–Brown failure criterion in [15]. The performance of ring footing on multilayered reinforced soil was reported by [16]. The interference effect in the case of square footing was presented in [17]. The decrease in ultimate bearing capacity due to the effect of interference was observed by [18]. They found that, the ultimate bearing capacity reduces irrespective of the spacing between the footings. The literature showed that the increase in stiffness of reinforcement beyond a threshold value does not affect the bearing capacity of interfering footings. However, very limited literature is available to determine the effect of interference on the ultimate bearing capacity of footings resting over multilayered reinforced soil. The current research focused on the effect of interference on the ultimate bearing capacity of two surface strip footings resting on clay overlying sand in both unreinforced and reinforced conditions.

2 Materials Used

2.1 Soil

Two soils, namely soft clay (cohesive soil) and dry sand (cohesionless soil), together represent the multi-layered soil mass system considered in the present study. The soils are assumed to behave as elastic-perfectly plastic material and hence considered Mohr–Coulomb failure criterion. A cubical soil volume of $2 \text{ m} \times 0.37 \text{ m} \times 0.5 \text{ m}$ ($L \times B \times H$) is simulated to resemble the full soil geometry. The geometry of soil volume for the case of $H/B = 3$ cases is shown in Fig. 1. The full 3D soil geometry with two nearby strip footings resting on two-layered soil mass with the associated parameters b , l , u , h , s , B and N representing width of reinforcement layer, length of reinforcement layer, depth of first reinforcement layer from bottom of the footing, vertical spacing of reinforcement, clear distance between the footings, width of footings and the number of reinforcement layers, respectively, and is shown in Fig. 2.

The undrained type of behavior is adapted to the clay for which the shear strength parameters are incorporated in terms of undrained shear strength and drained behavior is adopted for the sand. The mechanical properties of soils are presented in Table 1.

The undrained character of the clay preferred to include in the analysis is to simulate the field conditions. The drained behavior of sand is undertaken in the study to represent the very quick dissipation of pore water pressures from voids immediately after the application of load in practice.

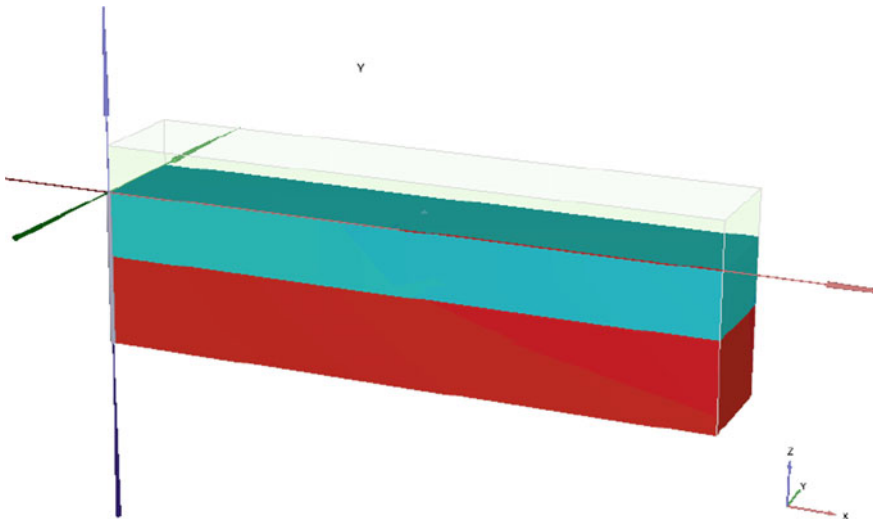


Fig. 1 The geometry of soil volume for $H/B = 3$ case

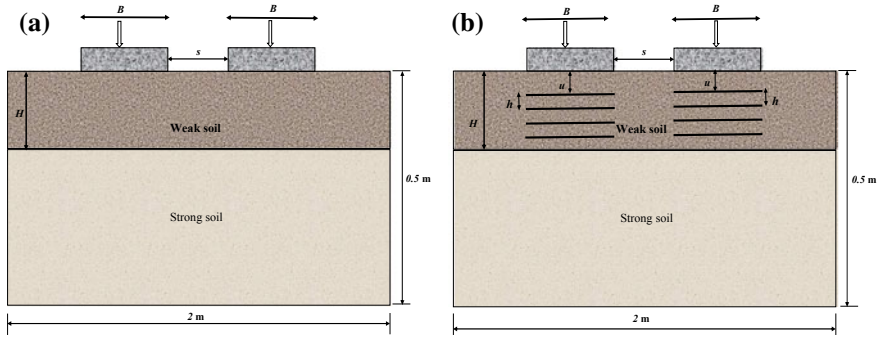


Fig. 2 Weak soil overlying relatively strong soil, (a) unreinforced case and (b) reinforced case

Table 1 Mechanical properties of soils

Property	Model/value	Model/value
Model type	Mohr–Coulomb	Mohr–Coulomb
Soil type	SP	CL
Drainage type	Drained	Undrained
γ_{dry} (kN/m ³)	16.2	17.5
γ_{sat} (kN/m ³)	18.0	19.5
D_{60} (mm)	0.75	–
D_{30} (mm)	0.37	–
D_{10} (mm)	0.20	–
C_u	3.75	–
C_c	0.91	–
Effective cohesion c' (kPa)	0.1	–
Undrained shear strength S_u (kPa)	–	30
Effective angle of internal friction ϕ' (°)	37.4	0
Modulus of elasticity E (kPa)	35,000	5000
Poisson’s ratio, μ	0.25	0.3
Relative density R_D (%)	67	–
k_X (m/day)	0.6	$0.05E^{-3}$
k_Y (m/day)	0.6	$0.05E^{-3}$
k_Z (m/day)	0.6	$0.05E^{-3}$

Table 2 Mechanical properties of footing and test box

Property	Footing	Test box
Modeled as	Plate	Plate
Model type	Linear-elastic	Linear-elastic
Thickness (m)	0.025	0.025
γ (kN/m ³)	78.5	78.5
Width, B (m)	0.07	0.37
Modulus of elasticity, E (kPa)	200×10^6	200×10^6
Poisson's ratio, μ	0.25	0.25

2.2 Footing and Test Box

A semi-rigid strip footing with the dimensions of $0.36 \text{ m} \times 0.07 \text{ m}$ ($L \times B$) is simulated to represent footing for the numerical analysis. The footing is modeled by a steel plate of thickness 0.03 m. The steel plate is relatively stiff enough compared to the stiffness of soils used in the current study to assume it as a semi-rigid footing. Two such identical symmetrical footings are used to determine the interference effect on the ultimate bearing capacity of footings in the two-layered soil mass. Linear-elastic nature is adopted for the footing used in the numerical analysis. Table 2 lists the mechanical properties of the footing and test box.

2.3 Reinforcement

Reinforcement layers were modeled using geogrids option in PLAXIS 3D which represents a structural tensile element with unit thickness and tensile strength. The biaxial geogrid elements are placed at a specified depth and at specified regular vertical intervals below the bottom of the footing. No slip between the soil and reinforcement is assumed, and hence, no interface elements are used in the current study. The geogrid behaves as an elastic material which can have only tensile resistance but no compressive and flexural resistance. The tensile strength of geogrid is incorporated in terms of the axial stiffness per meter length of the geogrid. The magnitude of the tensile strength of the geogrid used for the numerical analysis has been adopted from the majorly illustrated literature. The mechanical properties of the reinforcement element are tabulated in Table 3.

Table 3 Mechanical properties of reinforcement

Property	Model/value
Reinforcement type	Geogrid
Model type	Elastic-isotropic
Axial stiffness, EA_1 (kN/m)	40
Axial stiffness, EA_2 (kN/m)	40

3 Methodology

3.1 Schematic Explanation of Modeling

In the current study, a finite element program PLAXS 3D is employed to model interfering surface strip footings resting on two-layered soil system without reinforcement and with reinforcement. In broad, the procedure consists of the determination of the optimum top layer thickness for the unreinforced case and then the continuation of the similar study with reinforcement for the optimum top layer thickness.

The stress-controlled approach is adopted by applying the load till the failure of the soil mass occurs. It is assumed that no groundwater table exists below the footing, and hence, it is simulated by applying groundwater well below the footings, so that it does not affect the ultimate bearing capacity of the footings in dry condition. The whole soil volume is enclosed in a steel tank to represent the laboratory conditions used for the similar kind of experimental investigations carried out by Kumar and Bhoi [19]. Validation study also has been carried out in the test box of dimensions as specified by Kumar and Bhoi [19]. 15 noded elements are used to generate the meshing. The staged construction mode has been adopted to simulate the procedure of construction practices. The vertical concentric point loads are applied to make the calculations easy and time-effective.

The whole analysis is presented in two cases, unreinforced and reinforced, as shown in Fig. 2. The most common problems are addressed by considering both stages, which is the most reliable pattern of analysis. In addition, all possible cases are considered by the means of different parameters which includes significant depth or the top layer thickness, critical spacing and the optimum number of reinforcement layers. Failure patterns also are shown in the present study to support numerical analysis. Both isolated and interfering footings of optimum cases are also compared by taking assistance from the failure patterns. In the present study, the inclusion of reinforcement is done by considering the deep slab mechanism explained by Huang and Menq [20].

4 Numerical Modeling

The procedure of modeling the geometry, simulating the experimental conditions and generation of mesh and the calculations are elaborated with the help of respective PLAXIS 3D images. Two cases, unreinforced and reinforced of weak soil, overlying relatively strong soil are simulated and analyzed. The number of reinforcement layers is varied from one to four in both cases. The interference effect is determined in various terminology defined by the various researchers in literature. The terminology related to this interference effect used in the current study is explained as below.

Various terminology related to interference effect used in the current study:

$$\xi = \frac{(q_{u,int})}{(q_{u,single})} \text{ for homogeneous soil mass} \tag{1}$$

$$E_f = \frac{(q_{u,int})}{(q_{u,single})} \text{ for multi-layered unreinforced soil mass} \tag{2}$$

$$E'_f = \frac{(q_{u,int})}{(q_{u,single})} \text{ for multi-layered reinforced soil mass} \tag{3}$$

where ξ , E_f and E'_f are efficiency factors in respective conditions and $(q_{u,int})$ and $(q_{u,single})$ are the ultimate bearing capacities of interfering footing and single footing, respectively. For all the cases, the geometry of the model and the material properties used are kept unchanged as the observing variables only change accordingly. The procedure employed to reach the output is also kept constant throughout the analysis. All the analyses are performed to reach the ultimate failure of the soil mass and the corresponding bearing resistance is determined from the graphs plotted as load intensity (q_u) versus settlement curves. The ultimate bearing capacity is determined by using the double tangent method. The procedure adopted to model and analyzing the problem is clearly explained in the preceding sections. First, the unreinforced case is carried out for isolated and interfering footing by varying first (top) layer thickness from the bottom of the footing (H) with the thickness equal to one time of the footing width to five times of the footing width. From these unreinforced cases ($H = B, 2B, 3B, 4B$ and $5B$), the optimum thickness of the top layer is obtained in terms of maximum ultimate bearing capacity and the reinforcement layers ($N = 1, 2, 3, 4$) are being incorporated to evaluate the optimum reinforcement depth. The optimum case is selected based on the highest ultimate bearing capacity observed among all the unreinforced cases and this case is utilized to carry the reinforced cases by varying the number of reinforcement layers (N) from one to four. The geometry of the model, structural elements and generated mesh of the optimum case ($H/B = 3$) are shown in Figs. 3, 4 and 5, respectively, for both isolated and interference footings. The analysis of interference of strip footings is preceded further to the reinforced case for the optimum top layer thickness by varying the number of reinforcement layers. The four number of reinforcement layers are introduced at a vertical spacing of ($h/B =$

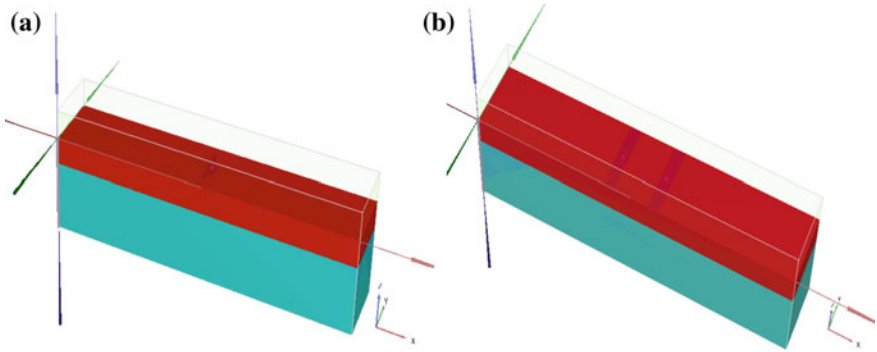


Fig. 3 The geometry of soil volume for $H/B = 2$ cases, (a) isolated footing and (b) interfering footings, clay overlying sand

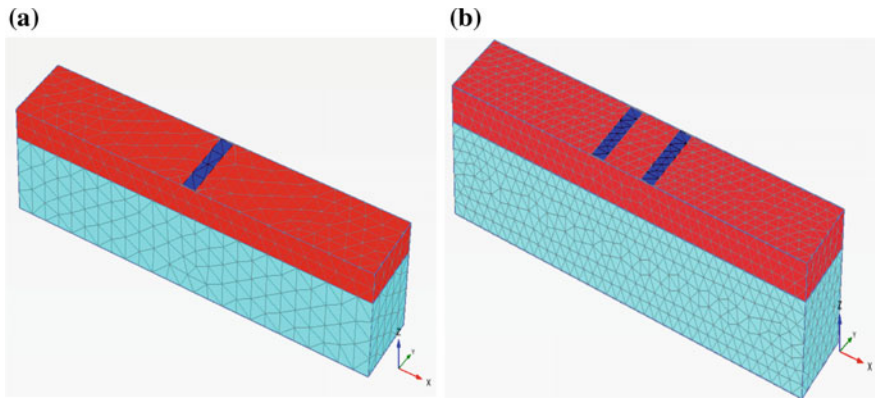


Fig. 4 Meshing for $H/B = 2$ case (a) isolated footing and (b) interfering footings, clay overlying sand

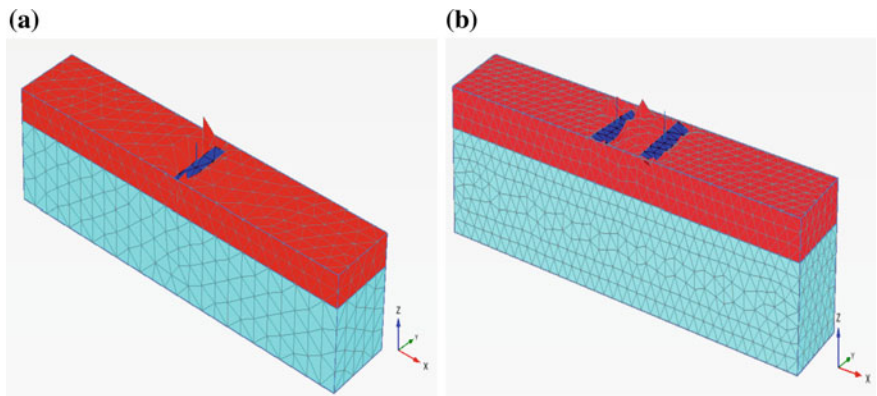


Fig. 5 The deformed mesh of isolated footing, for $H/B = 2$ case (a) Isolated footing and (b) interfering footings, clay overlying sand

0.25) with the depth of first or top reinforcement layer from the bottom of the footings as ($u/B = 0.35$). The use of geogrid as reinforcement in geotechnical applications become unique advantage program especially in foundations overlying weak soils or the soils with very low bearing capacity. The soil–reinforcement interface friction is the key factor which derives additional shear strength to the original soil.

It is well established that the inclusion of reinforcement in soils make them stronger, stiffer and durable, and hence, the application of reinforcement become quite common in geotechnical engineering applications.

5 Validation

In the present study, validation has been carried out with the experimental investigation of a similar study in the homogeneous soil.

The numerical results obtained from PLAXIS 3D are compared with the experimental investigation carried out by Kumar and Bhoi [19]. In which, the effect of interference of footing on ultimate bearing capacity in terms of efficiency factor (ξ) at ultimate failure for a dry density of 16.2 kN/m^3 in homogeneous soil mass has been presented. The geometrical model adopted in the current study is clearly shown in Fig. 6.

From the validation study, it is found that both finite element software and experimental investigation of Kumar and Bhoi [19] yielded similar results. The results obtained from numerical analysis are very well agreed with experimental results presented by Kumar and Bhoi [19] as shown in Fig. 7.

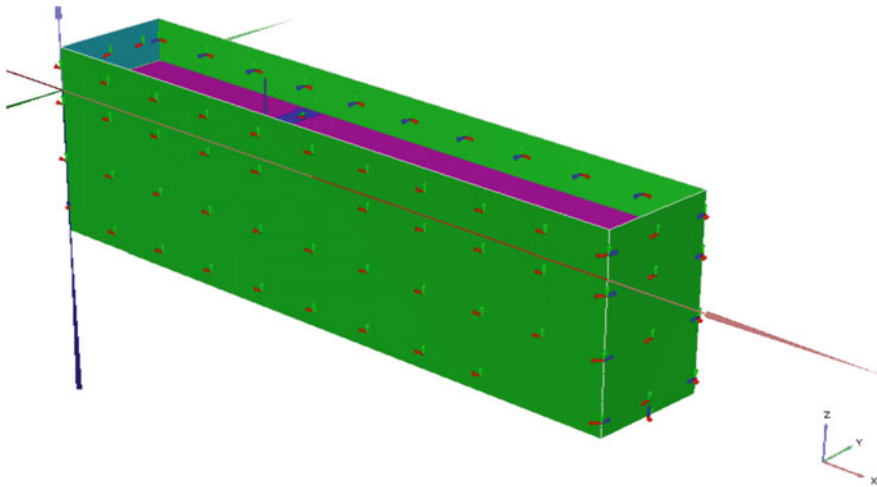


Fig. 6 The geometrical model generated in PLAXIS 3D for validation

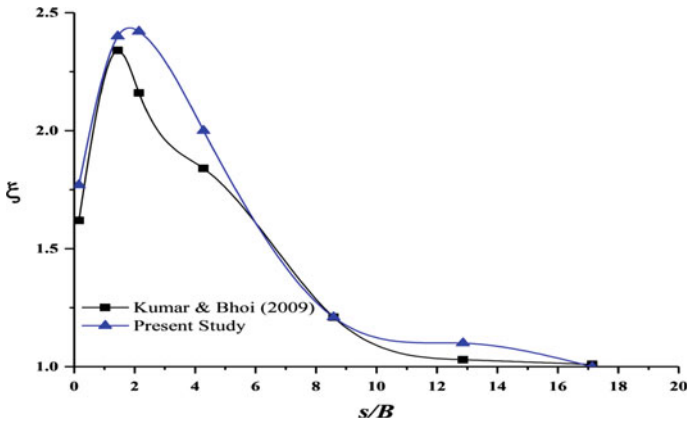


Fig. 7 Validation of present study with Kumar and Bhoi [19]

6 Results and Discussion

6.1 Clay Overlying Sand Without Reinforcement

The analysis of weak soil overlying strong soil has been carried out. As an initial step, the analysis was carried out without reinforcement to find the optimum clay layer thickness. Later, the study is continued by reinforcing the clay layer with a different number of reinforcement layers. The interference effect of the footings on ultimate bearing capacity in terms of efficiency factor has shown in Fig. 8. From Fig. 8, it is clearly observed that there is an increment of bearing capacity in terms of efficiency factor (E_f) up to $s/B = 3$ and descends till $s/B = 5$ for all the case of H/B . It is also observed that the efficiency factor (E_f) is increased up to a top layer thickness of $2B$ and decreases till $5B$. So, $s/B = 3$ and $H/B = 2$ are found to be optimum spacing and optimum thickness, respectively, after which the interference effect is minimal.

Further, the study is continued with the inclusion of a different number of reinforcement layers for the optimum case ($H/B = 2$). The failure patterns of the optimum case ($H/B = 2$) for both isolated and interfering footings of $s/B = 3$ are as shown in Figs. 9 and 10, respectively.

6.2 Clay Overlying Sand with Reinforcement

The analysis of interference of strip footings is proceeded further to the reinforced case for the optimum top layer thickness ($H = 2B$) by varying the number of reinforcement layers. The four number of reinforcement layers are introduced at a vertical spacing of ($h/B = 0.25$) with the depth of first or top reinforcement layer from the

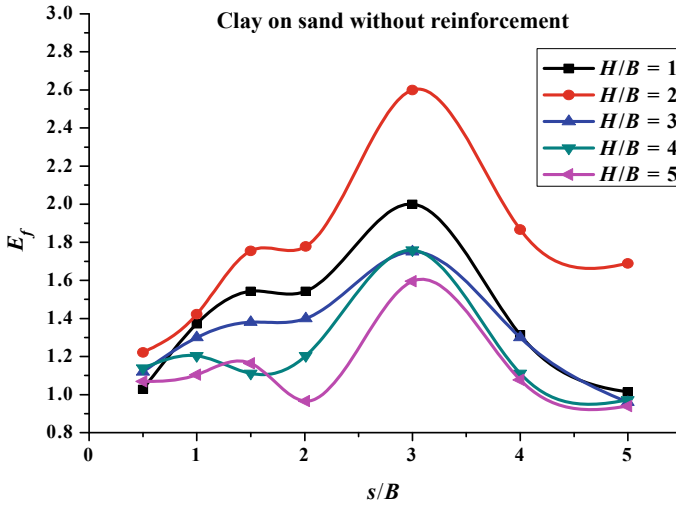


Fig. 8 Interference factor versus s/B with a variation of top layer thickness

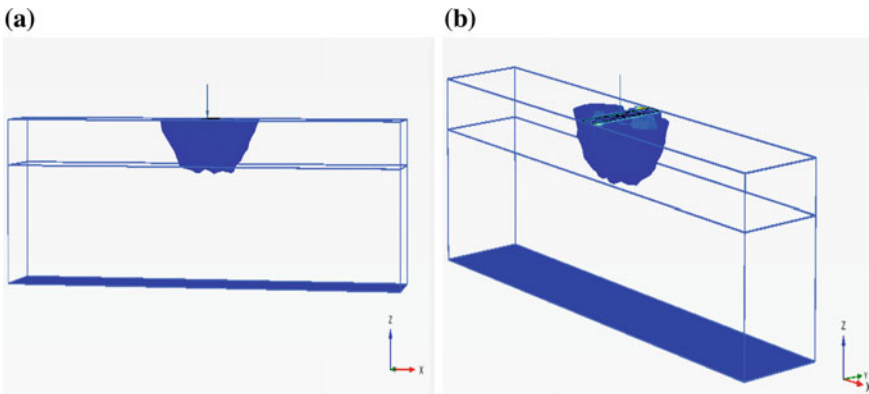


Fig. 9 Failure pattern of isolated footing, for $H/B = 2$ case (a) front view and (b) isometric view

bottom of the footings as ($u/B = 0.35$). Figure 11 shows the variation of the ultimate bearing capacity of interfering footings in terms of efficiency factor with the number of reinforcement layers. In the reinforced case, the efficiency factor is designated as E_f' to differentiate it from the unreinforced case. From Fig. 11, it is observed that as the number of reinforcement layers increased, the interference effect also increased. It is also noted that the optimum interference effect on ultimate bearing capacity observed for $N_{opt} = 3$.

Figure 12 depicts the failure patterns of three and four number of reinforcement layers of the top layer thickness (H) of $2B$ for the clear spacing (s) of $1.5B$, respectively.

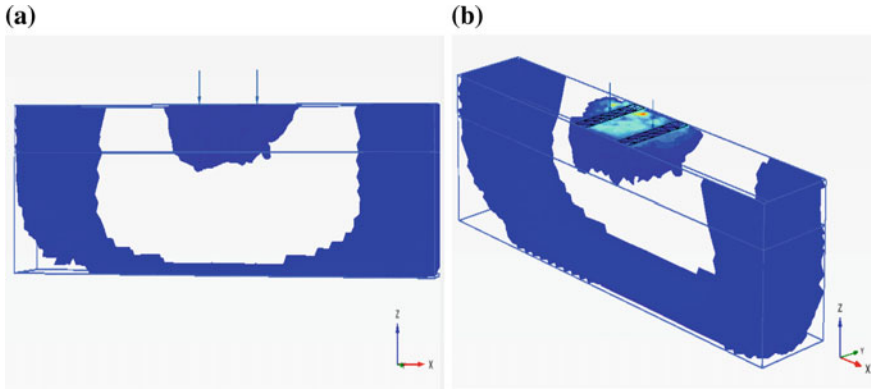


Fig. 10 Failure pattern of interfering footing ($s/B = 3$), for $H/B = 2$ case (a) front view and (b) isometric view

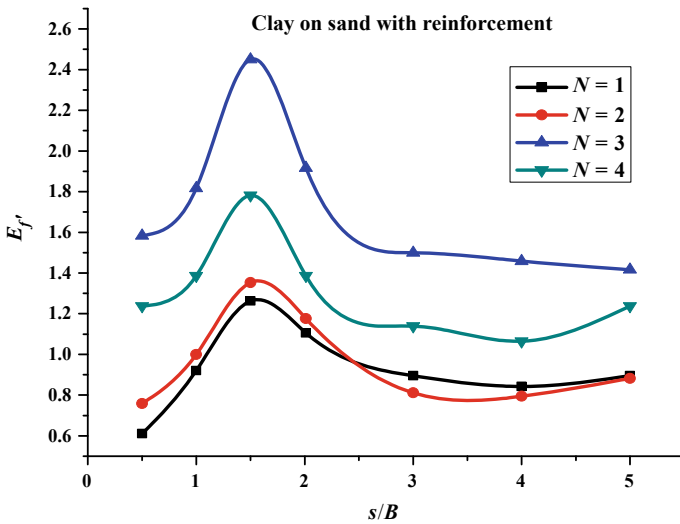


Fig. 11 Interference factor versus s/B with a variation of number of reinforcement layers

7 Conclusions

In the present study, the effect of clear spacing between two closely spaced footings, effect of reinforcement, effect of top layer thickness on ultimate bearing capacity (q_u) of interfering footings resting over two-layered soil (weak soil overlying on a strong soil) with and without reinforcement have been analyzed, and the results are presented in the form of critical spacing (s_{cr}), significant depth (H_s) and optimum number of reinforcement layers (N_{opt}).

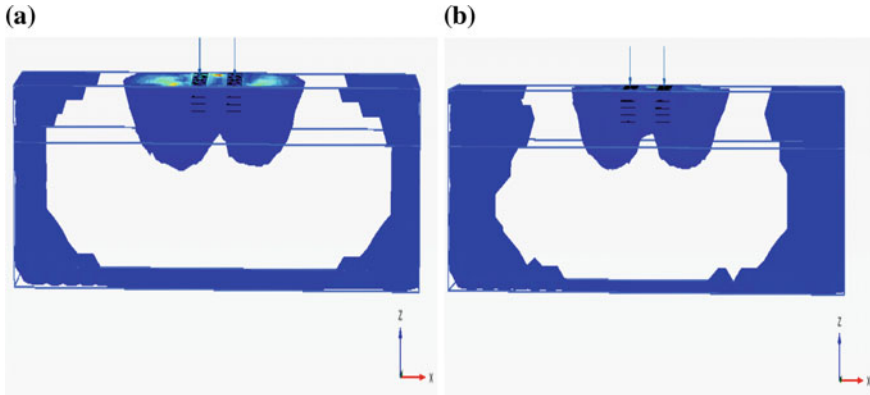


Fig. 12 Failure pattern of (a) three reinforcement layers and (b) four reinforcement layers of $H/B = 2$ case

In the unreinforced soil system,

- The critical spacing (s_{cr}) is observed as $3B$.
- The critical depth (H_{cr}) is observed as $2B$.

In the reinforced soil system,

- The critical spacing (s_{cr}) is observed as $1.5B$.
- The optimum number of reinforcement layers (N_{opt}) is observed as 3.

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