

# Elastic settlements of identical angular footings in close proximity

R. Sarvesh<sup>a</sup>, V. Srinivasan\* and Anjan Patel<sup>b</sup>

Department of Civil Engineering, Visvesvaraya National Institute of Technology, Nagpur – 440 010, India

(Received July 22, 2022, Revised January 7, 2023, Accepted January 8, 2023)

**Abstract.** In general, the numerous classical approaches available in the literature can anticipate the settlement of shallow foundations. As long as the footings are not in close proximity to other subsurface buildings, the findings achieved using these methods are legitimate and acceptable. However, due to increased urbanisation and land scarcity, footings are frequently built close together. As a result, these footings' settlement behaviour differs from those of isolated footings. A simpler approach for assessing the settlement behaviour of two square or rectangular footings placed in close proximity is presented in this work. A Parametric study has been carried out to examine the interference effect on the settlement of these footings placed in close vicinity on the surface of a homogeneous, isotropic and elastic soil medium. The interaction factors are examined by varying the different aspect ratios ( $L/B$ ), clear spacing ratio ( $S/B$ ) and intensity of loading on the right footing with respect to the left footing. Further, variation of the settlement ratio ( $\delta/B$ ) with respect to embedment depth ratio  $D_f/B$  is examined. For square and rectangular footings, the interference settlement profile is also investigated by varying the clear spacing ratio ( $S/B$ ) and the degree of loading. The results were compared to 3D finite element analysis and experimental data that were available.

**Keywords:** interference effect; intensity of loading; interaction factor; settlement; square and rectangular footings

## 1. Introduction

The allowable bearing capacity of shallow foundations is predicted based on ultimate bearing capacity and settlement of soil under the footing. The ultimate bearing capacity and settlement predictions are theoretically obtained by assuming that the footings are placed in isolated condition with sufficient distance from nearby foundations as prescribed by various buildings codes and guidelines. But in most of the cases, due to scarcity of land, other foundations in the vicinity are made closer to the existing footings and the whole system behaves as a group. Under such condition, behaviour of a footings under the influence of the adjacent one shall be different. Although, bearing capacity and settlements for isolated footings can be predicted with the available traditional methods (Terzaghi 1943, Meyerhof 1951, Vesic 1973, Burland and Burbidge 1985, Bowles 1987, Bowles 1988, Berardi and Lancellotta, 1991), related studies in literature especially the settlement behaviour of footings in closed proximity is scanty (Saran and Agarwa 1974, Nainegali *et al.* 2013, Nainegali 2013, Shahein and Hefdhallah 2013, Srinivasan and Ghosh 2013, Roy and Deb 2019). It is to mention here that, for all practical purpose, the settlements are more predominant criteria for adopting the type of footing rather than ultimate bearing capacity.

However, in many circumstances because of paucity of land, regulations in property lines and architecture of the buildings or to accommodate structural details etc., it is compelled to construct the footings close to each other. This may lead serious damage to the structures in strength as well as in serviceability point of view.

As per the foundation failure mechanism proposed by Terzaghi (1942), the failure plane is likely to be extended up to a distance 3 to 5 times of the width of the footing on either side of the footing. This in general is known to be influence zone in the semi-infinite half space. Prediction of bearing capacity and settlement for isolated shallow footings has been determined considering that there was no adjacent footing with in the influence zone on either side or at a sufficiently greater distance beyond the influence zone.

If the footings are placed in close proximity, then the behaviour (i.e., bearing capacity and settlement) of the footings are distinct from the single isolated footing, since the failure zone may overlap when the footings are placed in close vicinity. Due to this, there should be some interference effect between the footings. Hence, the failure mechanism for single isolated footing is not at all valid in such case.

West and Stuart (1965) determined the solution for the interference effect of strip footings resting on sandy soil by method of stress characteristics. The analysis was carried out for the soil having friction angle of  $35^\circ$ . The efficiency factors obtained from the literature (West and Stuart 1965) was less as compared to the available literature (Stuart 1962). Later, Kumar and Ghosh (2007b) determined the interference effect of strip footings resting on sand by upper bound limit analysis and suggested collapse mechanism and velocity hodographs. The obtained results were well comparable with the literature (Stuart 1962).

\*Corresponding author, Assistant Professor

E-mail: srinivasanv@civ.vnit.ac.in

<sup>a</sup>Ph.D. Scholar

E-mail: sarveshsai21@students.vnit.ac.in

<sup>b</sup>Associate Professor

E-mail: anjanpatel@civ.vnit.ac.in

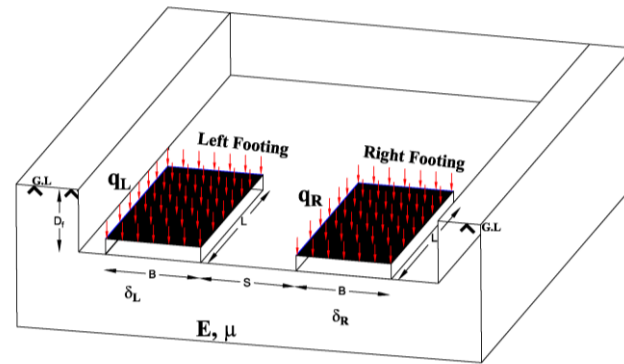


Fig. 1 Problem definition and soil foundation domain along the sectional view at the edge of the footings

Kumar and Bhattacharya (2010) examined the interference effect on ultimate bearing capacity of multiple strip footings spaced identically by lower bound finite element limit analysis. The effect of interference of footing was similar to that of the literature (Stuart 1962) but the values obtained were little less. Kouzer and Kumar (2010) also reported the same results as obtained by Stuart (1962) from the upper bound finite element analysis.

Ghosh and Sharma (2010) investigated the interference effect on settlement under the shallow rough footings spaced nearby and resting on layered soils by theory of elasticity approach. Finite difference scheme was adopted on two layered soil, a feeble layer was present below the strong layer and a partial differential equation was established from theory of elasticity and resolved numerically. The results were discussed in the form of settlement ratio with reference to the variation of spacing and depth ratio and modulus of elasticity ratio of two layers. The reported settlement ratio decreases as the spacing increases between the footings spaced closely and behaves like an isolated footing beyond the critical spacing ratio. Nainegali *et al.* (2013), conducted the study on interference effect of two asymmetric closely spaced strip footings resting on non-homogeneous and linearly varying elastic soil bed. The interference effect on settlement for shallow footings spaced nearby was studied by using finite-element method. The results were reported in terms of interaction factors for left and right footings. The results were found to be similar to the literature (Ghosh and Sharma 2010).

Ghosh *et al.* (2017), inspected the interaction factor for the settlement of strip footings spaced closely on linear and non-linear elastic soil bed by Pasternak model. The parameters considered in the analysis were exactly same as the literature (Nainegali *et al.* 2013) except the non-linearity consideration. The non-linearity of soil was considered by hyperbolic stress-strain relationship equations. The results were presented in terms of interaction factor of left footing and right footing they were similar to the literature (Nainegali *et al.* 2013).

It can be observed that most of the research articles have accomplished the work based on theoretical, analytical, finite element analysis, upper bound, lower bound and model testing and reported that the ultimate bearing capacity of footings increases as the spacing decreases and

vice versa. Settlements corresponding to ultimate loads increases as the spacing between the footings decreases and vice versa.

Further, number of experimental, analytical and numerical studies have been carried out on the interference effect of footings placed in closed proximity by several researchers (Nainegali *et al.* 2013, Srinivasan and Ghosh 2013, Roy and Deb 2019, West and Stuart 1965, Kumar and Ghosh 2007b, Das and Larbi – Cherif 1983, Das *et al.* 1993, Kumar and Saran 2003, Griffiths *et al.* 2006, Kumar and Ghosh 2007a, Lee *et al.* 2008, Kumar and Bhoi 2009, Lee and Eun 2009, Mabrouki *et al.* 2010, Ghosh and Kumar 2011, Kumar and Bhattacharya 2011, Ghosh *et al.* 2015) and reported that the ultimate bearing capacity of the interfering footings increases as the spacing between the footings decreases and vice versa. But the interference effect on settlement of closely spaced footings has not been greatly reported. Most of the investigations were carried out on strip footings resting on sandy soils.

Very few investigations (Nainegali 2013, Shahein and Hefdhallah 2013, Srinivasan and Ghosh 2013, Gupta and Sitharam 2018, Roy and Deb 2019) have reported on the interference effect on settlements for square, rectangular and circular footings. Further it is worth to note that most of them have reported the settlement at failure in case of interacting footings whereas in the real-time condition, the loads are applied only up to service condition (Shahein and Hefdhallah 2013), hence the study on effect of settlements due to service loads shall be more viable.

Therefore, it is more essential to determine the interference effect on immediate settlement of shallow footings placed in closed proximity on geomaterials. The work is accomplished through a comprehensive look into all relevant literature regarding prediction of settlement of shallow footings placed in close proximity on an elastic soil medium or immediate settlement of cohesive-frictional materials.

## 2. Description of the problem

Parametric study has been carried out to examine the interference effect on settlement of surface and embedded square and rectangular footings placed in close proximity. The

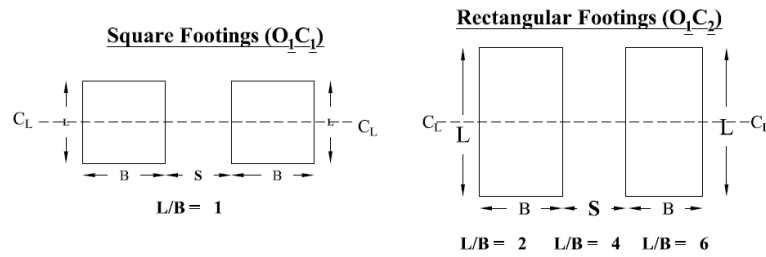


Fig. 2 Geometrical configuration of square and rectangular footings

Table 1 Parameters considered in the analysis

Parameter	Value
Elastic modulus of the soil at the surface, $E$	30 MPa
Poisson's ratio of soil, $\mu$	0.3
Footing shape considered	Square ( $L/B = 1.0$ ) and Rectangular ( $L/B > 1.0$ )
Width of left footing = Width of right footing = $B$	1 m
Pressure on left footing $q_L$	0.25 MPa
Pressure on right footing $q_R = n * q_L$	$n = 1.0, 1.25, 1.5, 1.75, 2.0$
Spacing ( $S/B$ ) varies	0.5 to 10
$D_f/B$	0.0, 0.5 and 1.0
Type of Soil	Granular medium

soil medium is considered to be an isotropic, homogeneous elastic half-space. Fig. 1. represents sectional view at the edge of two identical rigid footings of width  $B$ , length  $L$ , embedded at depth  $D_f$ , separated by a clear distance  $S$ , subjected to asymmetrical service loads  $q_L$  and  $q_R$  on left and right footing respectively whose elastic settlements corresponds to  $\delta_L$  and  $\delta_R$ . Ratio of the intensity of load on left footing ( $q_L$ ) to the right footing ( $q_R$ ) is taken as  $n$ . In order to lucidly facilitate the design engineers, the results are presented in the form of interaction factors which would provide information about the effect of interference phenomenon in comparison to the single or isolated footing. The interaction factors are examined by varying the aspect ratio ( $L/B$ ), clear spacing ratio ( $S/B$ ) and intensity of loading on right footing with respect to left footing and; the variation of settlement ratio ( $\delta/B$ ) with respect to embedment depth ratio ( $D_f/B$ ) are also examined. Attempts are also made to study the Interference settlement profile by varying the clear spacing ratio ( $S/B$ ) and intensity of loading for square and rectangular footings. The geometrical configuration of square and rectangular footings is shown in Fig. 2.

The square and rectangular footings are designated as  $O_1C_1$  and  $O_1C_2$  respectively. The interfering footings are symmetrical with respect to centre line  $C_L$ . Parameters used in the analysis are given in Table 1.

### 3. Method of analysis

#### 3.1 Assumptions

Analysis has been carried out by assuming that the soil beneath the footings is homogeneous, isotropic, and elastic. Stiffness parameters, Young's modulus ( $E$ ) and Poisson ratio ( $\mu$ ) of the soil below the footings are uniform to infinite depth and constant throughout the analysis for all the cases. The base of the footings is assumed to be rigid and perfectly rough to prevent from any horizontal displacement. Loads on the footings are always perfectly vertical throughout the analysis for all cases. Hence, neither eccentricity nor inclination is considered. Intensity of loading on right footing is varying in comparison with left footing by keeping intensity of loading on left footing constant throughout the analysis. The present problem is a typical 3D space domain rather a plane strain problem considered in several reported literatures (Ghosh and Sharma 2010, Ghosh and Kumar 2011, Nainegali *et al.* 2013) which shall represent the true condition.

#### 3.2 Formulation

A traditional method which is used to estimate the elastic settlement of an isolated flexible footing resting on semi-infinite solid subjected to vertical load on a finite area is given in Eq. (1), which was proposed by Terzaghi (1943). He assumed that the solid is perfectly elastic; the law of superposition of loads and displacements is valid. Eq. (1) is used to estimate the elastic settlement at any given point of an isolated square and rectangular footings.

$$\Delta_s = qB \frac{(1 - \mu^2)}{E} I_s \quad (1)$$

Where,

$\Delta_s$  = Elastic settlement at the corner of the footing.

$q$  = Uniformly distributed surcharge per unit of area.

$B$  = width of the footing.

$E$  = Young's modulus of the soil below the footing.

$I_s$  = Steinbrennr's Influence factor.

$$I_s = \frac{1}{\pi} \left[ l \log_e \frac{1 + \sqrt{l^2 + 1}}{l} + \log_e \left( l + \sqrt{l^2 + 1} \right) \right] \quad (2)$$

$$l = \frac{L}{B} \quad (3)$$

The above equation proposed by Schleicher (1926) is used in the present study for developing the simplified equation for the computation of interfering elastic settlement of shallow rectangular and square footings (Fig.

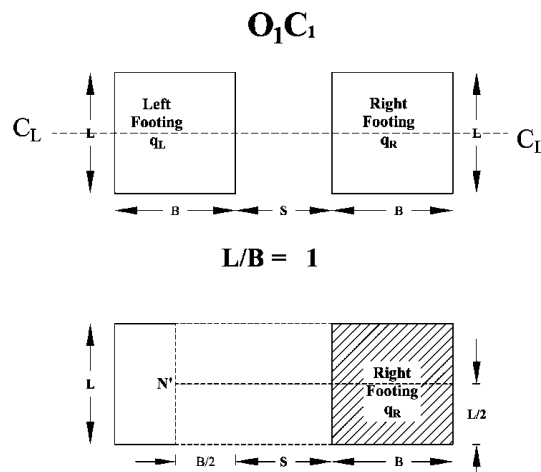


Fig. 3 Average Elastic Settlement of left footing at  $N'$  due to the interference of right footing

2) placed in closed proximity on homogeneous soil extended to an infinite depth.

The equations are derived in terms of dimensionless parameter called as interaction factor. The analysis has been carried out for geometrical configuration of square and rectangular footings (Fig. 2) by varying  $L/B$  ratios, clear spacing,  $S$  between the footings and the intensity of loading on right footing with respect to left footing.

$$\text{Interaction factor for left footing } (\xi_{\delta L}) = \frac{\text{Average settlement of interfering left footing}}{\text{Average settlement of isolated left footing}}$$

$$\text{Interaction factor for right footing } (\xi_{\delta R}) = \frac{\text{Average settlement of interfering right footing}}{\text{Average settlement of isolated right footing}}$$

### 3.3 Procedure

For the purpose of understanding the calculation procedure, the symmetrical square footings resting on the surface of homogeneous and isotropic soil in closed proximity has been considered.

*Interaction factor for left footing due to the interference of right footing:*

The average settlement of isolated left footing can be calculated by using Eq. (1). The average settlement of left footing at  $N'$  due to the interference of right footing can be calculated from the Fig. 3. Here,  $N'$  is the centre of the left footing. The complete area is split into two rectangles through  $N'$  to analyse the average interfering settlements at  $N'$  owing to the existence of the right footing. Fig. 3 depicts the loaded area taken into account in determining  $S_R$  (the shaded portion). The average interference settlements at  $N'$  due to the presence of right footing have been calculated.

The settlement interaction factor for left footing is proposed as

$$\xi_{\delta L} = \frac{SCR}{S_i} \quad (4)$$

Where,

$SCR$  = Average settlement of interfering left footing.

$$SCR = S_i + S_R \quad (5)$$

$S_i$  = Average settlement of isolated left footing.

$S_R$  = Average settlement of left footing due to the interference of right footing.

$$\xi_{\delta L} = \frac{S_i + S_R}{S_i} \quad (6)$$

$$\xi_{\delta L} = 1 + \frac{S_R}{S_i} \quad (7)$$

$$S_R = q_R \left( \frac{1 - \mu^2}{E} \right) 2(B_1 I_1 - B_2 I_2) \quad (8)$$

$I_1$  and  $I_2$  are the influence factors for considering rectangular portions in Fig. 3. Determine the values of  $B_1$ ,  $B_2$ ,  $I_1$  and  $I_2$  and substitute in Eq. (7). Then, the simplified equation for assessment of interaction factor as defined for left footing due to the presence of right footing is as follows

$$\xi_{\delta L} = 1 + \frac{n[(B_1 X_1 - B_2 X_2)]}{BXL} \quad (9)$$

$$X_1 = l_1 \ln \frac{1 + \sqrt{1 + l_1^2}}{l_1} + \ln(l_1 + \sqrt{1 + l_1^2}) \quad (10)$$

$$X_2 = l_2 \ln \frac{1 + \sqrt{1 + l_2^2}}{l_2} + \ln(l_2 + \sqrt{1 + l_2^2}) \quad (11)$$

$$X_L = l \ln \frac{1 + \sqrt{1 + l^2}}{l} + \ln(l + \sqrt{1 + l^2}) \quad (12)$$

$$l = \frac{L}{B} \quad (13)$$

where

$l_1$  = It is the ratio of maximum dimension to minimum dimension of  $[2S+3B, L]$ .

$l_2$  = It is the ratio of maximum dimension to minimum dimension of  $[2S+B, L]$ .

$l_2 =$  It the ratio of maximum dimension to minimum dimension of  $[2S+B, L]$ .

$$B_2 = \min \text{ of } [(2S+B)/2, L/2]$$

Similarly, the interaction factor for right footing  $\xi_{\delta R}$  due to the presence of left footing is given by

$$\xi_{\delta R} = 1 + \frac{[(B_3 X_3 - B_4 X_4)]}{n B X_R} \quad (14)$$

as the footings are symmetrical and the centroid of the closely spaced footings are in the same line i.e.,  $C_L$ . Therefore, the parameters  $B_3, B_4, X_3, X_4$  and  $X_R$  are same as that of  $B_1, B_2, X_1, X_2$  and  $X_L$  respectively.

The parameters  $B_1, B_2, B_3$  and  $B_4$  are the width of the considered rectangular/squared portion in Fig. 3. Parameters  $l_1, l_2, l_3$  and  $l_4$  are aspect ratios of the considered rectangular/squared portions in Fig. 3. These parameters are changed according to  $S/B$  ratio of a particular geometry configuration of an interfering footings. The values of  $B_1, B_2, B_3, B_4, l_1, l_2, l_3$  and  $l_4$  are the function of  $S/B$  ratio and length of left and right footings. So, a computational program has been developed for resolving the above equations and the results are presented in the context of non-dimensional parameters  $\xi_{\delta L}$  and  $\xi_{\delta R}$ .

In order to explore the parametric study on interaction settlement factors for left and right footings placed in closed proximity on homogeneous soil, the graphs between  $\xi_{\delta L} V_S \frac{S}{B}$  and  $\xi_{\delta R} V_S \frac{S}{B}$  for different  $L/B$  ratios and intensity of loading (i.e., the intensity of load on left footing keeping constant and varying on right footing with respect to left footing) have been developed.

#### 4. Results and discussion

The analysis of referred problem mentioned above was investigated for the predefined parameter values in Table 1. Average settlements of the interaction footings resting on the surface of infinite, homogeneous, and isotropic soil were calculated. The evaluated results have been presented in the form of settlement interaction factors  $\xi_{\delta L}$  and  $\xi_{\delta R}$  for left and right footings respectively. According to the footing geometric configuration (Fig. 2) and variation of intensity of loading on footings, the overall analysis has been classified into the following two cases:

**Case a:** Symmetrical footing and symmetrical loading ( $O_1 C_1, O_1 C_2$ ). ( $n=1.0, L/B=1, 2, 4$  and  $6$ )

**Case b:** Symmetrical footing and asymmetrical loading ( $O_1 C_1, O_1 C_2$ ). ( $n = 1.25, 1.5, 1.75$  and  $2.0, L/B=1, 2, 4$  and  $6$ )

##### 4.1 Variation of Interaction factors

**Case a:** Symmetrical footing and symmetrical loading ( $O_1 C_1, O_1 C_2, n=1.0$ ):

The analysis has been carried out for the present case i.e., symmetrical footing and symmetrical loading. In this case, according to the geometry of the footings and intensity of loading, the two interfering footings are symmetrical to their shape and size as well as in loading condition. The

interfering settlements are calculated for left and right footings by using Eqs. (9) and (14) by varying the clear spacing  $S$  between the footings resting on the surface of homogenous soil.

The settlement interaction factors  $\xi_{\delta L}$  and  $\xi_{\delta R}$  are calculated for left and right footings. The variation of settlement interaction factors i.e.,  $\xi_{\delta L}$  and  $\xi_{\delta R}$ , for left and right footings pertaining to  $S/B$  ratio are presented in Fig. 4. From the graph it is seen that the interaction factors for left and right footings are indistinguishable as they are symmetrical in size, shape and loading condition. From the graph it is noticed that the interaction factors for square footings ( $L/B=1$ ) are decreasing with increasing the clear spacing ratio ( $S/B$ ). At greater clear spacing ratio ( $S/B$ ) the interaction factor attains to a value of one where the footings behave like an isolated or free from interference. When two square footings are placed in closed proximity on homogenous soil, the settlements are increased by 20% as compared to the settlement of an isolated square footing for clear spacing ratio ( $S/B$ ) of 0.5.

Further it is also evident from Fig. 4, for a particular  $S/B$ , as the aspect ratio increases ( $L/B = 1, 2, 4$  and  $6$ ) then the interaction factors increase considerably displaying the effect of increase in the coalescence along the longer dimension of the foundation and this increment was observed to be highest in the nearest clear spacing ratio ( $S/B$ ) of 0.5. But as the separation ratio ( $S/B$ ) raises, the increase in interaction factor values for aspect ratios ( $L/B = 2, 4$  and  $6$ ) slowly decays. In comparison with isolated rectangular footing, the interfering rectangular footing settlements are increasing by 27%, 37% and 42 % for  $L/B = 2, L/B=4$  and  $L/B = 6$  respectively at  $S/B=0.5$ .

**Case b:** Symmetrical footing and asymmetrical loading ( $O_1 C_1, O_1 C_2, n=1.25, 1.5, 1.75$  and  $2.0$ ).

The analysis has been carried out for the present case i.e., symmetrical footing and asymmetrical loading. In this case, according to the geometry of the footings the two

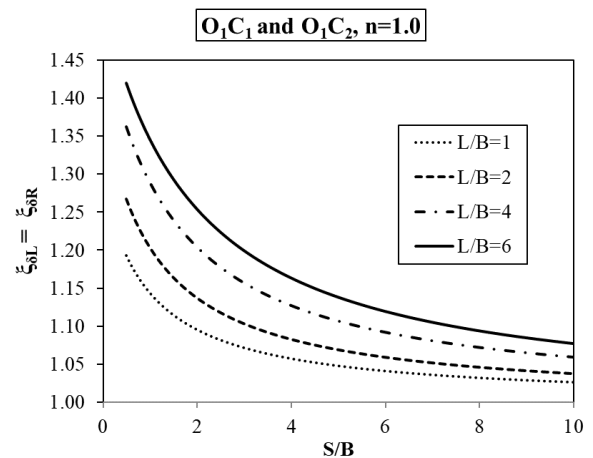


Fig. 4 Variation of settlement interaction factors with respect to  $S/B$  ratio for square ( $L/B=1$ ) and rectangular ( $L/B=2, 4, 6$ ) footings with different aspect ratios ( $L/B$ )

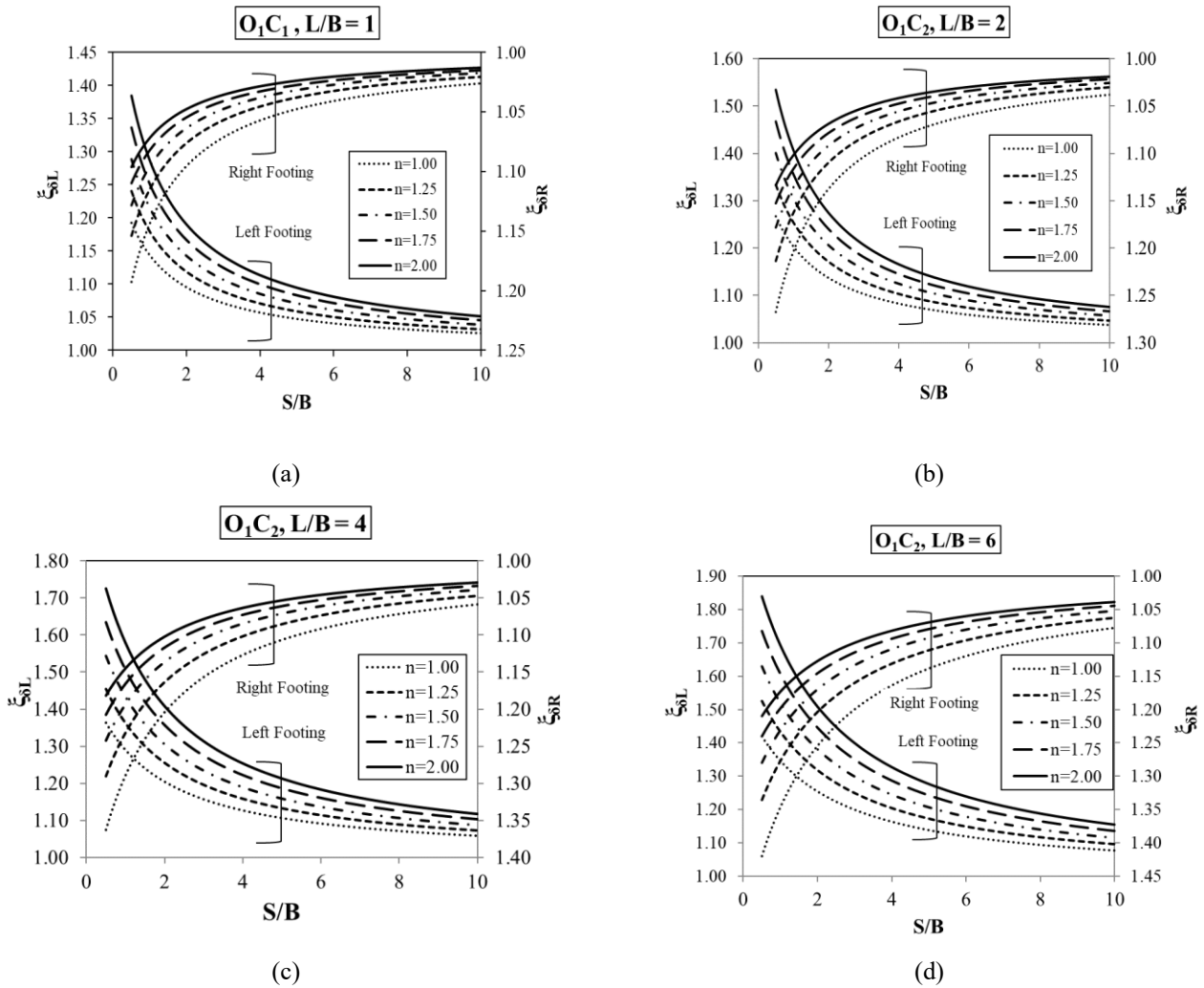


Fig. 5 Variation of settlement interaction factors for square footings with respect to  $S/B$  ratio for (a)  $O_1C_1$  ( $L/B=1$ ), for and (b)  $O_1C_2$  ( $L/B=2$ ), (c)  $O_1C_2$  ( $L/B=4$ ) and (d)  $O_1C_2$  ( $L/B=6$ )

interfering footings are symmetrical to their shape and size, but they are asymmetrical ( $n > 1.0$ ), according to the intensity of loading conditions. For asymmetrical case, the intensity of loading on left footing is kept constant, whereas the intensity of loading on right footing with respect to left footing is increased (i.e.,  $n=1.25, 1.5, 1.75$  and  $2.0$ ). The interfering settlement are calculated for left and right footings for  $O_1C_1$  and  $O_1C_2$  combinations by varying the clear spacing ratio ( $S/B$ ) between the footings resting on the surface of homogenous soil.

The settlement interaction factors  $\xi_{\delta L}$  and  $\xi_{\delta R}$  are calculated for left and right square footings for asymmetrically loaded condition. For asymmetrically loaded two square footings, the variation of settlement interaction factors  $\xi_{\delta L}$  and  $\xi_{\delta R}$  for left and right footings with respect to clear spacing ratio ( $S/B$ ) for  $O_1C_1$  are presented in Fig. 5(a). From the graph, it can be noticed that both interference factors  $\xi_{\delta L}$  and  $\xi_{\delta R}$  for square footings decrease with increase in the clear spacing ratio ( $S/B$ ). The maximum influence attains for both the footings are at the closest clear spacing ratio ( $S/B$ ) of  $0.5$ . At greater spacing, the interaction factors for left and right square footings

attains to a value of one where the footings behave like an isolated for all the cases  $n=1.25$  to  $2.0$ .

Further, it can be observed that the interaction factor for left square footing ( $\xi_{\delta L}$ ) increasing as the intensity of load on right square footing increases. This is due to the extension of influence zone of right-side square footing due to the higher intensity of load on right footing, whereas the interaction factor for right square footing ( $\xi_{\delta R}$ ) is lesser than the left footing due to the lower intensity of loading on the left footing. In other words, the percentage of increase in settlement of interfering right square footing is less as compared to left square footing for the particular intensity of loading and clear spacing ratio ( $S/B$ ). This is a classic exemplar of high intensity foundation constructed in the vicinity of existing low intensity footing on an elastic soil medium. When two square footings are placed in closed proximity on homogenous soil for increasing  $n$  from  $1$  to  $2$ , at clear spacing ratio ( $S/B$ ) of  $0.5$ , the percentage increase in settlement for left footing is varying from  $20\%$  to  $39\%$  as compared to isolated footing having same properties. Similarly, the percentage increase in settlement for right footing is varying from  $20\%$  to  $10\%$  as compared to isolated

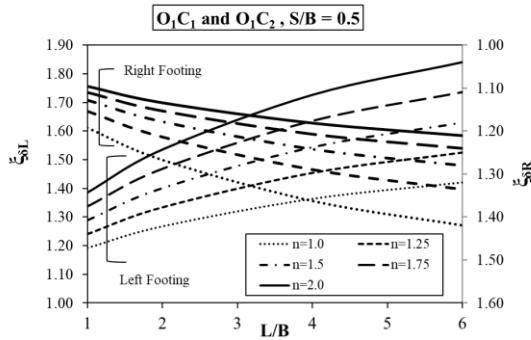


Fig. 6 Variation of interaction factor with respect to aspect ratio ( $L/B$ ) for  $O_1C_1$  and  $O_1C_2$  at  $S/B=0.5$

footing. The clear spacing ratio ( $S/B$ ) required for left square footing to behave like an isolated footing, i.e.,  $(S/B)_{\max}$  of  $L$  as compared with right-side square footing which is carrying more intensity of load than left footing, i.e.,  $(S/B)_{\max}$  of  $R$  is more. This is attributed to the increase of influence zone in the right square footing due to the increase of intensity of load on right footing.

Fig. 5 limns the interaction factors versus separation distance ( $S/B$ ) for  $O_1C_2$  configuration under asymmetrical loads. Similar to square footings, it can be observed that the interaction factor for left rectangular footing ( $\xi_{\delta_L}$ ) increases as the intensity of load ( $n$ ) on right rectangular footing increases for all aspect ratios ( $L/B$ ) at a particular  $S/B$  ratio. In other words, the percentage of increase in interference settlement in right rectangular footing is less as compared to left rectangular footing for the particular intensity of loading, aspect ratio ( $L/B$ ) and clear spacing ratio ( $S/B$ ).

When two rectangular footings are placed in closed proximity on homogenous soil, as the intensity of load on right rectangular footing increases, i.e., by increasing  $n$  from 1 to 2, the percentage increase in settlement for left footing varies from 27% to 54% at the closest spacing ( $S/B = 0.5$ ) as compared to isolated rectangular footing ( $L/B = 2$ ) having same properties. For the same case, percentage increase in settlements for right rectangular footing is varying from 27% to 14% as compared to isolated footing. Similarly, at clear spacing ratio ( $S/B$ ) of 0.5 and  $L/B=4$ , the percentage increase in settlements for left footing is varying from 37% to 73% as compared to isolated rectangular footing. For the same case, percentage increase in settlements for right rectangular footing is varying from 37% to 18% as compared to isolated footing. Further at clear spacing ratio ( $S/B$ ) of 0.5 and  $L/B=6$ , the percentage increase in settlements for left footing is varying from 42% to 84% as compared to isolated rectangular footing. For the same case percentage increase in settlements for right rectangular footing is varying from 42% to 21% as compared to isolated footing. This is a clear evident of enhanced zone of coalescence with increase in aspect ratio ( $L/B$ ) as observed in Fig. 6.

As a consequence, the clear spacing ratio ( $S/B$ ) required for left rectangular footing to behave like an isolated footing as compared with right rectangular footing which is carrying more intensity of load than left footing for all  $L/B = 1$  to 6, is more.

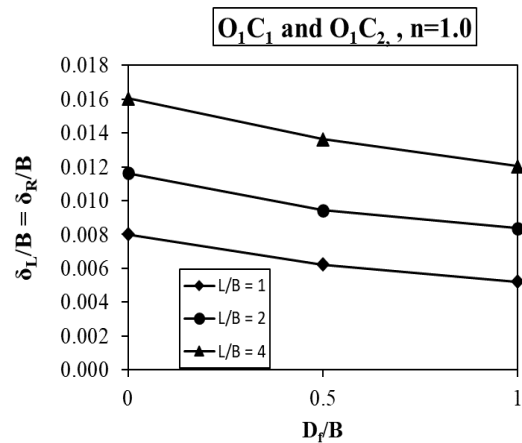


Fig. 7 Variation of settlement with respect to embedment depth for square and rectangular footing are spaced at  $S/B = 0.5$  for different aspect ratios  $L/B$

#### 4.2 Variation of settlement with respect to embedment depth ( $D_f$ )

By using proposed simplified method, the effect of settlement of the interfering footings with respect to embedment depth ( $D_f$ ) are examined for closely spaced symmetrical square ( $O_1C_1$ ) and rectangular ( $O_1C_2$ ) footings at different aspect ratio ( $L/B$ ) by varying the intensity of loading on right footing by keeping the intensity of loading on left footing constant. The variation of interfering settlement values with respect to embedment depth ( $D_f/B = 0.0, 0.5$  and  $1.0$ ) are determined based on the predefined parameters in Table.1 and are presented in terms of non-dimensional factors  $\delta/B$  Vs  $D_f/B$ . Fox (1948) influence factors are used to study the effect of interference settlements due to the embedment depth ( $D_f$ ). The variation of interfering settlement values with respect to embedment depth for symmetrical footings and symmetrical loading ( $O_1C_1$  and  $O_1C_2$  &  $n=1.0$ ) at spacing ratio ( $S/B$ ) of 0.5 for  $L/B$  ratio of 1, 2 and 4 are presented in Fig. 7. It is observed that as the embedment depth increases interfering settlement decreases. It can also be observed that as the  $L/B$  ratio (1, 2 and 4) increases, settlements also increases as expected. Similarly, symmetrical footings and asymmetrical loading ( $O_1C_1$  and  $O_1C_2$  &  $n=1.25, 1.5, 1.75$  and  $2.0$ ) case also studied. The variation of settlement with respect to embedment depth for ( $O_1C_1$  and  $O_1C_2$  &  $n=1.25, 1.5, 1.75$  and  $2.0$ ), spacing ratio ( $S/B$ ) of 0.5 are presented in Figs. 8(a)-8(c). From the curves, it is again evident that the settlement decreases as the embedment depth increases for all  $L/B$  ratios. It is also observed that at a spacing ratio ( $S/B$ ) of 0.5, for a particular  $L/B$  ratio, the interfering settlements on right footing increases as the intensity of loading on right footing increases as compare to left footing.

#### 4.3 Variation of interference settlement profile with respect to spacing ratio ( $S/B$ )

By using the proposed method, settlement profile variation with respect to spacing ratio ( $S/B$ ) by varying the

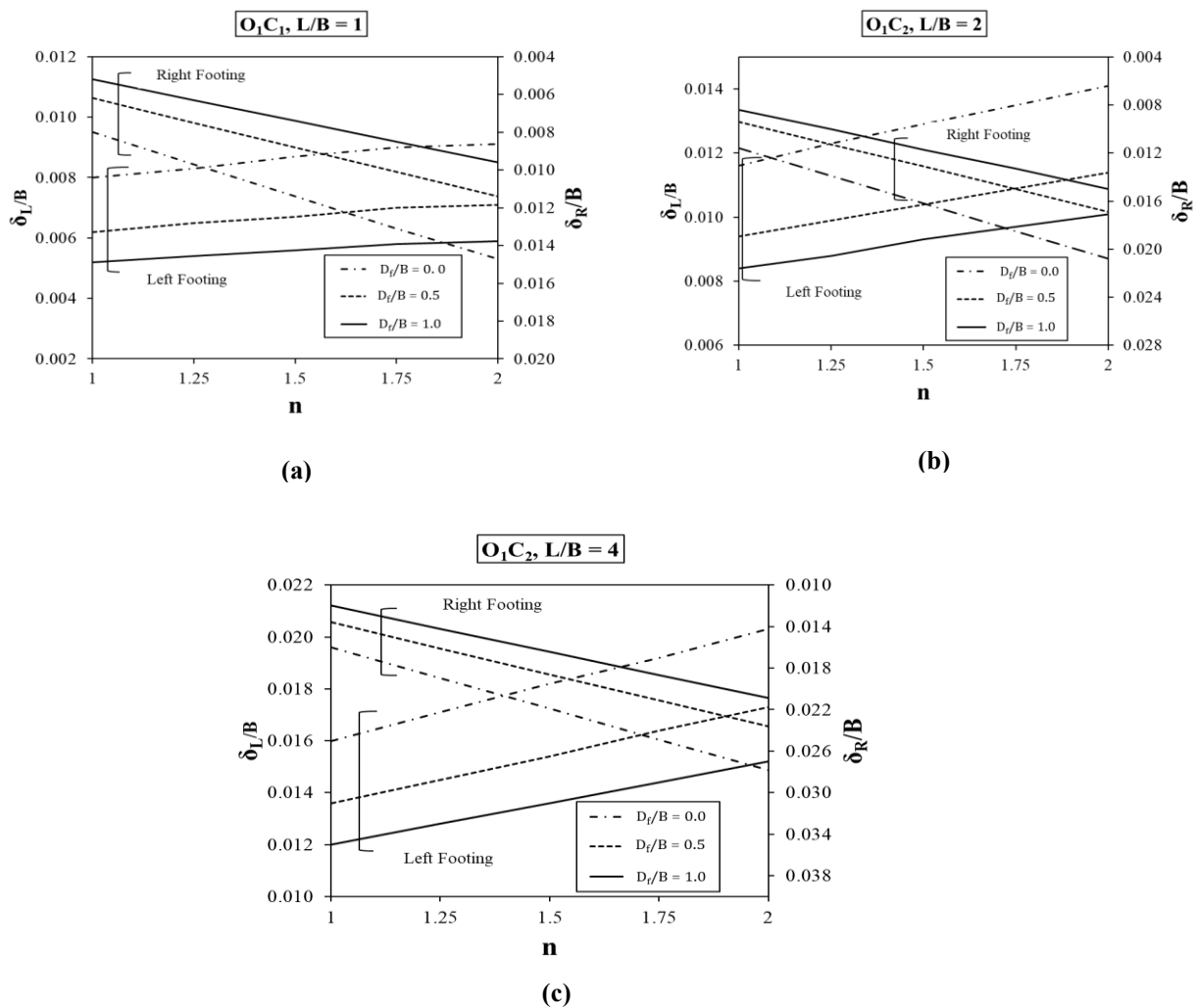


Fig. 8 Variation of settlement with respect to embedment depth at  $S/B = 0.5$  for different  $n$  values for (a) square footing ( $L/B=1$ ), (b) rectangular footing ( $L/B=2$ ) and (c) rectangular footing ( $L/B=4$ )

intensity of loading on right footing has been examined for square and rectangular footings ( $O_1C_1, O_1C_2$ ) resting on the surface of a homogeneous soil. The settlements are calculated by using the predefined parameters given in Table 1. The adaption of settlement profile for closely spaced two square and rectangular footings ( $O_1C_1, O_1C_2$ ) resting on the surface of a homogeneous soil subjected to symmetrical and unsymmetrical loading for different spacing ratios ( $S/B$ ) are accorded in Figs. 9 and 10. Figs. 9 and 10 indicates the settlement profile for square ( $L/B=1$ ) and rectangular ( $L/B=2$ ) footings for symmetrical ( $n=1.0$ ) and asymmetrical loading ( $n=1.5$  and  $2.0$ ) conditions. From Figs. 9 and 10, it is observed that as the spacing ratio ( $S/B$ ) increases, interfering settlement beneath the footing decreases. Similarly, the settlements between the spacing are determined and are found to be decreasing as the spacing increases. The settlement profile between the footings are formed like an arch as the spacing ratio increases. These settlement profiles are exactly comparable with the settlement profile presented by Roy and Deb (2019) from his experimental studies and Gupta and

Sitharam (2018) from his FLAC 3D FEM analysis. For an ideal case of spacing ratio  $S/B=0$  (i.e., two square or rectangular footings are touching together) and  $n=1.0$ , the settlement profile shall be similar to the isolated footing of width twice the interfering footings.

From the settlement profile it can also be noted that, for square footings, as the intensity of loading on right footing increases (i.e.,  $n = 1.0$  to  $2.0$ ), the interfering settlements under the right footing increases. Similarly, for rectangular footings, the interfering settlements of right footing increases as the loading intensity increases on right footing (i.e.,  $n = 1.0$  to  $2.0$ ).

## 5. Comparison

Predicted settlement interaction factors  $\xi_{\delta L}$  and  $\xi_{\delta R}$  from the proposed method for closely spaced left and right footings resting on the surface of homogeneous sand for case a and case b are compared with the available experimental and FEM methods. Table 2. shows the error

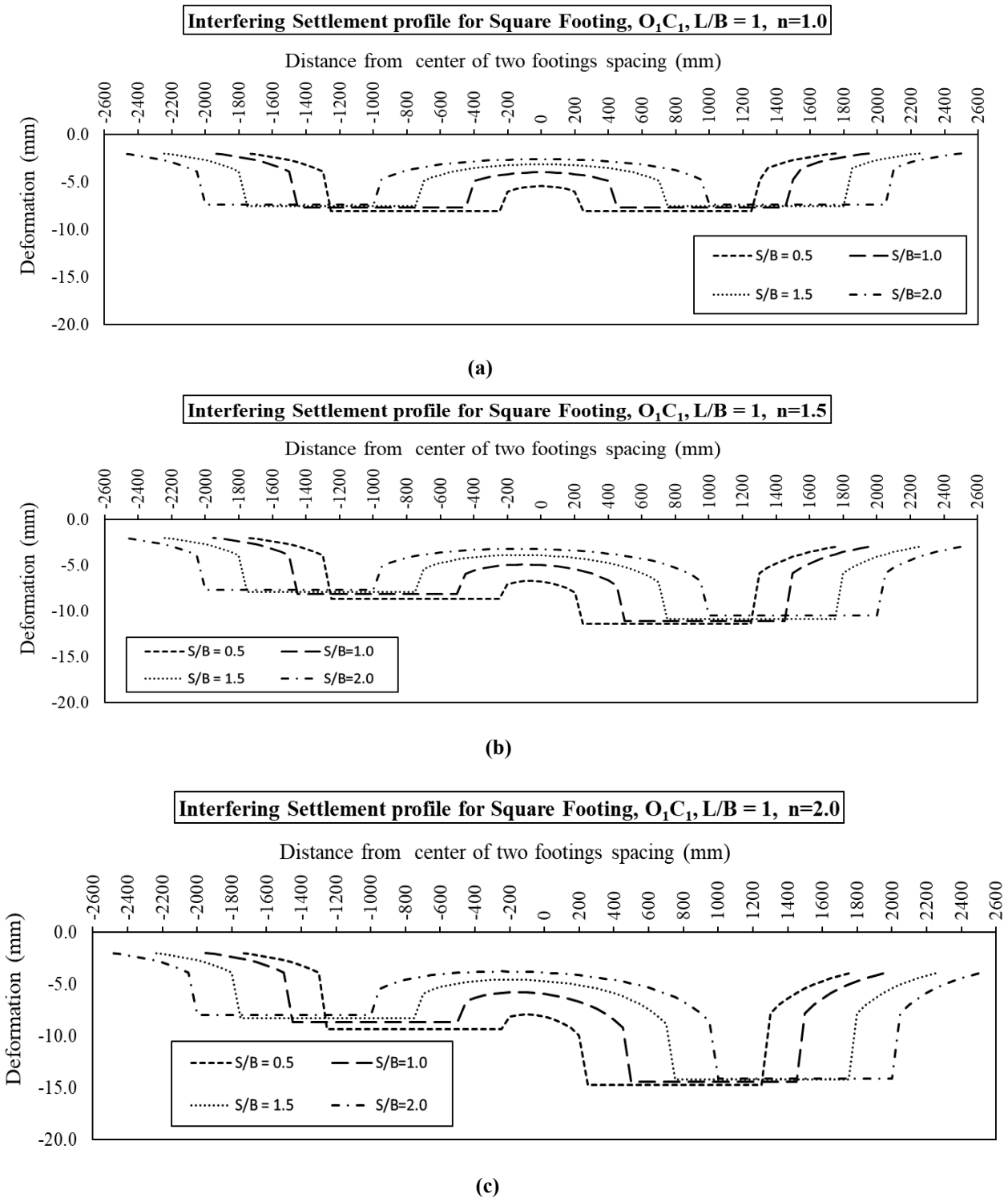
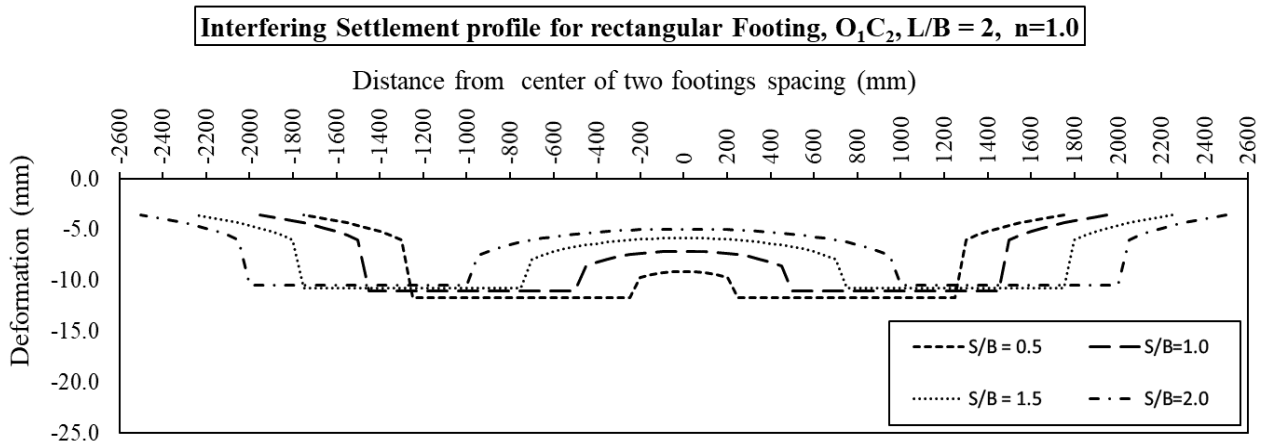


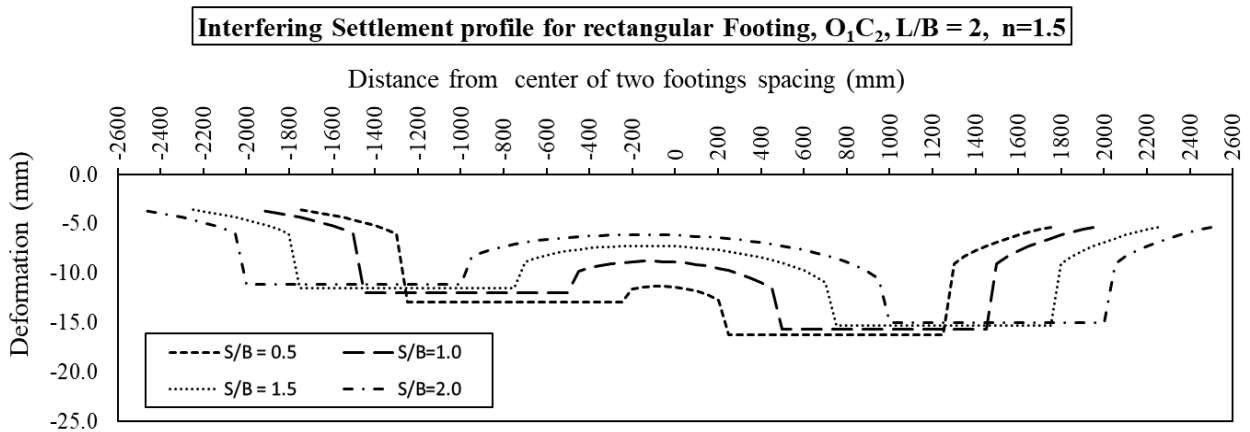
Fig. 9 Variation of settlement profile for closely spaced two square footings ( $O_1C_1$ ,  $L/B=1$ ) resting on the surface of sand subjected to symmetrical and unsymmetrical loading (a)  $n = 1$ , (b)  $n = 1.5$  and (c)  $n = 2$

percentage in the interaction factor between the proposed method with respect to Nainegali (2013), 3D finite element analysis for Case a: Symmetrical footing and symmetrical loading ( $O_1C_1$ ,  $O_1C_2$ ,  $n=1.0$ ). Similarly, Table 3, indicates the percentage difference between the proposed method

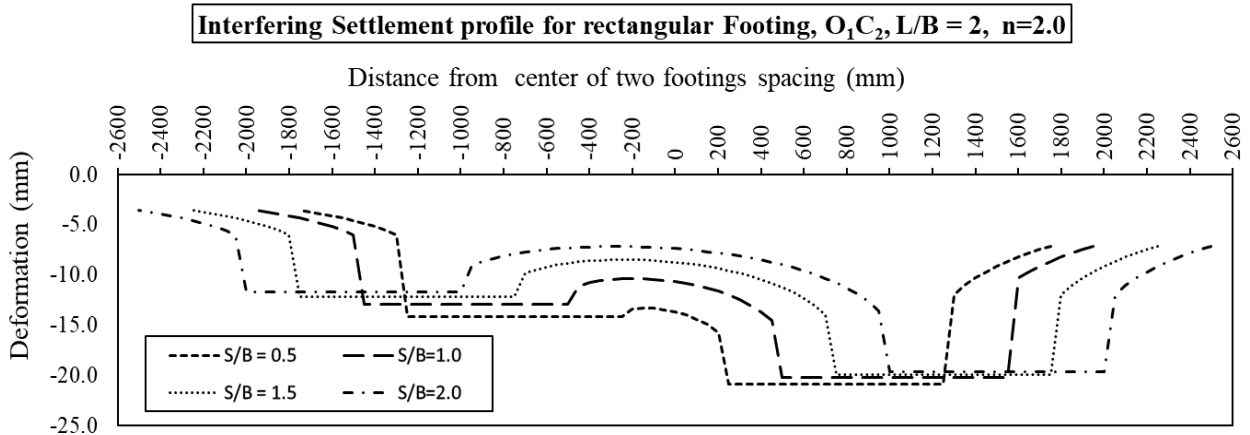
with respect to Nainegali (2013), 3D finite element analysis for Case b: Symmetrical footing and asymmetrical loading ( $O_1C_1$ ,  $O_1C_2$ ,  $n=1.25, 1.5, 1.75$  and  $2.0$ ). The predicted interaction factors from the present proposed method for case a and case b are in good correspondence with the



(a)



(b)



(c)

Fig. 10 Variation of settlement profile for closely spaced two rectangular footings ( $O_1C_2, L/B=2$ ) resting on the surface of sand subjected to symmetrical and unsymmetrical loading (a)  $n = 1.0$ , (b)  $n = 1.5$  and (c)  $n = 2.0$

Table 2 Comparison Table for Case a: Symmetrical footing and symmetrical loading ( $O_1C_1, O_1C_2, n=1.0$ )

Comparison Table for Case a: Symmetrical footing and symmetrical loading ( $O_1C_1, O_1C_2, n=1.0$ ): - Percentage difference in interference factors ( $\xi_{\delta L} = \xi_{\delta R}$ ) between Present Analysis and literature i.e., Nainegali (2013), 3D Finite Element Analysis				
S/B	L/B=1	L/B=2	L/B=4	L/B=6
0.5	-6.11	-3.33	-0.52	2.00
1	-3.52	-0.49	2.74	5.48
2	-0.46	2.64	5.62	8.12
4	2.60	4.83	7.32	10.71
6	3.03	5.09	7.02	10.41
8	3.15	4.61	7.15	9.40
10	2.58	3.78	5.87	7.73

**Note:**

+ve sign- % difference in interaction factor increased with respect to Nainegali (2013) 3D FEM Analysis

-ve sign - % difference in interaction factor decreased with respect to Nainegali (2013) 3D FEM Analysis

existing literature (Nainegali 2013). Further, it is worth mentioning here that the proposed procedure for the evaluation of interaction factors in an elastic half-space is much simple and lucid thereby enabling the design engineers to reproduce and quickly calculate for different field parameters in comparison to the rigorous finite element scheme proposed in the literature (Nainegali 2013) wherein advanced methods and considerable computational time and efforts are demanded. Further, for the sake of real-time field comparison, the interaction factors obtained from the proposed analyses are compared with the case study reported by Shahein and Hefdhallah (2013) on Electrical Power Plant near Cairo, Egypt. Table 4. indicates the percentage difference between the proposed method in connection with Shahein and Hefdhallah (2013) and are found to be reasonably well. Table 5. shows the exhaustive comparison of settlement interaction factors with experimental and computational findings available in literature. It is worth mentioning here that in case of comparison with experimental studies, the elastic settlements are found from the load settlement curves by initial tangent method. At the outset, indubitably it can be said that the interaction factor with respect to spacing ratio ( $S/B$ ) from the present analysis are in fair agreement with the existing literatures qualitatively.

## 6. Conclusions

A simplified method is proposed to carry out the interference effect on settlement of identical square and rectangular footings placed in closed proximity on the surface of a homogeneous, isotropic and an elastic soil medium subjected to vertical loads or immediate settlement in case of cohesive-frictional material. The interaction factors are examined by varying the different aspect ratio ( $L/B$ ), clear spacing ratio ( $S/B$ ) and intensity of loading on right footing with respect to left footing and variation of settlement ratio ( $\delta/B$ ) with respect to embedment depth ratio ( $D_f/B$ ) with predefined parameters. Interference settlement

profile is also presented by varying the clear spacing ratio ( $S/B$ ) and intensity of loading for square and rectangular footings. The following outcomes are summarized from the proposed method.

- In case of symmetrical footings and symmetrical loading, for  $L/B=1$  to 6, the interaction factor for left and right footings are indistinguishable as they are symmetrical in size, shape and loading condition for all spacing ratio ( $S/B$ ).
- At a particular loading condition, interaction factors for square and rectangular footings ( $L/B=1$  to 6) are decreasing with increasing the clear spacing ratio ( $S/B$ ). In case of square footings ( $L/B = 1$ ), the interaction factors are negligible beyond a clear spacing ratio ( $S/B$ ) of about 8 and the footings behave like an isolated. Similarly, the clear spacing ratio ( $S/B$ ) required for rectangular footings ( $L/B = 2, 4$  and 6) to behave like an isolated is varying from 10 to 12.
- In case of symmetrical footings, as the aspect ratio increases ( $L/B=1, 2, 4$  and 6), the interaction factors increase at clear spacing ratio ( $S/B$ ) of 0.5. But, at greater clear spacing ratio ( $S/B$ ), the difference in interaction factor for aspect ratios ( $L/B=1, 2, 4$  and 6) are insignificant.
- For symmetrical footing and asymmetrical loading ( $n=1.25$  to 2.00), the percentage increase in interaction factor of right footing ( $\xi_{\delta R}$ ) varies from 42 % to 14%. It is less as compared to left footing ( $\xi_{\delta L}$ ) i.e., 27% to 84% for the closest spacing ratio ( $S/B=0.5$ ) and aspect ratio ( $L/B$ ) varies from 2 to 6. This is because of expansion in the influence zone of right footing due to the increase of intensity of load on right footing.
- The effect of settlement of the interfering footings with respect to embedment depth ( $D_f$ ) are examined for symmetrical footings symmetrical loading (case a) and symmetrical footings asymmetrical loading (case b). At spacing ratio ( $S/B$ ) of 0.5, for different  $L/B$  ratio (1, 2 and 4), if the embedment depth ( $D_f$ ) increases, interfering settlement decreases. It can also be observed

Table 3 Comparison Table for Case b: Symmetrical footing and Asymmetrical loading ( $O_1C_1$ ,  $O_1C_2$ ,  $n=1.25, 1.5, 1.75$  and  $2.0$ )

Comparison Table for Case b: Symmetrical footing and Asymmetrical loading ( $O_1C_1$ , $O_1C_2$ , $n=1.25, 1.5, 1.75$ and $2.0$ ): - Percentage difference in interference factors between Present Analysis and literature i.e., Nainegali (2013), 3D Finite Element Analysis for left and right footing								
$L/B=1$								
	$n=1.25$		$n=1.5$		$n=1.75$		$n=2.0$	
$S/B$	$\xi_{\delta L}$	$\xi_{\delta R}$	$\xi_{\delta L}$	$\xi_{\delta R}$	$\xi_{\delta L}$	$\xi_{\delta R}$	$\xi_{\delta L}$	$\xi_{\delta R}$
0.5	-7.42	-5.19	-8.60	-4.42	-9.71	-3.76	-10.56	-3.48
1	-4.53	-3.02	-5.09	-2.55	-5.76	-2.17	-6.50	-2.01
2	-0.97	-0.50	-0.70	-0.46	-0.66	-0.41	-1.13	-0.44
4	2.98	1.87	4.33	1.59	4.24	1.28	4.85	1.02
6	4.06	2.50	5.05	2.15	5.95	1.61	6.65	1.45
8	3.90	2.36	4.70	2.10	5.50	1.66	6.01	1.60
10	3.20	2.10	3.90	1.70	4.50	1.50	5.20	1.30
$S/B$	$L/B=2$							
0.5	-3.81	-2.89	-4.43	-2.62	-5.11	-2.31	-5.67	-1.42
1	-0.60	-0.61	-0.81	-0.81	-0.93	-0.77	-1.15	-0.29
2	3.08	1.83	3.43	1.11	4.11	0.75	4.51	0.85
4	6.26	3.50	7.25	3.43	8.63	2.65	9.38	2.06
6	6.34	3.66	7.82	2.97	9.09	2.38	10.36	1.98
8	5.80	3.70	6.90	3.10	8.10	2.60	8.98	2.30
10	5.80	3.00	6.90	2.50	8.10	2.20	9.20	1.90
$S/B$	$L/B=4$							
0.5	-0.44	0.03	-1.00	0.16	-0.90	-0.22	-0.81	0.12
1	3.16	2.20	3.17	1.96	3.53	1.78	4.21	1.30
2	6.36	3.84	7.05	3.27	7.70	3.43	9.15	2.04
4	9.34	5.87	11.21	5.34	12.11	4.08	14.00	3.20
6	9.22	6.24	11.47	5.05	13.73	4.16	15.98	3.56
8	8.90	5.70	10.70	4.80	12.50	4.10	14.30	3.60
10	7.30	4.70	8.80	3.90	10.30	3.40	11.70	2.90
$S/B$	$L/B=6$							
0.5	2.54	1.90	2.50	1.66	2.53	1.55	2.61	1.50
1	6.34	4.61	7.11	3.98	7.78	3.56	8.35	3.25
2	9.20	6.46	10.83	5.51	12.28	4.85	13.38	4.35
4	12.84	8.44	14.64	7.05	17.55	5.91	19.44	5.36
6	12.65	8.30	15.59	6.72	18.30	5.95	20.41	5.26
8	11.70	7.50	14.10	6.30	16.40	5.40	18.80	4.70
10	9.70	6.20	11.60	5.20	13.50	4.40	15.50	3.90

**Note:**

+ve sign - % difference in interaction factor increased with respect to Nainegali (2013) 3D FEM Analysis

-ve sign - % difference in interaction factor decreased with respect to Nainegali (2013) 3D FEM Analysis

Table 4 Comparison table for symmetrical footing and symmetrical loading ( $O_1C_1$ ,  $n=1.0$ ).

Comparison Table for Symmetrical footing and symmetrical loading ( $O_1C_1$ , $n=1$ ): - Percentage difference in interference factors between Present Analysis with respect to Case Study by Shahein and Hefdhallah (2013) on Electrical Power Plant near Cairo, Egypt		
% difference in interactions factors ( $\xi_{\delta L} = \xi_{\delta R}$ )		
Fire Fighting building (S/B varies from 0.85 to 1.22, B=2.7 m & Load 60 kN/m <sup>2</sup> )	Workshop building (S/B varies from 1.6 to 2.0, B=2.3 m to 2.6 m & Load 168 to 172 kN/m <sup>2</sup> )	Dormitory building (S/B varies from 0.5 to 0.85, B=2 m to 2.5 m & Load 57 to 118 kN/m <sup>2</sup> )
- 8.33 to -12.7	6.571 to 4.283	-17.696

**Note:**

+ve sign- % difference in interaction factor increased with respect to case study by Shahein and Hefdhallah (2013)

-ve sign - % difference in interaction factor decreased with respect to case study by Shahein and Hefdhallah (2013)

Table 5 Comparison of settlement interaction factors with experimental and computational findings available in literature

Case a: Symmetrical Footing and Symmetrical loading ( $O_1C_1, O_1C_2, n = 1$ )		S/B							
Type of Footing	Author	0.5	1.0	1.5	2.0	3.0	4.0	5.0	
L/B = 1	Proposed Method	1.19	1.14	1.11	1.09	1.07	1.06	1.05	
	Srinivasan and Ghosh (2011) (Experimental)	1.22	1.17	1.13	1.10	1.01	-	-	
	(Equivalent Square B=132.93 mm)	-	-	-	1.12	-	1.03	1.00	
	Reddy <i>et al.</i> (2012) (Experimental)	-	1.22	-	1.16	1.01	-	-	
	Naderi and Hataf (2014) (Experimental)	-	-	-	-	1.17	1.00	-	
	(Equivalent Square B= 106.34 mm)	1.20	1.10	1.10	1.05	-	-	-	
	Pusadkar <i>et al.</i> (2013) (Experimental)	1.30	1.20	-	1.04	-	-	-	
	Pusadkar and Ninghot (2016) (Model study with MIDAS3D)	1.17	1.11	1.09	-	-	-	-	
	Gupta and Sitharam (2018) (Experimental)	-	1.20	-	1.05	-	-	-	
	Jacob and Sindhu (2018) (Experimental)	1.26	1.20	1.16	1.14	1.10	1.08	-	
L/B = 2	Dehkoedi <i>et al.</i> (2019) (Experimental)	-	-	-	-	1.07	1.03	-	
	(Equivalent square B = 132.93 mm)	1.20	1.13	1.10	-	-	-	-	
L/B = 6	Proposed Method	1.42	1.35	1.29	1.25	1.19	1.16	1.14	
	Ghosh and Sharma (2010) (Theory of Elasticity Approach)	1.39	1.30	1.23	1.18	1.10	1.05	1.02	
	(Equivalent Strip)								
S/B		0.7	1.4	2.1					
L/B = 5	Proposed Method	1.34	1.26	1.24					
	Kumar and Bhoi (2009) (Experimental on Sand)	1.35	1.17	1.10					

that as the  $L/B$  ratio (1, 2 and 4) increases, settlement increases.

- In case of symmetrical footings asymmetrical loading (case b), for a particular  $L/B$  ratio, the interfering settlement on right footing increases as the intensity of loading on right footing increases ( $n=1.0$  to  $2.0$ ) as compare to left footing.

The settlement profile between the footings are formed like an arch as the spacing ratio increases. These settlement profiles as obtained from the present simplified method are well comparable with those available in literature.

## References

- Berardi, R. and Lancellotta, R. (1991), "Stiffness of granular soil from field performance", *Geotechnique*, **41**(1), 149-157. <https://doi.org/10.1680/geot.1991.41.1.149>.
- Boufarh, R., Abbeche, K., Abdi, A. (2019), "Experimental investigation of interference between adjacent footings on layered cohesionless soil", *Soil Mech. Found. Eng.*, **56**, 128-135. <https://doi.org/10.1007/s11204-019-09580-z>.
- Bowles, J.E. (1987), "Elastic foundation settlements on sand deposits", *J. Geotech. Eng. - ASCE*, **113**(8), 846-860. [https://doi.org/10.1061/\(ASCE\)0733-9410\(1987\)113:8\(846\)](https://doi.org/10.1061/(ASCE)0733-9410(1987)113:8(846)).
- Bowles, J.E. (1988), "Foundation analysis and design", 5<sup>th</sup> Ed., McGraw Hill, Inc., New York.
- Burland, J.B. and Burbidge, M.C. (1985), "Settlement of foundations on sand and gravel", *Proc. Institute of Civil Eng. Part I*, **78**(6), 1325-138. <https://doi.org/10.1680/iicep.1985.1058>.
- Das, B.M. and Larbi-Cherif, S. (1983), "Bearing capacity of two closely spaced shallow foundations on sand", *Soils Found.*, **23**(1), 1-7. <https://doi.org/10.3208/sandf1972.23.1>.
- Das, B.M., Puri, V.K. and Neo, B.K. (1993), "Interference effects between two surface footings on layered soil", *Transp. Res. Rec.*, **1406**, 34-40.
- Dehkordi, P.F., Ghazavi, M., Ganjian, N. and Karim, U.F.A. (2019), "Parametric study from laboratory tests on twin circular footings on geocell-reinforced sand", *Sci. Iranica*, 1-30. <https://doi.org/10.24200/SCI.2019.51471.2208>.
- Fox, E.N. (1948), "The mean elastic settlement of a uniformly loaded area at a depth below the ground surface", *Proceedings of the 2<sup>nd</sup> Int. Conf. on Soil Mechanics and Foundation Eng.*, **I**, 129-132.
- Ghosh, P., Basudhar, P.K., Srinivasan, V. and Kunal, K. (2015), "Experimental studies on interference of two angular footings resting on surface of two-layer cohesionless soil deposit", *Int. J. Geotech. Eng.*, **9**(4), 422-433. <https://doi.org/10.1179/1939787914Y.0000000080>.
- Ghosh, P. and Kumar, S.R. (2011), "Interference effect of two nearby strip surface footings on cohesionless layered soil", *Int. J. Geotech. Eng.*, **5**(1), 87-94. <https://doi.org/10.3328/ijge.2011.05.01.87-94>.
- Ghosh, P., Rajesh, S. and Chand, J.S. (2017), "Linear and nonlinear elastic analysis of closely spaced strip foundations using Pasternak model", *Front. Struct. Civil Eng.*, **11**(2), 228-243. <https://doi.org/10.1007/s11709-016-0370x>.
- Ghosh, P. and Sharma, A. (2010), "Interference effect of two nearby strip footings on layered soil: theory of elasticity approach", *Acta Geotechnica*, **5**, 189-198. <https://doi.org/10.1007/s11440-010-0123-2>.
- Griffiths, D.V., Fenton, G.A. and Manoharan, N. (2006), "Undrained bearing capacity of two-strip footings on spatially

- random soil”, *Int. J. Geomech.*, **6**(6), 421-427. [https://doi.org/10.1061/\(ASCE\)1532-3641\(2006\)6:6\(421\)](https://doi.org/10.1061/(ASCE)1532-3641(2006)6:6(421)).
- Gupta, A. and Sitharam, T.G. (2018), “Experimental and numerical investigations on interference of closely spaced square footings on sand”, *Int. J. Geotech. Eng.*, 1-9. <https://doi.org/10.1080/19386362.2018.1454386>.
- Jacob, B.S. and Sindhu, A.R. (2018), “An experimental investigation on effect of interference on bearing capacity of adjacent footings in sand”, *Int. Res. J. Eng. Technol.*, **5**(4), 2123-2129. <https://www.irjet.net/archives/V5/i4/IRJET-V5I4474.pdf>.
- Kumar, J. and Bhattacharya, P. (2010), “Bearing capacity of interfering multiple strip footings by using lower bound finite elements limit analysis”, *Comput. Geomech.*, **37**, 731-736. <https://doi.org/10.1016/j.compgeo.2010.05.002>.
- Kumar, J. and Bhattacharya, P. (2011), “Bearing capacity of two interfering strip footings from lower bound finite elements limit analysis”, *Int. J. Numer. Anal. Method. Geomech.*, **37**(5), 441-452. <https://doi.org/10.1002/nag.1104>.
- Kumar, J. and Bhoi, M. (2009), “Interference of two closely spaced strip footings on sand using model tests”, *J. Geotech. Geoenviron. Eng.*, **135**(4), 595-604. [https://doi.org/10.1061/\(ASCE\)1090-0241\(2009\)135:4\(595\)](https://doi.org/10.1061/(ASCE)1090-0241(2009)135:4(595)).
- Kumar, J. and Ghosh, P. (2007a), “Ultimate bearing capacity of two interfering rough strip footings”, *Int. J. Geomech.*, **7**(1), 53-62. [https://doi.org/10.1061/\(ASCE\)1532-3641\(2007\)7:1\(53\)](https://doi.org/10.1061/(ASCE)1532-3641(2007)7:1(53)).
- Kumar, J. and Ghosh, P. (2007b), “Upper bound limit analysis for finding interference effect of two nearby strip footings on sand”, *Geotech. Geol. Eng.*, **25**(5), 499-507. <https://doi.org/10.1007/s10706-007-9124-9>.
- Kumar, A. and Saran, S. (2003), “Closely spaced footings on geogrid reinforced sand”, *J. Geotech. Geoenviron. Eng.*, **129**(7), 660-664. [https://doi.org/10.1061/\(ASCE\)1090-0241\(2003\)129:7\(660\)](https://doi.org/10.1061/(ASCE)1090-0241(2003)129:7(660)).
- Kouzer, K.M. and Kumar, J. (2010), “Ultimate bearing capacity of a footing considering the interference of an existing footing on sand”, *Geotech. Geologic. Eng.*, **28**(4), 457-470. <https://doi.org/10.1007/s10706-010-9305-9>.
- Lee, J. and Eun, J. (2009), “Estimation of bearing capacity for multiple footings in sand”, *Comput. Geotech.*, **36**, 1000-1008. <https://doi.org/10.1016/j.compgeo.2009.03.009>.
- Lee, J., Eun, J., Prezzi, M. and Salgado, R. (2008), “Strain influence diagrams for settlement estimation of both isolated and multiple footings in sand”, *J. Geotech. Geoenviron. Eng.*, **134**(4), 417-427. [https://doi.org/10.1061/\(ASCE\)1090-0241\(2008\)134:4\(417\)](https://doi.org/10.1061/(ASCE)1090-0241(2008)134:4(417)).
- Mabrouki, A., Benmeddour, D., Frank, R. and Mellas, M. (2010), “Numerical study of the bearing capacity for two interfering strip footings on sands”, *Comput. Geotech.*, **37**(4), 431-439. <https://doi.org/10.1016/j.compgeo.2009.12.007>.
- Meyerhof, G.G. (1951), “The ultimate bearing capacity of foundations”, *Géotechnique.*, **2**(4), 301-332. <https://doi.org/10.1680/geot.1951.2.4.301>.
- Naderi, E. and Hataf, N. (2014), “Model testing and numerical investigation of interference effect of closely spaced ring and circular footings on reinforced sand”, *Geotext. Geomembranes*, **42**(3), 191-200. <https://doi.org/10.1016/j.geotexmem.2013.12.010>.
- Nainegali, L.S. (2013), “Finite element analysis of two symmetric and asymmetric interfering footings resting on linearly and non-linearly elastic soil bed”, *Ph.D thesis, IIT Kanpur*.
- Nainegali, L.S., Basudhar, P.K. and Ghosh, P. (2013), “Interference of two asymmetric closely spaced strip footings resting on nonhomogeneous and linearly elastic soil bed”, *Int. J. Geomech.*, **13**(6), 840-851. [https://doi.org/10.1061/\(ASCE\)GM.1943-5622.0000290](https://doi.org/10.1061/(ASCE)GM.1943-5622.0000290).
- Pusadkar, S.S., Gupta, R.R. and Soni, K.K. (2013), “Influence of interference of symmetrical footings on bearing capacity of soil”, *Int. J. Eng. Inventions*, **2**(3), 63-67. <http://www.ijejournal.com/papers/v2i3/102036367.pdf>.
- Pusadkar, S.S. and Ninghot, K.R. (2016), “Interference of square footing on layered soil subjected to vertical load”, *SSRG Int. J. Civil Eng.*, **3**(6), 9-13. <https://doi.org/10.14445/23488352/IJCE-V3I6P102>.
- Reddy, E.S., Borzooei, S. and Reddy, G.N. (2012), “Interference between adjacent footings on sand”, *Int. J. Adv. Eng. Res. Studies*, **1**(4), 95-98. <https://www.researchgate.net/publication/270880188>.
- Roy, S. and Deb, K. (2018), “Closely spaced rectangular footings on sand over soft clay with geogrid at the interface”, *Geosynth. Int.*, **25**(4), 412-426. <https://doi.org/10.1680/jgein.18.00025>.
- Roy, S.S. and Deb, K. (2019), “Interference effect of closely spaced footings resting on granular fill over soft clay”, *Int. J. Geomech.*, **9**(1), 1-17. [https://doi.org/10.1061/\(ASCE\)GM.1943-5622.0001324](https://doi.org/10.1061/(ASCE)GM.1943-5622.0001324).
- Shahein, M. and Hefdhallah, A. (2013), “Effect of neighbouring footing on single footing settlement”, *Proceedings of the 7<sup>th</sup> Int. Conf. on Case Histories in Geotech. Eng.*, Chicago:1-9. <https://scholarsmine.mst.edu/icchge/7icchge/session01/19>.
- Srinivasan, V. and Ghosh, P. (2013), “Experimental investigation on interaction problem of two nearby circular footings on layered cohesion-less soil”, *Geomech. Geoeng.*, **8**(2), 97-106. <https://doi.org/10.1080/17486025.2012.695401>.
- Stuart, J.G. (1962), “Interference between foundations with special reference to surface footings in sand”, *Geo-technique*, **12**(1), 15-22. <https://doi.org/10.1680/geot.1962.12.1.15>.
- Terzaghi, K. (1943), *Theoretical soil mechanics*. New York: John Wiley & Sons,
- Vesic, A.S. (1973), “Analysis of ultimate loads of shallow foundations”, *J. Soil Mech. Found. Div.*, **99**(1), 45-73. <https://doi.org/10.1061/JSFEAQ.0001846>.
- West, J.M. and Stuart, J.G. (1965), “Oblique loading resulting from interference between surface footings on sand”, *Proceedings of the 6<sup>th</sup> Int. Conf. on Soil Mechanics and Foundation Eng.*, 214-217, Montreal: University of Toronto Press.

GC

### Appendix: Practical implementation

Considering two footings which are placed in close proximity on an elastic soil medium. The settlement interaction factors are determined for different aspect ratios ( $L/B$ ), clear spacing ratio ( $S/B$ ).  $q_R = n \cdot q_L$ . The table shows the settlement interaction factors for different cases i.e. case a and case b.

Parameters	L/B=1, n=1		L/B=2, n=1		L/B=1, n=2		L/B=2, n=2		Remarks
	S/B =0.5	S/B =1.0	S/B =0.5	S/B =1.0	S/B =0.5	S/B =1.0	S/B =0.5	S/B =1.0	
n	1	1	1	1	2	2	2	2	
S/B	0.5	1	0.5	1	0.5	1	0.5	1	
B	1	1	1	1	1	1	1	1	
L	1	1	2	2	1	1	2	2	
B <sub>1</sub>	0.5	0.5	1	1	0.5	0.5	1	1	min of [(2S+3B)/2, L/2]
B <sub>2</sub>	0.5	0.5	1	1	0.5	0.5	1	1	min of [(2S+B)/2, L/2]
l	1	1	2	2	1	1	2	2	L/B
l <sub>1</sub>	4	5	2	2.5	4	5	2	2.5	Ratio of maximum dimension to minimum dimension of [2S+3B, L]
l <sub>2</sub>	2	3	1	1.5	2	3	1	1.5	Ratio of maximum dimension to minimum dimension of [2S+B, L]
X <sub>L</sub> = X <sub>R</sub>	1.763	1.763	2.406	2.406	1.763	1.763	2.406	2.406	(from Eq-12)
X <sub>1</sub>	3.085	3.306	2.406	2.622	3.085	3.306	2.406	2.622	(from Eq-10)
X <sub>2</sub>	2.406	2.801	1.763	2.132	2.406	2.801	1.763	2.132	(from Eq-11)
$\varepsilon_{\delta L}$	<b>1.19</b>	<b>1.14</b>	<b>1.27</b>	<b>1.20</b>	<b>1.38</b>	<b>1.29</b>	<b>1.53</b>	<b>1.41</b>	From Eq-9
$\varepsilon_{\delta R}$	<b>1.19</b>	<b>1.14</b>	<b>1.27</b>	<b>1.20</b>	<b>1.10</b>	<b>1.07</b>	<b>1.13</b>	<b>1.10</b>	From Eq-14