

# Finite element limit analysis of the bearing capacity of an obliquely loaded strip footing on granular soil placed adjacent to vertically loaded existing footing

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**Abstract.** The present study explores the impact of strip footing's ultimate load-carrying capacity on granular soil under oblique loads. At the same time, it is lined up subsequently nearer to the existing footing. The numerical simulations have been done by finite element limit analysis (FELA). Upper-bound (UB), lower-bound (LB) and adaptive mesh refinement proficiencies have been harnessed to predict the précised solution for assessing the new footing ultimate load-carrying capacity under oblique loading while lined up subsequently nearer to vertically loaded existing footing. The impact of the new footing's ultimate load-carrying capacity has been well-considered by considering characteristics such as load inclination, angle of internal friction of the soil, footing width and spacing between the footings. The outcome of the current numerical analysis for isolated footing and interfering footing has been validated using accessible literature. For various soil friction angles, load inclination on the new footing interference ( $\zeta$ ) factors was computed using different spacing ratios for symmetrical and asymmetrical footing widths. The charts were developed for the new footing lined up nearer to the existing footing in response to interference factor that varies with the spacing ratio, load inclination and width ratio of the new footing.

**Keywords:** adaptive mesh refinement; design charts; FELA; interference effect; upper-bound and lower-bound

## 1. Introduction

Oblique loads are fairly often committed by the foundations of retaining walls, abutments, waterfront structures, projects built on steep terrain or askew ground, broadcast towers, and portal-framed structures. Ultimate bearing capacity and admissible settlements that the footing can undergo without affecting the superstructure are the two key points in the design of foundations. Soil's ultimate bearing capacity is its ability to carry loads before it fails under shear. Admissible settlement is the settlement caused by the superstructure that should not exceed the permissible limits.

Terzaghi (1943) presented a theoretical approach to evaluate the ultimate bearing capacity of a shallow strip footing laying on a levelled surface. In addition, variations to this theory have indeed been shown as bearing capacity factors that consider shape, depth, and loading inclination (Meyerhof 1957, Hansen 1970, Vesic 1973).

In most cases, without considering the neighbouring structures, the ultimate bearing capacity of footings can be determined. However, rapid urbanization, lack of land, and guidelines in property lines force us to construct the foundations nearer to each other on level or sloped ground.

The assessment of footings' ultimate bearing capacity when lined up in closed proximity is more complex, as the failure mechanism is completely different from isolated footing. Whenever the foundations are in the near vicinity, the assessment of the failure mechanism is even more complicated under oblique loading.

From the method of limit equilibrium, Stuart (1962) investigated the ultimate load-carrying capacity of two interfering strip footings identical in shape and size, and they were subjected to symmetrical loads. The outcomes were provided as interaction factors. Further, several experimental, analytical, and numerical studies were carried out on the interference effect of footings placed in closed proximity by several researchers (West and Stuart 1962, Saran and Agarwal 1974, Das and Larbi-Cherif 1983, Kumar and Saran 2003, Hazell 2004, Griffiths and Fenton 2006, Kumar and Ghosh 2007, Ghazavi and Lavasan 2008, Kumar and Kouzer 2008, Kumar and Bhoi 2009, Mabrouki *et al.* 2010, Ghosh and Kumar 2011, Srinivasan and Ghosh 2013, Ghosh *et al.* 2015, Lavasan *et al.* 2018, Van-Linh *et al.* 2019; Chungsik and Shuaishuai, 2020; Schmu"dderich *et al.* 2020, Ghazavi *et al.* 2023, Sarvesh *et al.* 2023).

From the review of the literature, very few researchers (Kouzer and Kumar 2010, Christoph and Lavasan 2019) addressed the interfering effects, taking note of construction subsequently nearer to the existing footings subjected to vertical loads. To the best of the author's knowledge, no studies were reported on the oblique loaded footings lined up subsequently nearer to the vertically loaded existing footing. As a result, determining the interference impact on the ultimate load-carrying capacity of footings located next to an existing footing resting on cohesionless soils subjected to oblique loads becomes even more vital. The task has

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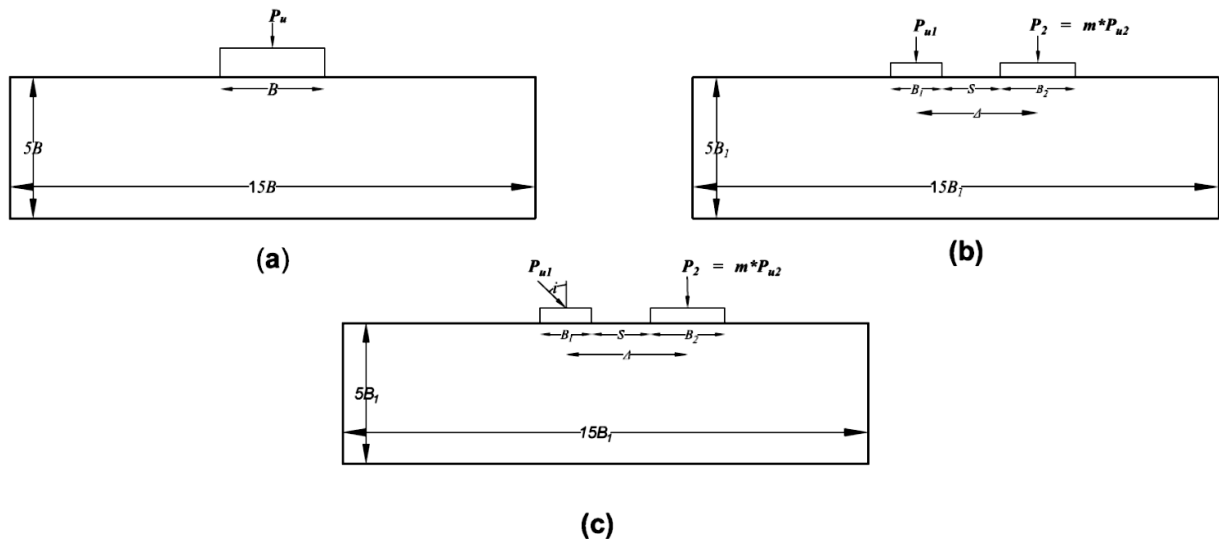


Fig. 1 Geometry of strip footing models and soil foundation domain for (a) Isolated footing, (b) Interfering strip footing under vertical loads, and (c) Interfering footing under oblique loads

been completed by carefully reviewing all pertinent literature on the ultimate load-carrying capacity of strip footings placed in closed proximity and on cohesionless soils under oblique loads.

## 2. Finite element numerical model study

### 2.1 Problem description and discretisation

When lined up nearer to the existing footing under vertical service loads, the interference effect over the strip footing's ultimate load-carrying capacity under oblique loads has been investigated using a finite element limit analysis (FELA). Three models have been created in *OptumG2* (2021) finite element software to investigate this ultimate load-carrying capacity problem. The primary one is an isolated strip footing resting on the surface of homogeneous and cohesionless soil. The second one is a strip footing loaded up to vertical ultimate loads lined up subsequently nearer to the existing footing under vertical service loads. The third model is a strip footing loaded up to oblique ultimate load, which is lined up subsequently nearer to the existing footing under vertical service loads. The geometry and dimensions of three different models employed for this analysis are revealed in Fig. 1. To verify the validity of the current model against the body of literature, the primary and secondary models are utilised.

Later, these models are went to assess the interference effect on the ultimate load-carrying capacity of obliquely loaded footing lined up subsequently nearer to the existing footing under vertical service loading. The third model is used not only for developing design charts for interference factors,  $\xi_y$ , but also for comparing obtainable results from the literature. In this study, the interface concerning the footing and the soil is assumed to be perfectly rough throughout the appraisal.

Table 1 Input parameters considered in the analysis

Parameter	Values
Youngs Modulus of the Soil, $E$	30 Mpa
Poisson Ratio of Soil, $\nu$	0.3
Angle of Internal Friction, $\varphi$	25°, 30°, 35° and 40°
Lateral Earth Pressure Coefficient at Rest, $K_0$ (Jaky 1944)	$1 - \sin \varphi$
Soil Unit Weight, $\gamma$	16 kN/m <sup>3</sup>
Clear Spacing Between the Footings, $S$	0.25 to 10
Width Ratio ( $B_1/B_2$ )	1.0, 0.5 and 2.0
Oblique Loading ( $i$ ) w.r.t. Vertical Axis	0°, 15°, 20° and 30°

### 2.2 Methodology

The soil domain has been considered concerning the new footing width ( $B$  or  $B_1$ ) to neglect the boundary effects. The new footing is loaded till the limit load ( $P_u$  or  $P_{u1}$ ). A constant load is applied on the existing footing ( $P_2 = m \cdot P_{u2}$ ).  $P_{u2}$  is the collapse load of isolated footing, and  $m$  is the load factor enclosed by 0 and 1. So, to resemble the accomplishments of Kouzer and Kumar (2010) and Christoph and Lavasan (2019), the load factor  $m$  varies between 0.1 and 0.5. The soil is modelled as an elastoplastic in FELA, and it follows the associated flow rule to obey the Mohr–Coulomb failure criterion. The input parameters evaluated for this investigation are listed in Table 1.

### 2.3 Mesh discretization and boundary condition

The finite element limit analysis (FELA) approach has been widely utilised to forecast the ultimate bearing load-carrying of footings (Shiau *et al.* 2003, Merifield *et al.* 2006, Anil *et al.* 2017, Xiao *et al.* 2018b, Christoph and

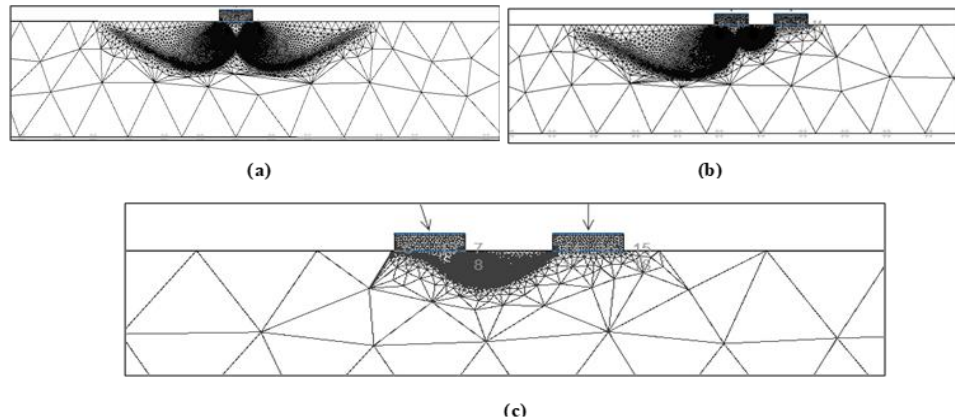


Fig. 2 Typical meshes after application of adaptive refinement for (a) isolated footing, (b) Interfering footings under vertical loads, and (c) Interfering footing under oblique loading

Table 2 Bearing capacity factors  $N_\gamma$  for isolated footings from different literature

$\phi$ (deg)	Kumar and Kouzer (2008)	Ukritchon <i>et al.</i> (2003)	Hjiaj <i>et al.</i> (2005)	Lavasan <i>et al.</i> (2008)	Christoph and Lavasan (2019)	FELA LB	Present Study		$\epsilon_{wc}$ [%] **	
							FELA UB	FELA*		
20	2.70 <sup>L</sup>	2.70 <sup>L</sup>	3.30 <sup>U</sup>	2.80 <sup>L</sup> 3.0 <sup>U</sup>	3.20 <sup>L</sup> 4.70 <sup>K</sup>	2.87 <sup>L</sup> 2.92 <sup>U</sup>	2.63	2.7	2.665	1.31
30	13.60 <sup>L</sup>	13.2 <sup>L</sup>	17.40 <sup>U</sup>	14.60 <sup>L</sup> 15.20 <sup>U</sup>	17.40 <sup>L</sup> 19.90 <sup>K</sup>	14.56 <sup>L</sup> 15.02 <sup>U</sup>	14.31	14.75	14.53	1.51
40	77.90 <sup>L</sup>	69.90 <sup>L</sup>	111.10 <sup>U</sup>	83.30 <sup>L</sup> 88.40 <sup>U</sup>	79.40 <sup>L</sup> 71.40 <sup>K</sup>	83.27 <sup>L</sup> 87.22 <sup>U</sup>	81.38	87	84.19	3.34

\* FELA = (UB+LB)/2 \*\*  $\epsilon_{wc}$  = (UB-LB)/(UB+LB) <sup>L</sup> Lower-Bound <sup>U</sup> Upper-Bound <sup>F</sup> Finite-Difference Method ( $\psi' = 0$ )  
<sup>K</sup> Kinematical - Element Method

Lavasan 2019, Ahmed M. Ebid *et al.* 2022, Ebid *et al.* 2022, Ahmed *et al.* 2022, Ahmed M. Ebid *et al.* 2023). It can also be used to solve stability concerns in geotechnical engineering (Merifield *et al.* 2001, Yamamoto *et al.* 2013, Zhang *et al.* 2019, Ahmed M. Ebid *et al.* 2021) by applying upper bound (UB) (Lyamin and Sloan, 2002a; Lyamin and Sloan, 2002b) or lower bound (LB) solutions (Krabbenhoft *et al.* 2005).

The limit theorem of plasticity (i.e., the lower bound and upper bound theorem) was employed by Drucker *et al.* (1952). Lysmer (1970) and Bottero *et al.* (1980) to several geotechnical problems under plane-strain conditions. Later, several researchers continuously refined these theorems during the following decade (Lyamin and Sloan 2002a, Lyamin and Sloan 2002b, Sloan 2013). Sloan (2013) provided a radical examination of finite element methods and their commitment to advancing FELA.

To reckon the ultimate load-carrying capacity of footings under various cases, as mentioned above, the commercially available FELA software *OptumG2* (2021) has been used. On the basis of the Mohr-Coulomb failure criterion, the soil was expected to fail according to the flow rule associated with it. The interface amidst the soil and the footing is perfectly rough. To realise this condition in *OptumG2*, the contact surface factor was set as 1. Within the numerical model, the restrained boundary conditions have been equipped with horizontal restraint to the vertical edges (restrained x-direction) and complete fixity to the underside barrier (restrained in x & y-directions). There is no restrained right at the top of the soil (free); hence, it

allows for free deformation caused by loading on the footing. With reference to the literature (Christoph and Lavasan 2019), the model domain has been chosen to overcome the boundary effects. A homogeneous and dry soil domine is further assumed. The adaptive meshing technique has been utilised in the present study.

In the current study's FELA simulations, three and six nodes of triangular elements were used to achieve meticulous lower-bound and upper-bound results, respectively. Adaptive mesh refinement has also distinguished the critical failure mechanism of the bearing capacity problem. This technique makes it possible to approximate finer details of the solution and failure mechanisms with fewer elements than uniform meshes. As a result, the computational costs will be reduced (Oberhollenzer *et al.* 2018). A ten-step adaptive refinement process has been used to refine the mesh in the current study. Figs. 2(a) to 2(c) show the indication of meshes that have been adaptively refined for isolated and interfering footings under vertical loads and interfering footing under oblique loading, respectively.

### 3. Validation of the numerical model

#### 3.1 Single strip footing

For cohesionless soil, FELA UB and LB analysis have been carried out for an isolated footing for different friction angles ( $\phi = 20^\circ, 30^\circ$  and  $40^\circ$ ) to determine the bearing

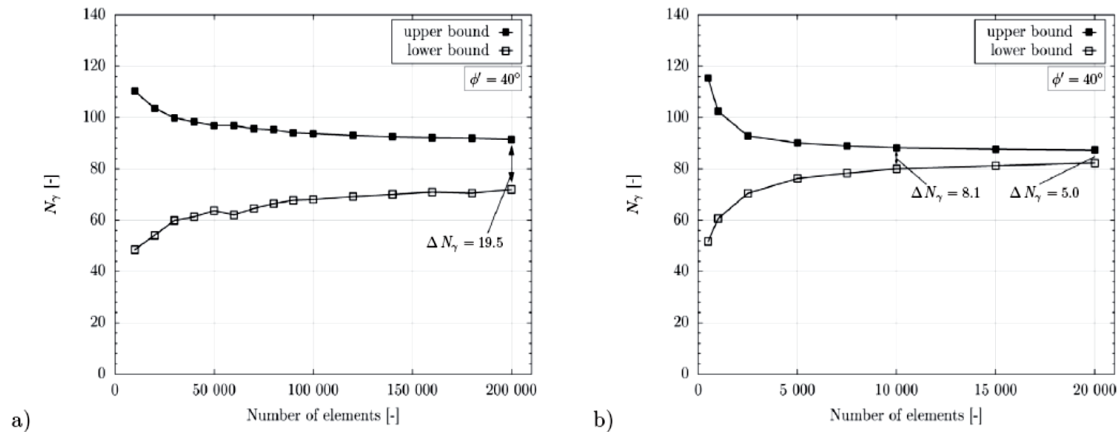


Fig. 3 Variation of bearing capacity factor  $N_\gamma$  of lower-bound and upper-bound analysis for isolated footing. (a) For uniform mesh (b) For adaptive refined mesh. (Ref: Christoph and Lavasan 2019)

capacity factor  $N_\gamma$ . These bearing capacity factors  $N_\gamma$  are compared with available literature (Ukritchon *et al.* 2003, Hjjaj *et al.* 2005, Kumar and Kouzer 2008, Lavasan *et al.* 2018, Christoph and Lavasan 2019). Table 2 portrays the  $N_\gamma$  values from the available literature. The FELA UB and LB analysis results are summarised in Table 2, along with their mean values and worst-case errors  $\varepsilon_{wc}$ . The values obtained from the present analysis are well comparable with Hjjaj *et al.* (2005) and Christoph and Lavasan (2019). For all friction angles, the bearing capacity factors  $N_\gamma$  elicited by Kumar and Kouzer (2008) and Ukritchon *et al.* (2003) are smaller for lower-bound and heftier for upper-bound in comparison with FELA. The main objective of conducting the FELA for isolated footing is to identify the optimum mesh options available in *OptumG2*.

Christoph and Lavasan (2019) have extensively assessed the optimum mesh options (i.e., uniform mesh and adaptive refined mesh) and the number of elements for isolated footing. Lower-bound and upper-bound FELA were carried out for both options, along with studying the range of elements to find the ultimate load-carrying capacity for a friction angle of  $40^\circ$ . Figs. 3(a) and 3(b) show the variation of bearing capacity factor  $N_\gamma$  with the number of elements for both options. From the graphs, for 20000 elements, the difference of  $N_\gamma$  between the upper and lower bound analysis is 19.5 and 5.0 for uniform mesh and adaptive refined mesh, respectively. To validate the model, the present analysis has been carried out with the same number of elements for LB and UB with an adaptive mesh option for isolated footing, and the results are comparable with the literature by Christoph and Lavasan (2019). Hence, for the present case, the adaptive refined mesh and 20000 elements have been considered throughout the analysis.

### 3.2 Strip footing lined up subsequently nearer to the existing footing under vertical loads

For the objective of confirming the validity of the current investigation of the interfering footing model, FELA UB and LB analysis was carried out to determine the new footing load-carrying capacity lined up subsequently nearer to existing footing under vertical loads for friction angle  $\phi$

$=40^\circ$  and  $m = 0.1$  to  $0.5$ . The results of the current study are presented in terms of interference factor  $\zeta_y$  with respect to the non-dimensional factor called spacing ratio  $\Delta/B = (S+B)/B$ .  $B$  signifies the footing width, and  $S$  denotes the clear spacing between the footings.  $\zeta_y$  is the fraction of an influential new footing's ultimate load-carrying capacity for that of an isolated footing. The results achieved by upper bound and lower bound analysis from FELA are compared along with mean values reported by Christoph and Lavasan (2019) for two similar footings (see Figs. 4(a) and 4(b), respectively).

Similarly, the study was carried out to distinguish the  $\zeta_y$  results with Kouzer and Kumar (2010) and Christoph and Lavasan (2019) for friction angle  $\phi = 40^\circ$  by altering the load factor  $m$  on an existing footing. In Fig. 4(c), the medians of the UB and LB values are compared and displayed. The  $\zeta_y$  values in the current FELA study are similar to Christoph and Lavasan's (2019). Kouzer and Kumar (2010) reported values greater than the current  $\zeta_y$  values since the reported values were the results of an upper-bound analysis with a uniform mesh.

To determine the exact bracket between the UB and LB, symmetrical footing widths under vertical loads have been analysed and presented in Fig. 4(a). The results obtained from FELA UB and LB interference factors  $\zeta_y$  are plotted with respect to  $\Delta/B = (S+B)/B$  for soil friction angle  $\phi = 40^\circ$  and load factor  $m = 0.33$ . For all spacings and friction angles considered, it is clear that the findings produced via upper-bound and lower-bound analysis confine the precise output to a narrow range. The worst-case error found at a spacing ratio of  $\Delta/B = 1.5$  is  $\varepsilon_{wc} = 2.23\%$  for an angle of internal friction of soil  $\phi = 40^\circ$ . The results were well compared with the literature (Christoph and Lavasan 2019). The interference factors in the present study are calculated from the mean of UB and LB analysis. The mean interference factors  $\zeta_y$  obtained from this investigation with respect to  $\Delta/B = (S+B)/B$  are shown in Figs. 4(b) and 4(c) and compared to the literature. To ensure that the current model is correct, it is necessary to compare the results to the available literature.

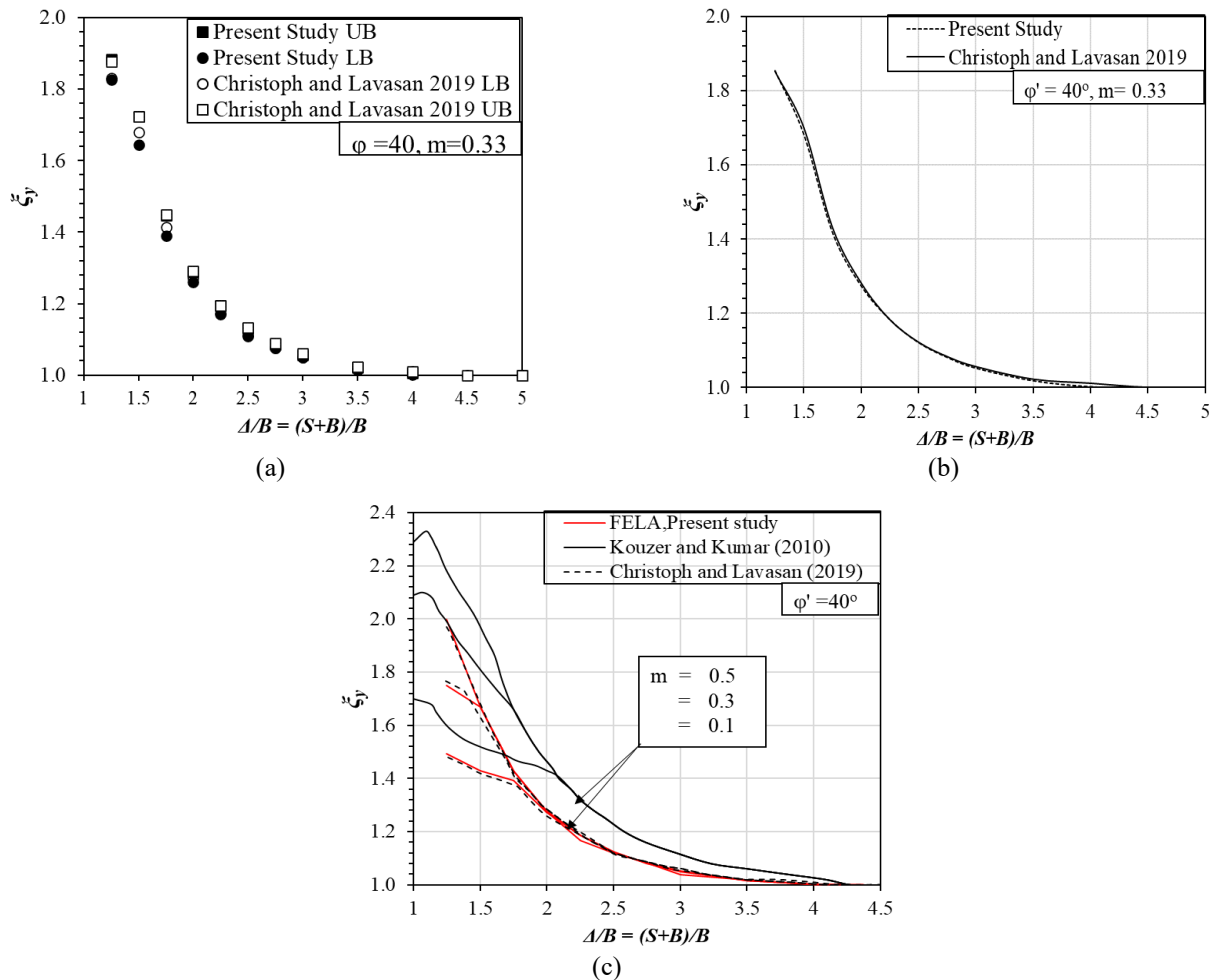


Fig. 4 Interfering effect of two similar footings (a) Comparison of results from FELA LB and UB analysis with Christoph and Lavasan (2019),  $\phi = 40^\circ$  and  $m = 0.33$ , (b) Comparison of FELA mean values with Christoph and Lavasan (2019) for  $\phi = 40^\circ$  and  $m = 0.33$  and (c) Distinguishing of FELA maiden values to Kouzer and Kumar (2010), Christoph and Lavasan (2019) for  $\phi = 40^\circ$  and  $m = 0.1, 0.3$  and  $0.5$

#### 4. Results and discussion

The overall investigation has been categorised into two parts to look over the effect of existing footings on the load-carrying capacity of obliquely loaded new footing lined up nearer to an existing footing under vertical loads. The influence of new footing load-carrying capacity under oblique loading due to existing footing is represented by the interference factor  $\xi_y$ , which is defined as the ratio of an interfering new footing's ultimate load-carrying capacity to that of an isolated footing. The interference effect has been studied by varying the inclination of load on the new footing concerning the vertical axis  $i = 15^\circ$  to  $30^\circ$  (towards the existing footing see Fig. 1(c)), the width of the existing footing ( $B_1$ ) with respect to the new footing ( $B_2$ ), i.e.,  $B_1/B_2 > 1$  larger the new footing,  $B_1/B_2 < 1.0$  smaller the new footing and the internal friction of the soil, i.e.,  $\phi = 25^\circ$  to  $40^\circ$ . The main principle involved in the present study is that when the new footing is lined up nearer to the existing footing and subjected to oblique loads towards the existing footing and loaded up to failure, the failure plane developed under the new footing passes through the bottom of the

existing footing, which impacts the performance of the new footing and leads interference effect. This overlap can increase the load-carrying capacity of the new footing compared to when there is no interference effect.

For the new footing under oblique loading lined up nearer to the existing footing, at an outward inclination (away from the existing footing) of the oblique loads, the development of the failure plane was noticed outward of the existing footing since the loading inclination is outward of the existing footing. As a result, no interference impact has been noticed. The interference impact of a new footing lined up nearer to an existing footing under oblique loading, i.e., inclination towards the existing footing, is investigated systematically in this paper. According to the literature, for width ratios of  $B_1/B_2 \leq 1.0$ , the modification of  $m$  has a negligible impact on  $\xi_y$  and has a moderate impact for  $B_1/B_2 \geq 2.0$  at tighter spacing ratio. As a result, in the current investigation, the load impact factor,  $m$ , was assumed to be 0.33 throughout the analysis.

**Case 1:** Interference effect of strip footing lined up subsequently nearer to an existing footing having symmetrical widths (i.e.,  $B_1/B_2 = 1$ ).

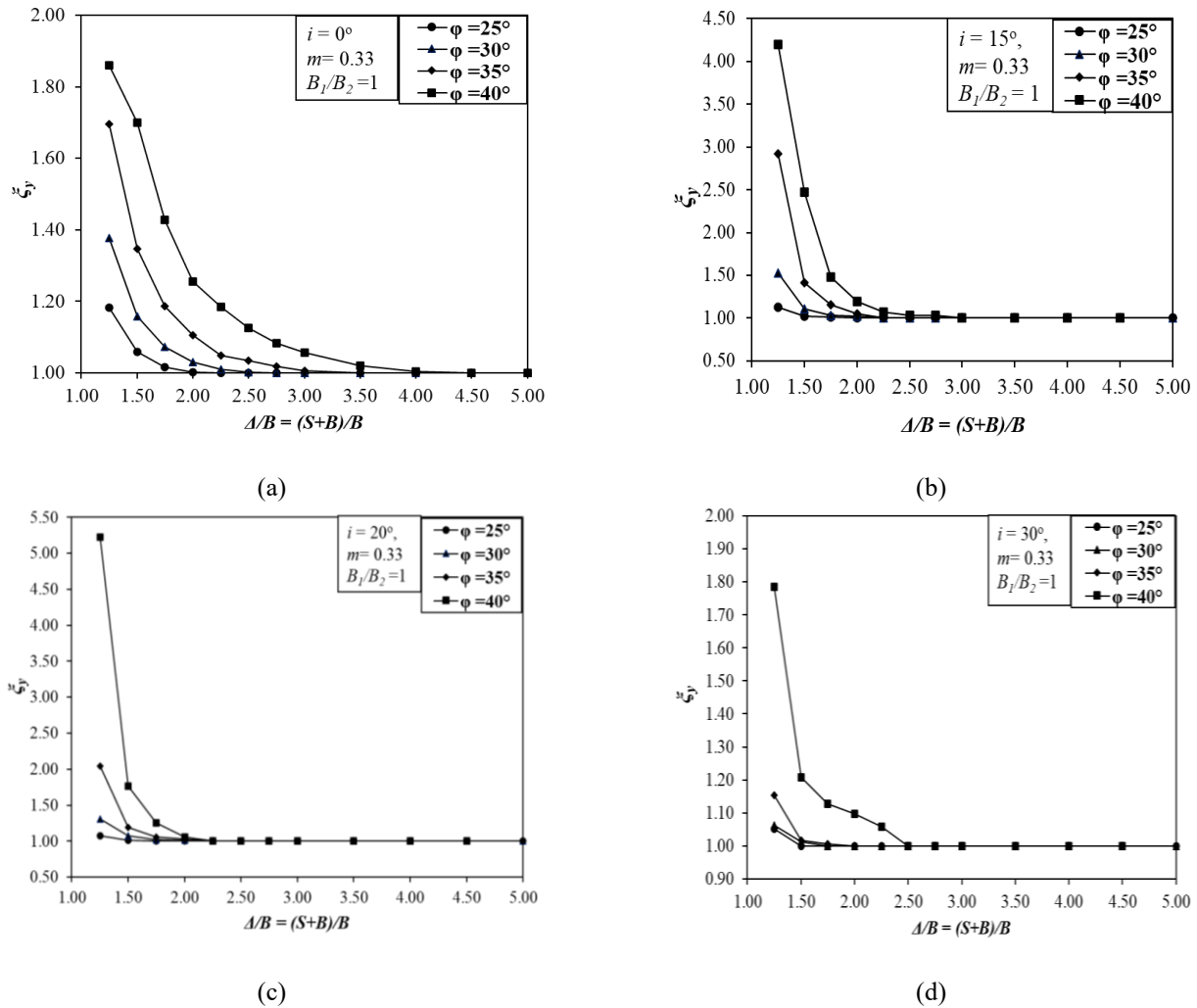


Fig. 5 Interference effect for footing lined up subsequently nearer to an existing footing  $B_1/B_2 = 1$  under oblique loading (a)  $i = 0^\circ$ , (b)  $i = 15^\circ$ , (c)  $i = 20^\circ$  and (d)  $i = 30^\circ$  respectively for different soil friction angle  $\phi = 25^\circ$  to  $\phi = 40^\circ$

**Case 2:** Interference effect of strip footing lined up subsequently nearer to an existing footing having asymmetrical widths (i.e.,  $B_1/B_2=2.0$  (larger the new footing) and  $B_1/B_2=0.5$  (smaller the new footing)).

**4.1 Case 1: Interference effect of strip footing lined up subsequently nearer to an existing footing having symmetrical widths (i.e.,  $B_1/B_2=1$ ):**

*(a) Symmetrical strip footings lined up subsequently in closed proximity under vertical loading*

The impact of the load-carrying capacity of footing lined up subsequently nearer to an existing footing under vertical and oblique loading has been examined by varying the inclination of loading to the vertical axis ( $i = 0^\circ, 15^\circ, 20^\circ$  and  $30^\circ$ ) for different angle of internal friction of soil ( $\phi = 25^\circ$  to  $40^\circ$ ) having symmetrical widths ( $B=B_1=B_2=1$ ) for  $m = 0.33$ .

The outcomes were addressed in terms of interference factor  $\zeta_y$  for  $\Delta/B = (S+B)/B$ . Figs. 5(a) to 5(d) depicts the variation of the interference factor of footing that is lined up nearer to an existing footing under vertical and oblique loading for different soil friction angles.

Fig. 5(a) shows the variation of  $\zeta_y$  with respect to the spacing ratio  $\Delta/B = (S+B)/B$  for different soil friction angles ( $\phi = 25^\circ$  to  $40^\circ$ ) under vertical loads. From the study, it was observed that the  $\zeta_y$  increases as the soil friction angle increases at a closer spacing ratio  $\Delta/B$ . For all soil friction angles, at a closer spacing ratio ( $\Delta/B=1.25$ ), the  $\zeta_y$  values are higher, and the values are reduced to unity as the spacing ratio increases, i.e., no interference impact on new footing due to the existing footing under vertical loads. Further, it was noticed that the maximum spacing ratio  $\Delta/B$  required to eliminate the impact on the load-carrying capacity of the new footing due to the existing footing under vertical loads varies from 2.0 to 4.5 for soil friction angles of  $25^\circ$  to  $40^\circ$ , respectively. As the angle of internal friction of soil increases, the spacing ratio required for the new footing also increases to eliminate the interference effect of the existing footing on a new footing.

*(b) Symmetrical strip footings lined up subsequently in closed proximity under oblique loading*

The variation of interference factor  $\zeta_y$  with respect to the spacing ratio  $\Delta/B = (S+B)/B$  for footing lined up

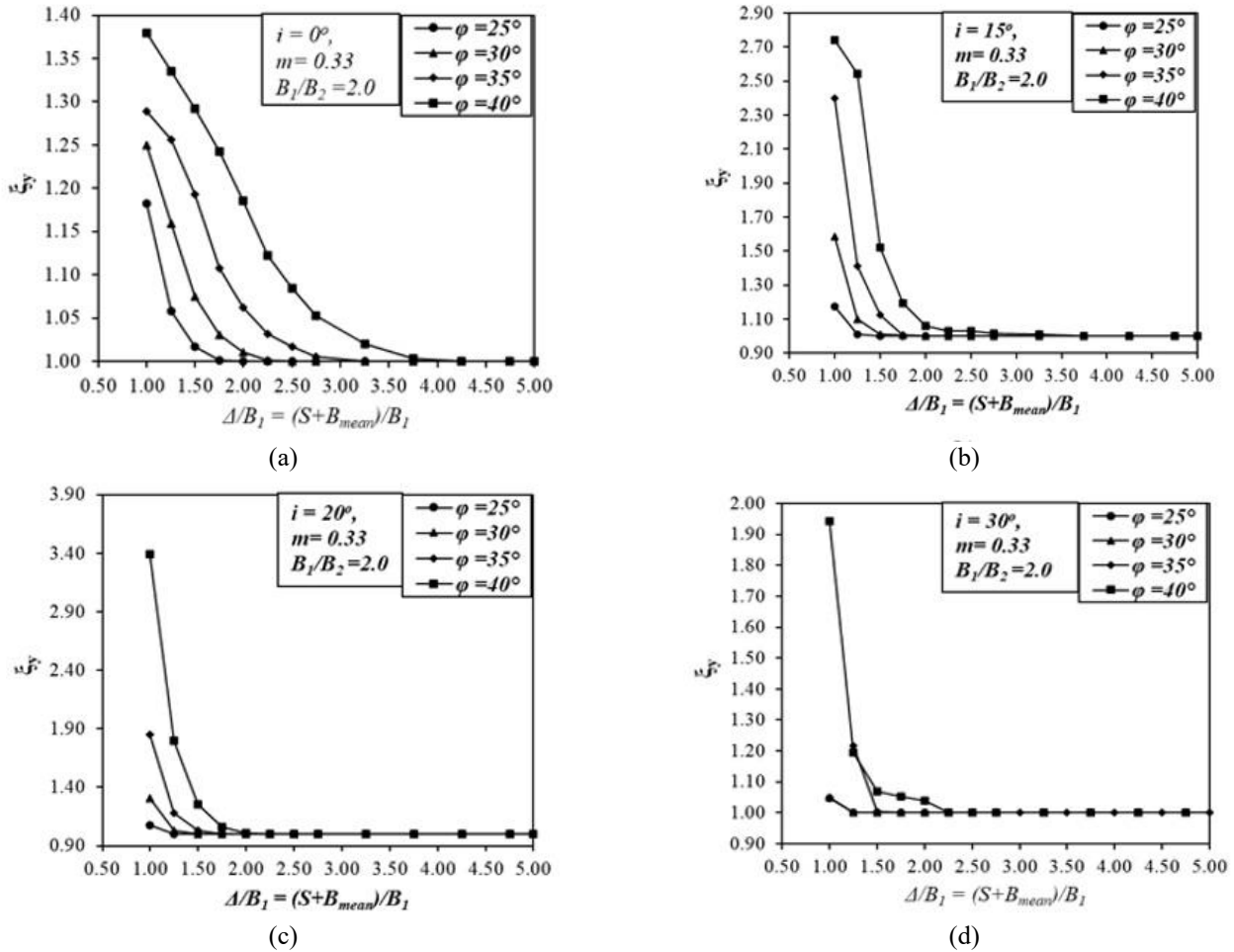


Fig. 6 Interference effect for footing lined up subsequently nearer to an existing footing  $B_1/B_2 = 2$  under oblique loading (a)  $i = 0^\circ$ , (b)  $i = 15^\circ$ , (c)  $i = 20^\circ$  and (d)  $i = 30^\circ$  respectively for different soil friction angle  $\phi = 25^\circ$  to  $\phi = 40^\circ$

subsequently nearer to an existing footing for different soil friction angles  $25^\circ$  to  $40^\circ$  under oblique loading  $i = 15^\circ, 20^\circ$  and  $30^\circ$  have been presented in Figs. 5(b) to 5(d). According to the findings, the interference effect increases with load inclination to  $i = 15^\circ$  and  $20^\circ$  and decreases with  $i = 30^\circ$  for soil friction angle  $40^\circ$ . Besides that, for soil friction angles  $25^\circ$  to  $35^\circ$ , the interference factors were increasing at  $i = 15^\circ$ , after they decreased in contrast to the interference effect of a vertically loaded new footing lined up subsequently nearer to an existing footing. Under oblique loading, the variation of  $\zeta_y$  with respect to the spacing ratio follows the same trend as the footing under vertical loading. The values of  $\zeta_y$  range from 1.12 to 4.2 for  $i = 15^\circ$ , 1.08 to 5.22 for  $i = 20^\circ$ , and 1.06 to 1.79 for  $i = 30^\circ$ , for soil friction angles  $25^\circ$  to  $40^\circ$ , respectively, at a closer spacing ratio of  $\Delta/B = 1.25$ .

For soil friction angles of  $25^\circ$  to  $40^\circ$ , the maximum spacing ratio  $\Delta/B$  required for a new footing under oblique loading lined up subsequently nearer to an existing footing to act as an isolated footing range from 1.75 to 3.5. The spacing ratio required for a new footing under oblique loading lined up nearer to an existing footing is less than that required for a new footing under vertical loads lined up nearer to an existing footing.

#### 4.2 Case 2: Interference effect of strip footing lined up subsequently nearer to an existing footing having asymmetrical widths (i.e., $B_1/B_2 = 2.0$ (Larger the new footing) and $B_1/B_2 = 0.5$ (Smaller the new footing))

##### (a) Asymmetrical strip footings lined up subsequently in closed proximity under vertical loading

The bearing capacity of footing lined up subsequently nearer to an existing footing under vertical and oblique loads for different footing width ratios, i.e.,  $B_1/B_2 = 2.0$  (larger the new footing) and  $B_1/B_2 = 0.5$  (smaller the new footing) have been obtained from FELA UB and LB analysis for different soil friction angle  $\phi = 25^\circ$  to  $40^\circ$ . The load-carrying capacity of a new footing lined up nearer to an existing footing has been quantified in the context of interference factors  $\zeta_y$ . The  $\zeta_y$  values have been evaluated from the UB and LB values average for different width ratios. The variation of  $\zeta_y$  concerning spacing ratio  $\Delta/B_1 = (S+B_{mean})/B_1$  under vertical loads ( $i = 0^\circ$ ) for different width ratios has been studied and is presented in Figs. 6(a) and 7(a). It should be mentioned that the existing footing width has a substantial impact on new footings bearing capacity. At a closer spacing ratio,  $\Delta/B_1 = (S+B_{mean})/B_1$ , when the width of the existing footing is larger than the width of the

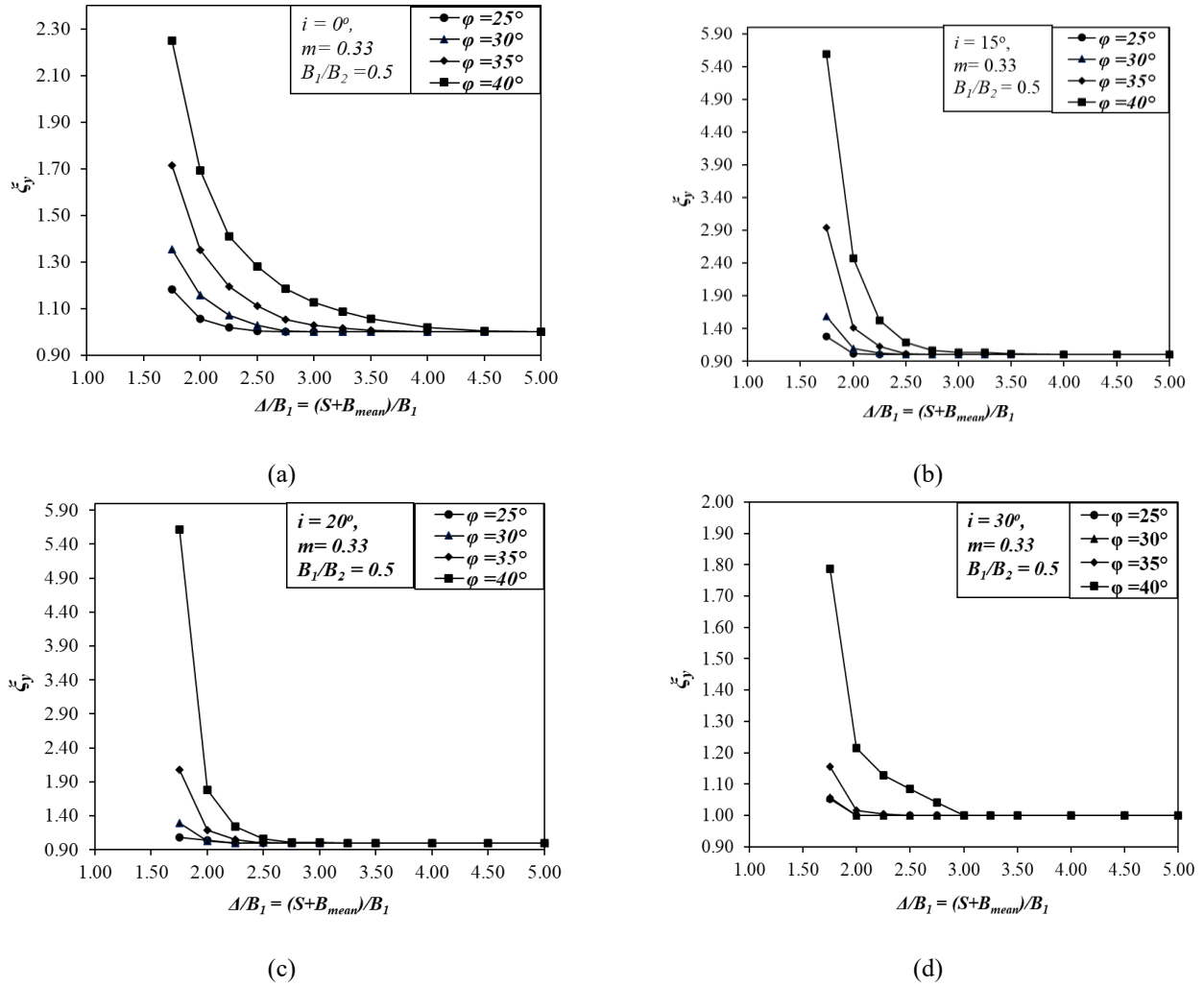


Fig. 7 Interference effect for footing lined up subsequently nearer to an existing footing  $B_1/B_2 = 0.5$  under oblique loading (a)  $i = 0^\circ$ , (b)  $i = 15^\circ$ , (c)  $i = 20^\circ$  and (d)  $i = 30^\circ$  respectively for different soil friction angle  $\phi = 25^\circ$  to  $\phi = 40^\circ$

new footing ( $B_1/B_2=0.5$ ), the magnitude of  $\zeta_y$  increases for all soil friction angles, whereas when the width of the existing footing is smaller than the new footing ( $B_1/B_2=2.0$ ), the magnitude of  $\zeta_y$  decreases in comparison with the symmetrical footing widths  $B_1/B_2=1$ . For asymmetrical footing widths, the variation of  $\zeta_y$  for the spacing ratio  $\Delta/B_1 = (S+B_{mean})/B_1$  follows the same trend as symmetrical footing widths  $B_1/B_2=1$  for all soil friction angles. When the width of the existing footing is smaller than the new footing  $B_1/B_2=2.0$  and closer spacing ratio  $\Delta/B_1 = 1.0$ , the magnitude of  $\zeta_y$  varies from 1.18 to 1.38 for a soil friction angle of  $\phi = 25^\circ$  to  $40^\circ$  respectively under vertical loads. Furthermore, for  $B_1/B_2=0.5$ , the values of  $\zeta_y$  range from 1.18 to 2.25, corresponding to soil friction angles of  $\phi = 25^\circ$  to  $40^\circ$  at a closer spacing ratio  $\Delta/B_1 = 1.75$ .

(b) *Asymmetrical strip footings lined up subsequently in closed proximity under oblique loading*

FELA analysis has been carried out to examine the impact of the footing width ratio ( $B_1/B_2$ ) on the ultimate load-carrying capacity of a new footing under oblique loading  $i = 15^\circ$ ,  $20^\circ$ , and  $30^\circ$  while lined up subsequently

nearer to an existing footing for varied internal angle of friction of soils. The magnitude of  $\zeta_y$  versus the spacing ratio  $\Delta/B_1 = (S+B_{mean})/B_1$  for the obliquely loaded new footing placed near an existing footing for different width ratios has been reported in Figs. 6 and 7. In a closer spacing ratio, the magnitude of  $\zeta_y$  increases as the load inclination increases from  $i=15^\circ$  to  $20^\circ$  then falls regardless of the footing width ratio for  $\phi \geq 40^\circ$ . The magnitude of  $\zeta_y$  increases at load inclination  $i=15^\circ$  and decreases as load inclination increases to  $i=20^\circ$  to  $30^\circ$  for all footing width ratios and for  $\phi < 40^\circ$ . The larger the existing footing  $B_1/B_2 = 0.5$ , at all load inclinations, at a closer spacing ratio, the  $\zeta_y$  values are intensified compared to the smaller the existing  $B_1/B_2 = 2.0$ . For footing width ratio  $B_1/B_2 = 0.5$ , the values of  $\zeta_y$  bounds from 1.28 to 5.93 for  $i=15^\circ$ , 1.085 to 5.61 for  $i=20^\circ$ , and 1.05 to 1.79 for  $i=30^\circ$ , for soil friction angles  $25^\circ$  to  $40^\circ$ , respectively at a closer spacing ratio. Similarly, at a closer spacing ratio, for soil friction angles  $25^\circ$  to  $40^\circ$ , the values of  $\zeta_y$  bound between 1.17 and 2.74 for  $i = 15^\circ$ , 1.08 to 3.39 for  $i = 20^\circ$ , and 1.05 to 1.94 for  $i = 30^\circ$ , respectively, for footing width ratio  $B_1/B_2 = 2.0$ .

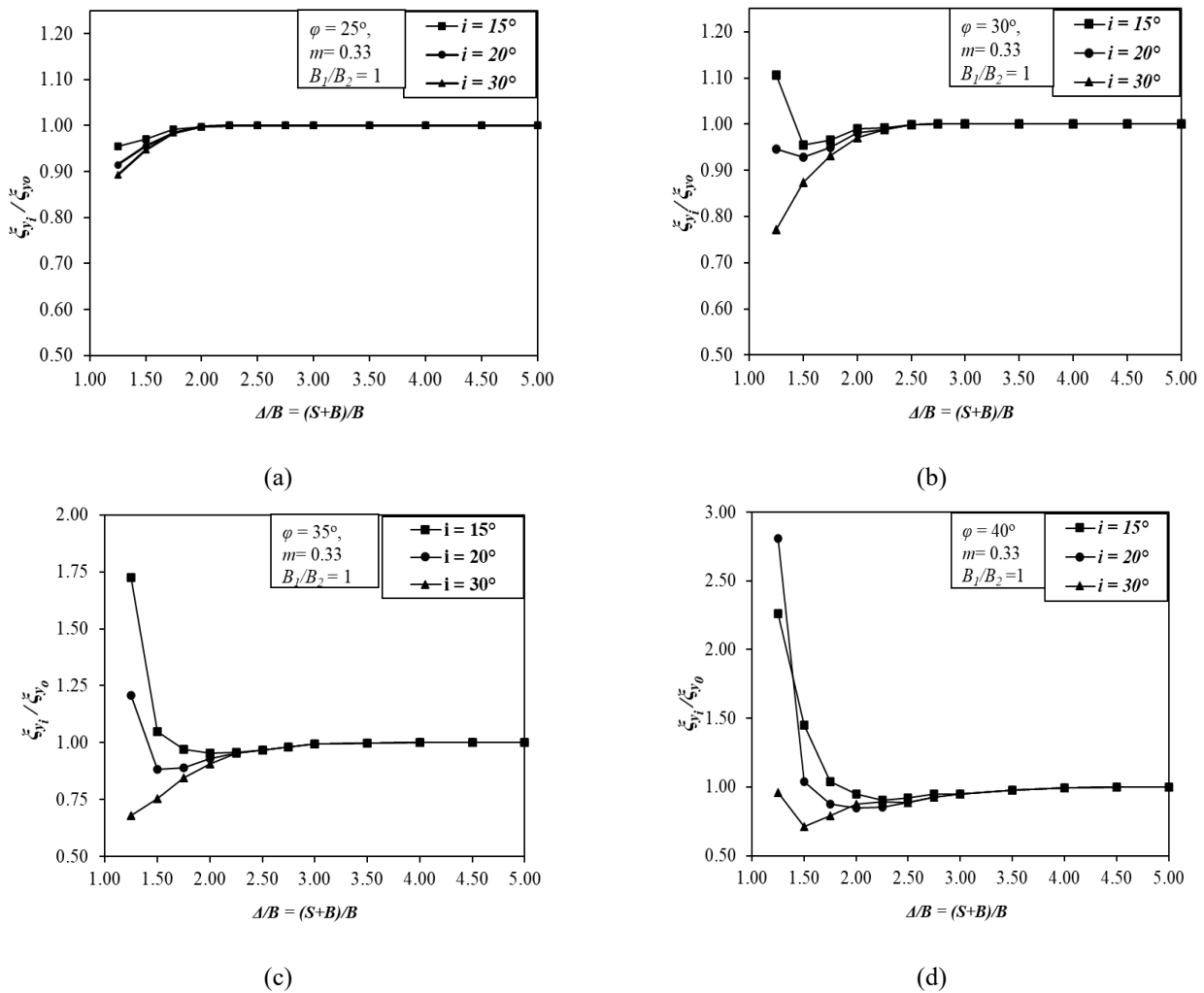


Fig. 8 Variation of factor  $\xi_{yi}/\xi_{yo}$  with respect to the spacing ratio of new footing under oblique loading placed next to the existing footing for (a)  $\phi = 25^\circ$ , (b)  $\phi = 30^\circ$  respectively, (c)  $\phi = 35^\circ$  and (d)  $\phi = 40^\circ$  respectively

**4.3 Variation of factor  $\xi_{yi}/\xi_{yo}$  concerning spacing ratio of new footing under oblique loading lined up subsequently nearer to an existing footing**

The impact of  $\xi_{yi}$  of new footing under oblique loading lined up subsequently nearer to an existing footing has been compared to the  $\xi_{yo}$  of new footing under vertical loading lined up nearer to an existing footing. The differentiation of  $\xi_{yi}$  to  $\xi_{yo}$  with regard to the spacing ratio for different soil friction angles and footing width ratio have been deliberated in terms of factor  $\xi_{yi}/\xi_{yo}$ .  $\xi_{yi}$  represents the interference factor of new footing under oblique loading lined up nearer to an existing footing, and  $\xi_{yo}$  represents the interference factor of new footing under vertical loading lined up nearer to an existing footing having the same width. Fig. 8 to 10 shows the variation of factor  $\xi_{yi}/\xi_{yo}$  with regard to the spacing ratio  $\Delta/B_1 = (S+B_{mean})/B_1$  for varied soil friction angles.

It should be noted that as the angle of internal friction increases ( $\phi = 25^\circ$  to  $40^\circ$ ) at a closer spacing ratio in spite of the footing width ratio, the interference factor of an obliquely loaded new footing lined up subsequently nearer

to an existing footing increases in comparison with the vertically loaded new footing lined up subsequently nearer to an existing footing. For all footing width ratios ( $B_1/B_2=1.0$ ,  $B_1/B_2=2.0$ , and  $B_1/B_2=0.5$ ), the impact of the interference effect increases as the load inclination increases for the obliquely loaded footing lined up subsequently nearer to an existing footing compared to the vertically loaded footing lined up subsequently nearer to an existing footing. Furthermore, the factors  $\xi_{yi}/\xi_{yo}$  are higher for smaller new footing widths  $B_1/B_2=0.5$  as compared to the factors  $\xi_{yi}/\xi_{yo}$  of symmetrical footing widths  $B_1/B_2=1.0$ .

There is not much variation in the factors  $\xi_{yi}/\xi_{yo}$  for larger the new footing width  $B_1/B_2=2.0$  compared with symmetrical footing width  $B_1/B_2=1.0$  at a closer spacing ratio for oblique loading.

**4.4 Variation of  $(\xi_y)_{max}$  and  $(\Delta/B_1)_{max}$  with the soil friction angle and load inclination for the new footing subjected to oblique loading lined up nearer to the existing footing**

From the current study, the interference factors of the new footing subjected to oblique loads (load inclination

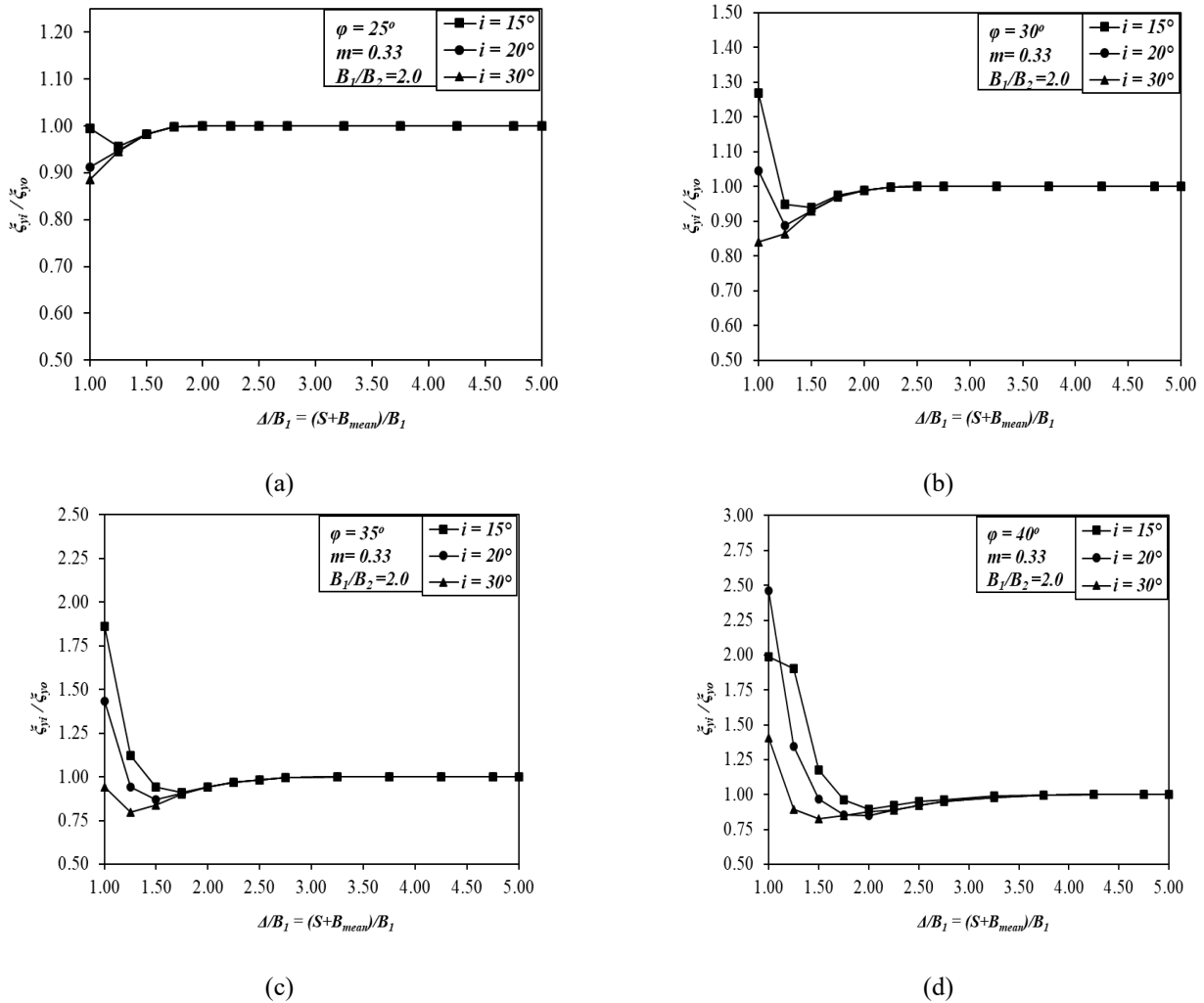


Fig. 9 Variation of factor  $\xi_{yi}/\xi_{yo}$  with respect to spacing ratio of new footing under oblique loading placed next to the smaller existing footing ( $B_1/B_2 = 2$ ) for (a)  $\phi = 25^\circ$ , (b)  $\phi = 30^\circ$ , (c)  $\phi = 35^\circ$  and (d)  $\phi = 40^\circ$  respectively

loaded existing footing for all the soil friction angles and footing widths were observed maximum, i.e.,  $(\zeta_y)_{max}$  at closest spacing ratios  $\Delta/B_1 = (S+B_{mean})/B_1$ . It becomes unity (i.e.,  $\zeta_y = 1$ , footing behaves like an isolated footing) at farthest spacing ratio  $(\Delta/B_1)_{max}$ . To visualise this concept being discussed and make the information easier to understand, the variation of maximum interference factors  $(\zeta_y)_{max}$  and the maximum spacing ratios  $(\Delta/B_1)_{max}$  for different soil friction angles ( $\phi = 25^\circ$  to  $40^\circ$ ) and load inclinations to the vertical axis ( $i = 15^\circ, 20^\circ$  and  $30^\circ$ ) for symmetrical footing widths ( $B_1/B_2 = 1$ ) and asymmetrical footing widths (i.e.,  $B_1/B_2 = 2$ , larger the new footing width;  $B_1/B_2 = 0.5$ , smaller the new footing width) have been presented in Figs. 11 to 14.

Figs. 11 and 12 show the variation of  $(\zeta_y)_{max}$  and  $(\Delta/B_1)_{max}$  with soil friction angle for the new footing placed next to the existing footing for different footing widths ( $B_1/B_2 = 0.5, 1.0$  and  $2.0$ ) and obliquity angles ( $i = 15^\circ, 20^\circ$  and  $30^\circ$ ). From the figures, in symmetrical footings, it has been noticed that the  $(\zeta_y)_{max}$  and  $(\Delta/B_1)_{max}$  values are intensified as the soil friction angle increases from  $25^\circ$  to  $40^\circ$ . Similar trends have been observed in asymmetrical

footing cases, i.e.,  $B_1/B_2 = 2$  and  $B_1/B_2 = 0.5$ . The charts show that at an internal friction angle of the soil of  $\phi \leq 30^\circ$ , the width of an existing footing has a minimal effect on the  $(\zeta_y)_{max}$  and  $(\Delta/B_1)_{max}$  values of a new footing lined up nearer to it under oblique loading. When the soil friction angle is more than  $\phi > 30^\circ$ , it could have a considerable influence on the  $(\zeta_y)_{max}$  and  $(\Delta/B_1)_{max}$  values of the new footing. It can also be seen that the  $(\zeta_y)_{max}$  and  $(\Delta/B_1)_{max}$  values are higher when the new footing width is smaller than that of the existing footing ( $B_1/B_2 = 0.5$ ) than when the new footing width is larger ( $B_1/B_2 = 2.0$ ).

Variations of  $(\zeta_y)_{max}$  and  $(\Delta/B_1)_{max}$  concerning load inclination to the vertical axis of the new footing placed next to the vertically loaded existing footing for different load inclination angles ( $i$ ) have been presented in Figs. 13 and 14. For soil friction angle  $\leq 30^\circ$ , the  $(\zeta_y)_{max}$  values of new footing are higher for the asymmetrical footings than the symmetrical footings for all load inclinations. For soil friction angle  $> 30^\circ$ , the  $(\zeta_y)_{max}$  values are higher for the smaller footing width and lower as the footing width is larger than the symmetrical footing width placed nearer to the existing footing. It is also noticed that the impact of the

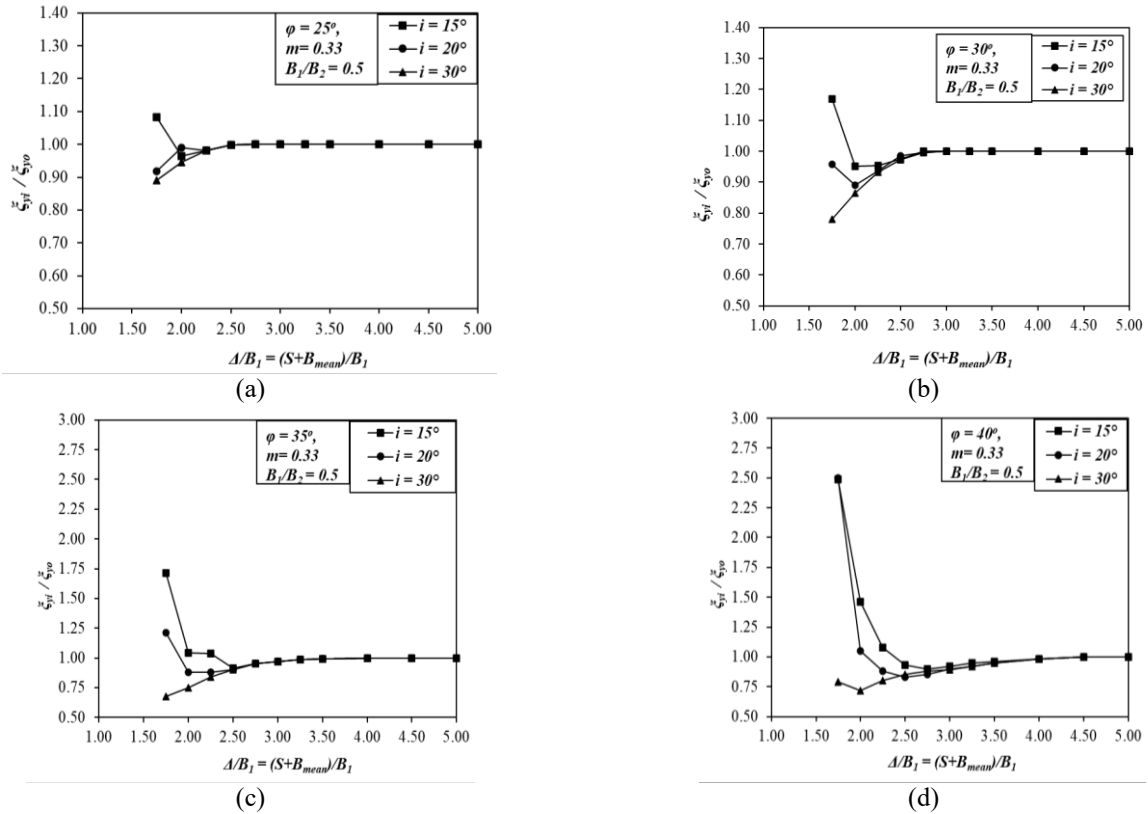


Fig. 10 Variation of factor  $\zeta_{yi}/\zeta_{y0}$  with respect to spacing ratio of new footing under oblique loading placed next to the smaller existing footing ( $B_1/B_2 = 0.5$ ) for (a)  $\phi = 25^\circ$ , (b)  $\phi = 30^\circ$ , (c)  $\phi = 35^\circ$  and (d)  $\phi = 40^\circ$  respectively

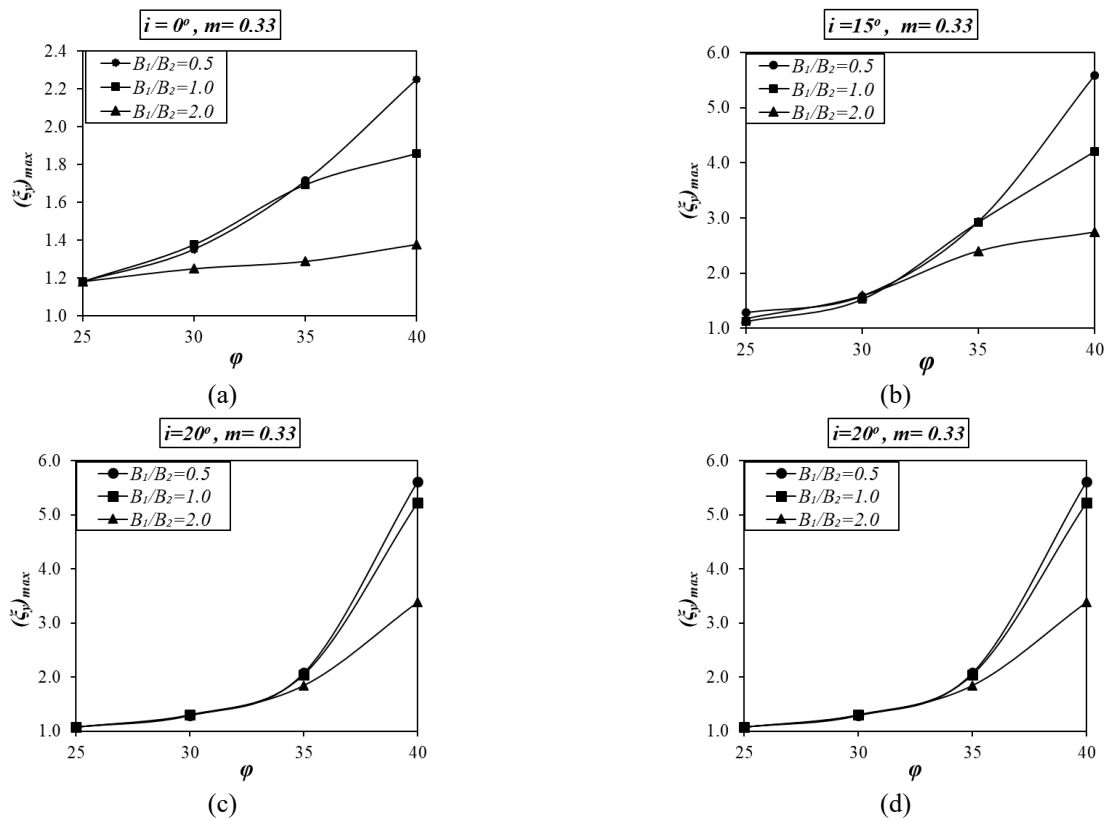


Fig. 11 Variation of maximum interference factor  $(\zeta_y)_{max}$  with soil friction angle for the new footing placed next to the existing footing for different footing widths ( $B_1/B_2 = 0.5, 1.0$  and  $2.0$ ) and oblique loading conditions: (a) for  $i=0^\circ$ , (b) for  $i=15^\circ$ , (c) for  $i=20^\circ$  and (d) for  $i=30^\circ$

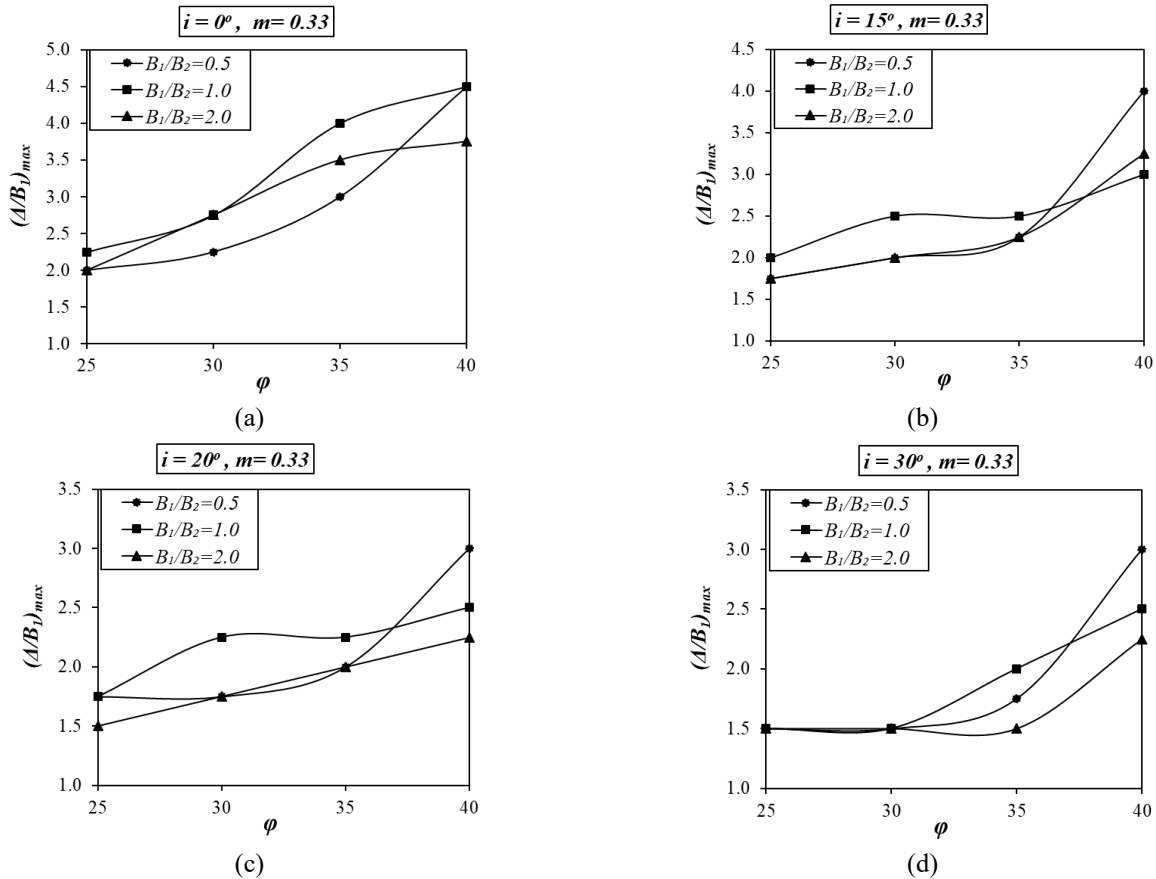


Fig. 12 Variation of maximum spacing ratio  $(\Delta/B_1)_{max}$  with soil friction angle for the new footing placed next to the existing footing for different footing widths ( $B_1/B_2 = 0.5, 1.0$  and  $2.0$ ) and oblique loading conditions: (a) for  $i=0^\circ$ , (b) for  $i=15^\circ$ , (c) for  $i=20^\circ$  and (d) for  $i=30^\circ$

Table 3 Study the effect of  $\gamma$ ,  $E$  and  $\nu$  for different values of  $\phi$  on interference factors

$B_1/B_2=1.0, m=0.33, i=15^\circ, \Delta/B_1=1.50$						
$\phi^\circ$	E (in MPa), $\nu, \gamma$ (in $\text{kN/m}^3$ ) [current study values]	$(\xi_y)_{\text{current study}}$	E (in MPa), $\nu, \gamma$ (in $\text{kN/m}^3$ ) [ideal values]	$(\xi_y)_{\text{ideal condition}}$	% difference b/w current study and ideal condition in $\xi_y$	
25	30, 0.3, 16	1.024	3, 0.35, 16	1.019	0.49	
30	30, 0.3, 16	1.107	10, 0.33, 18	1.1	0.63	
35	30, 0.3, 16	1.412	35, 0.30, 20	1.405	0.50	
40	30, 0.3, 16	2.469	65, 0.28, 22	2.463	0.24	

interference effect on new footing is increasing for the load inclination  $i = 0^\circ$  to  $15^\circ$ ; after that, it decreases for all the soil friction angles and footing widths. The maximum impact can be observed at  $15^\circ$  load inclination for all the mentioned cases. The maximum spacing ratio required for the new footing to behave like an isolated footing placed nearer to the existing footing is higher when the footing is subjected to vertical loads ( $i = 0^\circ$ ) than the footing subjected to inclined loads ( $i = 15^\circ, 20^\circ$  and  $30^\circ$ ) for all soil friction angle and footing width ratios (See Fig. 14). Further, it is worth mentioning here that, Figs. 12 and 14 shall be very useful for designers and consultants to fetch the necessary spacing between the footings to be free from interference.

4.5 Effect of  $\nu, E$  and  $\gamma$  of soil on  $\xi_y$  for different values of  $\phi$

To understand the variation of interference factors with the other soil parameters such as Poisson’s ratio ( $\nu$ ), Modulus of Elasticity ( $E$ ), and unit weight of soil ( $\gamma$ ) of the soil corresponding to the soil friction angle ( $\phi$ ), the FELA for UB and LB analysis has been carried out for the new footing lined up near the existing footing having symmetrical widths ( $B_1/B_2 = 1$ ) subjected to oblique loading with a load inclination of  $i = 15^\circ$  to vertical axis have been considered.

The current research has been carried out by considering the parameters in Table 1. Many recent research related to the subject (Kouzer and Kumar 2010, Lavasan *et al.* 2018, Christoph and Lavasan 2019) have also considered a similar parameter for conducting the finite element analysis. It is a well-known fact that stiffness ( $E$  and  $\nu$ ) and strength ( $\phi$ ) parameters govern the load-settlement response of the

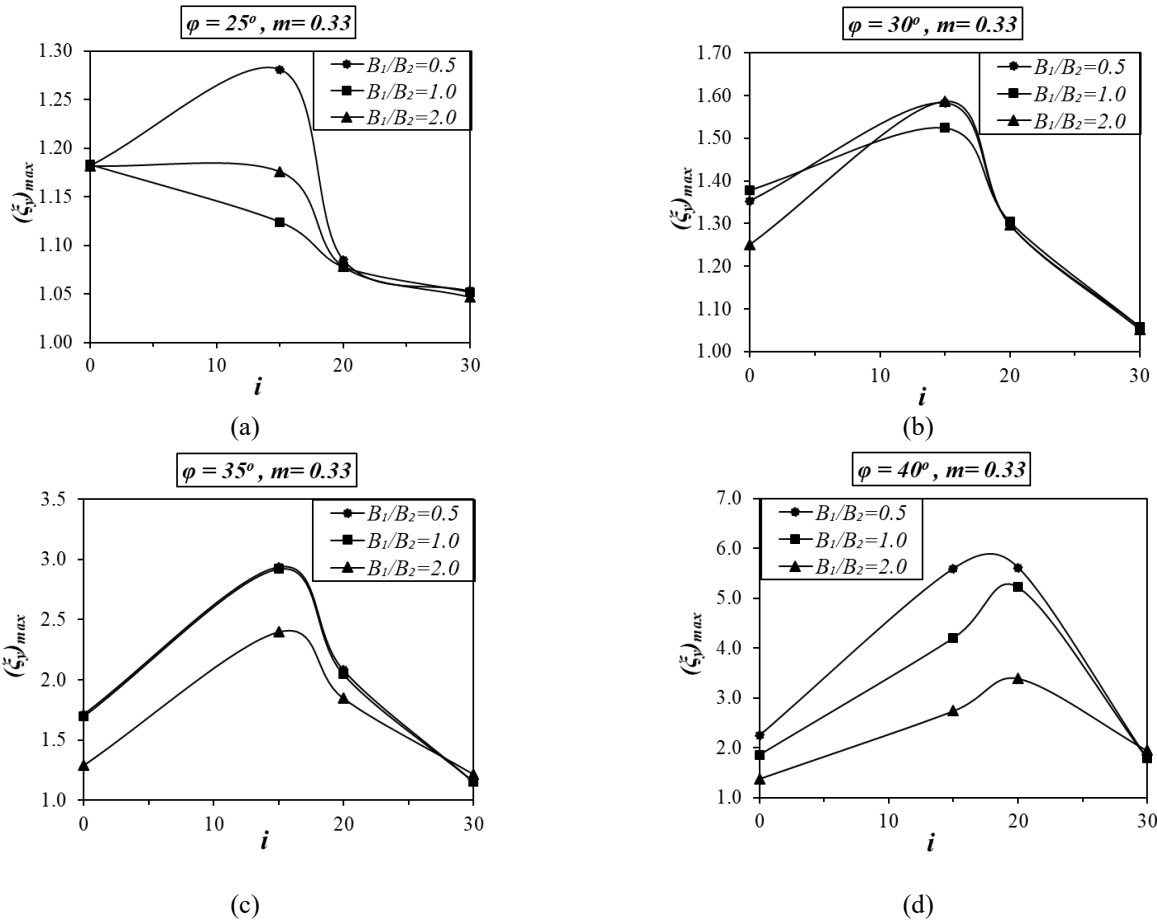


Fig. 13 Variation of maximum interference factor  $(\zeta_y)_{max}$  with load inclination ( $i = 0^\circ, 15^\circ, 20^\circ$  and  $30^\circ$ ) for the new footing placed next to the existing footing for different footing widths ( $B_1/B_2 = 0.5, 1.0$  and  $2.0$ ) and soil friction angles: (a) for  $\phi = 25^\circ$ , (b) for  $\phi = 30^\circ$ , (c) for  $\phi = 35^\circ$  and (d) for  $\phi = 40^\circ$

foundation system in addition to the unit weight ( $\gamma$ ) of the soil. In order to understand the effect of  $\gamma$ ,  $E$  and  $\nu$  for different values of  $\phi$ , ideal values have been considered as tabulated in Table 3. The FELA analysis has been carried out for the different ideal cases, and the results are compared with the current study values and are presented in Table 3. It can be observed that the interference factors  $\zeta_y$  of the new footing do not vary because this is the ratio of an influential new footing's ultimate load-carrying capacity to that of an isolated footing. The numerator and the denominator are related to the load-carrying capacity of the new footing for specific soil parameters. Hence, it can be understood that the effect of  $\gamma$ ,  $E$  and  $\nu$  is insignificant on the interaction factors,  $\zeta_y$ .

### 5. Conclusions

A series of numerical finite element upper and lower bound limit analyses (FELA) was accomplished to study the ultimate load-carrying capacity of obliquely loaded strip footing lined up nearer to an existing footing resting on granular soil in *OptumG2* by using the mesh refinement technique. The angle of internal friction of soil, ratio of

footing width, and footing spacing ratio were all taken into account in the analysis. The pronouncements are outlined in the interference factor ( $\zeta$ ) context. The current study's results were compared to the existing literature for isolated footing as well as interfering footing to validate and establish confidence in the current numerical model in *OptumG2*. The following significant findings are drawn from the present analysis.

- From the perspective of the data's comparison to the literature, the upper bound and lower bound ultimate load-carrying capacity of footings are strongly reliant on the number of components to be highly regarded in the analysis as well as the adaptive mesh refinement in the zone of high dissipation energy.
- The load-carrying capacity of footing lined up subsequently nearer to an existing footing is shot up as the spacing between the footings dwindles, intensifying with increasing the angle of internal friction. It behaves as an isolated footing at a greater spacing.
- When symmetrical footings ( $B_1/B_2 = 1.0$ ) are placed in close proximity under oblique loading, the interference ultimate load-carrying capacity of new footing for  $\phi \leq 30^\circ$  is intensified, for  $i = 0^\circ$ , 11% to 37%; for  $i = 15^\circ$ ,

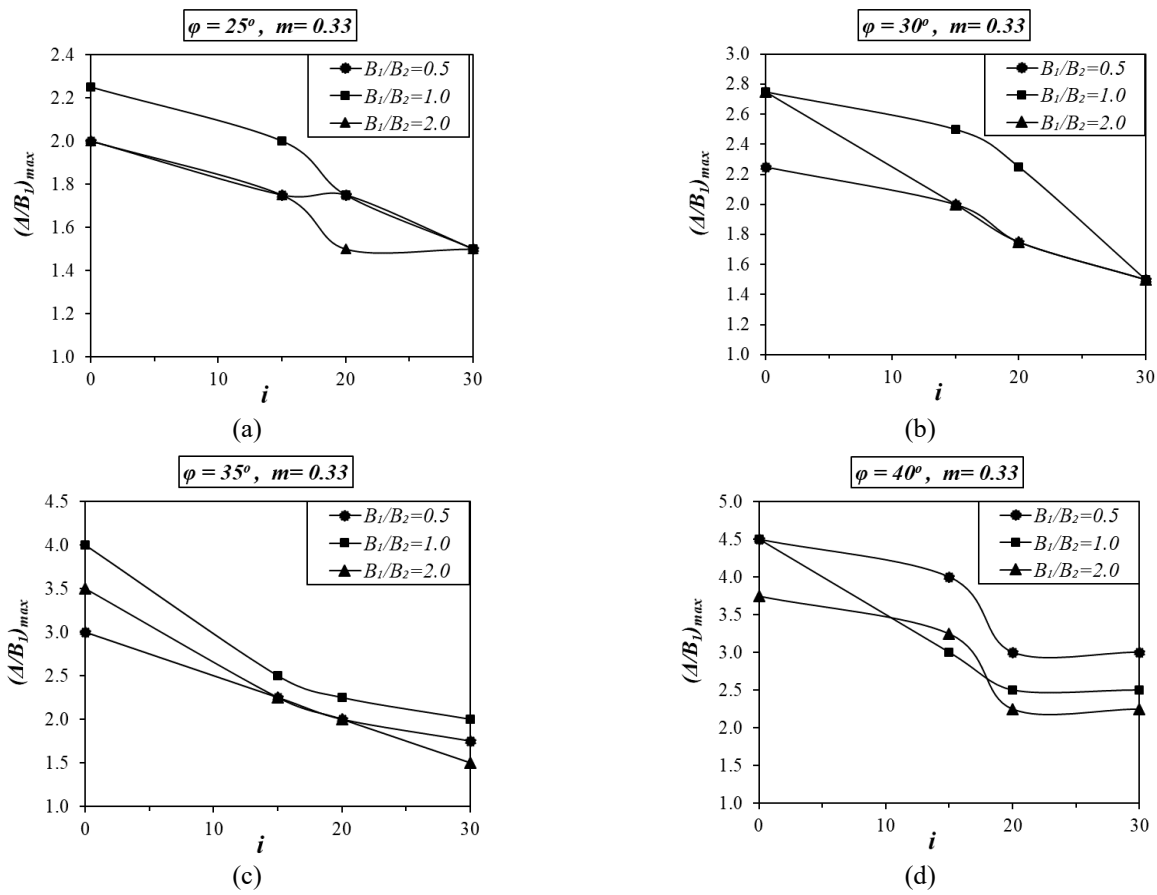


Fig. 14 Variation of maximum spacing ratio  $(A/B_1)_{max}$  with load inclination ( $i = 0^\circ, 15^\circ, 20^\circ$  and  $30^\circ$ ) for the new footing placed next to the existing footing for different footing widths ( $B_1/B_2 = 0.5, 1.0$  and  $2.0$ ) and soil friction angles: (a) for  $\phi = 25^\circ$ , (b) for  $\phi = 30^\circ$ , (c) for  $\phi = 35^\circ$  and (d) for  $\phi = 40^\circ$

12% to 50%; for  $i=20^\circ$ , 8% to 30% and for  $i=30^\circ$ , 5% to 6%. Similarly, for  $\phi > 30^\circ$  the interference ultimate load-carrying capacity intensifies, for  $i=0^\circ$ , 69% to 86%; for  $i=15^\circ$ , 190% to 320%; for  $i=20^\circ$ , 100% to 420% and  $i=30^\circ$ , 15% to 78%.

- Furthermore, as the smaller the existing footing ( $B_1/B_2=2.0$ ), the interference ultimate load-carrying capacity of new footing for  $\phi \leq 30^\circ$  proliferates, for  $i=0^\circ$ , 18% to 25%; for  $i=15^\circ$ , 17% to 58%; for  $i=20^\circ$ , 7% to 30% and for  $i=30^\circ$ , 4% to 5%. Likewise, for  $\phi > 30^\circ$ , the interference ultimate load-carrying capacity proliferates; for  $i=0^\circ$ , 28% to 38%; for  $i=15^\circ$ , 140% to 174%; for  $i=20^\circ$ , 84% to 240% and for  $i=30^\circ$ , 19% to 94%.
- If larger the existing footing ( $B_1/B_2=0.5$ ), the interference ultimate load-carrying capacity of new footing for  $\phi \leq 30^\circ$  is intensified, for  $i=0^\circ$ , 11% to 35%; for  $i=15^\circ$ , 12% to 58%; for  $i=20^\circ$ , 8% to 30% and for  $i=30^\circ$ , 5% to 5.6%. Similarly, for  $\phi > 30^\circ$ , the interference ultimate load-carrying capacity intensifies, for  $i=0^\circ$ , 70% to 125%; for  $i=15^\circ$ , 190% to 460%; for  $i=20^\circ$ , 108% to 460% and for  $i=30^\circ$ , 15% to 78%.
- It is also noticed that the impact of the maximum interference effect on new footing is increasing for the load inclination  $i = 0^\circ$  to  $15^\circ$ ; after that, it decreases for

all the soil friction angles and footing widths. The maximum impact can be observed at  $15^\circ$  load inclination for all the mentioned cases.

- The current research is limited to the footings resting on dry granular homogeneous soil medium with a horizontal datum whose constitutive relationship follows the Mohr-Coulomb failure criterion with the associated flow rule.
- The current study may be extended to footing resting on other types of geomaterials like rocky terrain or clayey deposits. Similarly, the present work could be further continued for simultaneously loaded two or multiple strip footings.

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## Appendix

The FELA upper-bound (UB) and lower-bound (LB) analysis results for the new footing lined up nearer to the existing footing subjected to oblique loads are presented.

Table A Database results from FELA analysis for  $\varphi = 25^\circ$ 

$\varphi$	$i$	$S/B_1$	UBC (kN/m <sup>2</sup> ) of new footing in the presence of existing footing					
			LB			UB		
			$B_1/B_2=0.5$	$B_1/B_2=1.0$	$B_1/B_2=2.0$	$B_1/B_2=0.5$	$B_1/B_2=1.0$	$B_1/B_2=2.0$
$0^\circ$	0.25		56.6	56.65	56.6	58.84	58.84	58.85
	0.5		50.63	50.77	50.76	52.57	52.57	52.6
	0.75		48.91	48.9	48.92	50.5	50.45	50.47
	1		48.1	48.18	48.1	49.7	49.7	49.72
	1.25		48.1	48.1	48.1	49.55	49.55	49.6
	1.5		48.1	48.1	48.1	49.55	49.55	49.6
	1.75		48.1	48.1	48.1	49.55	49.55	49.6
	2		48.1	48.1	48.1	49.55	49.55	49.6
	2.5		48.1	48.1	48.1	49.55	49.55	49.6
	3		48.1	48.1	48.1	49.55	49.55	49.6
	3.5		48.1	48.1	48.1	49.55	49.55	49.55
	4		48.1	48.1	48.1	49.55	49.55	49.55
	$15^\circ$	0.25		19.45	17.23	18.91	22.3	19.45
0.5			16.34	16.5	16.34	16.9	16.9	16.67
0.75			16.11	16.3	16.1	16.51	16.6	16.5
1			16.11	16.11	16.1	16.51	16.51	16.5
1.25			16.11	16.11	16.1	16.51	16.51	16.5
1.5			16.11	16.11	16.1	16.51	16.51	16.5
1.75			16.11	16.11	16.1	16.51	16.51	16.5
2			16.11	16.11	16.1	16.51	16.51	16.5
2.5			16.11	16.11	16.1	16.51	16.51	16.5
3			16.11	16.11	16.1	16.51	16.51	16.5
3.5			16.11	16.11	16.1	16.51	16.51	16.5
4			16.11	16.11	16.1	16.51	16.51	16.5
$25^\circ$		0.25		11.44	11.3	11.3	11.6	11.6
	0.5		11.3	10.52	10.54	10.9	10.9	10.74
	0.75		10.5	10.5	10.5	10.74	10.74	10.74
	1		10.5	10.5	10.5	10.74	10.74	10.74
	1.25		10.5	10.5	10.5	10.74	10.74	10.74
	1.5		10.5	10.5	10.5	10.74	10.74	10.74
	1.75		10.5	10.5	10.5	10.74	10.74	10.74
	2		10.5	10.5	10.5	10.74	10.74	10.74
	2.5		10.5	10.5	10.5	10.74	10.74	10.74
	3		10.5	10.5	10.5	10.74	10.74	10.74
	3.5		10.5	10.5	10.5	10.74	10.74	10.74
	4		10.5	10.5	10.5	10.74	10.74	10.74
	$30^\circ$	0.25		5.1	5.1	5.1	5.25	5.24
0.5			4.65	4.65	4.7	5.2	5.2	5.2
0.75			4.65	4.65	4.7	5.2	5.2	5.2
1			4.65	4.65	4.7	5.2	5.2	5.2
1.25			4.65	4.65	4.7	5.2	5.2	5.2
1.5			4.65	4.65	4.7	5.2	5.2	5.2
1.75			4.65	4.65	4.7	5.2	5.2	5.2
2			4.65	4.65	4.65	5.2	5.2	5.2
2.5			4.65	4.65	4.65	5.2	5.2	5.2
3			4.65	4.65	4.65	5.2	5.2	5.2
3.5			4.65	4.65	4.65	5.2	5.2	5.2
4			4.65	4.65	4.65	5.2	5.2	5.2

Table B Database results from FELA analysis for  $\varphi = 30^\circ$ 

$\varphi$	$i$	$S/B_1$	UBC (kN/m <sup>2</sup> ) of new footing in the presence of existing footing					
			LB			UB		
			$B_1/B_2=0.5$	$B_1/B_2=1.0$	$B_1/B_2=2.0$	$B_1/B_2=0.5$	$B_1/B_2=1.0$	$B_1/B_2=2.0$
$0^\circ$		0.25	147.9	153.7	138.6	161.7	161.6	147.1
		0.5	128.9	129.5	129.3	135.6	135.7	135.6
		0.75	119.8	120	120.3	125.3	125.4	125.4
		1	114.7	115.5	115.4	120.4	120.3	120.4
		1.25	112.2	113.3	113.3	117.5	117.9	117.9
		1.5	112.2	112.4	112.1	116.5	116.8	116.8
		1.75	112.2	112.2	112.1	116.5	116.5	116.5
		2	112.2	112.2	112.1	116.5	116.5	116.5
		2.5	112.2	112.2	112.1	116.5	116.5	116.5
		3	112.2	112.2	112.1	116.5	116.5	116.5
		3.5	112.2	112.2	112.1	116.5	116.5	116.5
		4	112.2	112.2	112.1	116.5	116.5	116.5
	$15^\circ$		0.25	57.68	53.32	57.9	60.01	60.01
		0.5	40.32	40.7	40.3	41.54	41.54	41.51
		0.75	37.1	38	37	38.92	38.92	38
		1	36.87	37.5	37	37.65	38.36	37.65
		1.25	36.87	36.87	36.7	37.65	37.65	37.65
		1.5	36.67	36.67	36.7	37.65	37.65	37.65
		1.75	36.67	36.67	36.7	37.65	37.65	37.65
		2	36.67	36.67	36.7	37.65	37.65	37.65
		2.5	36.67	36.67	36.7	37.65	37.65	37.65
		3	36.67	36.67	36.7	37.65	37.65	37.65
		3.5	36.67	36.67	36.7	37.65	37.65	37.65
		4	36.67	36.67	36.7	37.65	37.65	37.65
$30^\circ$			0.25	29.3	29.6	29.6	30.2	30.2
		0.5	23.3	25.41	23.24	23.87	23.9	23.88
		0.75	22.8	23.14	22.6	23.2	23.6	23.2
		1	23.1	23.1	22.6	23.3	23.3	23.2
		1.25	22.66	22.66	22.6	23.2	23.2	23.2
		1.5	22.66	22.66	22.6	23.2	23.2	23.2
		1.75	22.66	22.66	22.6	23.2	23.2	23.2
		2	22.66	22.66	22.6	23.2	23.2	23.2
		2.5	22.66	22.66	22.6	23.2	23.2	23.2
		3	22.66	22.66	22.6	23.2	23.2	23.2
		3.5	22.66	22.66	22.6	23.2	23.2	23.2
		4	22.66	22.66	22.6	23.2	23.2	23.2
	$20^\circ$		0.25	9.75	9.75	9.65	9.78	9.87
		0.5	9.18	9.18	9.2	9.3	9.55	9.3
		0.75	9.18	9.18	9.2	9.3	9.3	9.3
		1	9.18	9.18	9.2	9.3	9.3	9.3
		1.25	9.18	9.18	9.2	9.3	9.3	9.3
		1.5	9.18	9.18	9.2	9.3	9.3	9.3
		1.75	9.18	9.18	9.2	9.3	9.3	9.3
		2	9.18	9.18	9.2	9.3	9.3	9.3
		2.5	9.18	9.18	9.2	9.3	9.3	9.3
		3	9.18	9.18	9.2	9.3	9.3	9.3
		3.5	9.18	9.18	9.2	9.3	9.3	9.3
		4	9.18	9.18	9.2	9.3	9.3	9.3

Table C Database results from FELA analysis for  $\varphi = 35^\circ$ 

$\varphi$	$i$	$S/B_1$	UBC (kN/m <sup>2</sup> ) of new footing in the presence of existing footing					
			LB			UB		
			$B_1/B_2=0.5$	$B_1/B_2=1.0$	$B_1/B_2=2.0$	$B_1/B_2=0.5$	$B_1/B_2=1.0$	$B_1/B_2=2.0$
$0^\circ$	0.25		445.3	436	330.9	480.1	480	367
	0.5		353	350.4	328.8	377.2	377.2	351
	0.75		312.4	308.9	312.7	332.5	332.6	332.6
	1		291.1	288.1	290.7	308.7	308.9	308.8
	1.25		273.37	272.2	279.3	295.3	294.5	295.1
	1.5		269.5	271.9	271.9	286.5	286.6	286.5
	1.75		266.7	268	267.8	282	281.6	282.2
	2		264.3	264.5	264.9	278.9	279.1	279.1
	2.5		263.6	263.6	264	276.5	276.8	277
	3		263.6	263.6	263.7	276.5	276.5	276.6
	3.5		263.6	263.6	263.7	276.5	276.5	276.6
	4		263.6	263.6	263.7	276.5	276.5	276.6
	$15^\circ$	0.25		241.9	240.5	199.1	264	263
0.5			118.2	118.4	118	125.1	124.8	124.7
0.75			95	97	94.8	100	101.4	98.6
1			85.6	88.86	85	88.4	92.55	88.32
1.25			84.76	84.83	84.78	87.4	87.88	87.4
1.5			84.76	84.76	84.78	87.4	87.4	87.4
1.75			84.76	84.76	84.7	87.4	87.4	87.4
2			84.76	84.76	84.7	87.4	87.4	87.4
2.5			84.76	84.76	84.7	87.4	87.4	87.4
3			84.76	84.76	84.7	87.4	87.4	87.4
3.5			84.76	84.76	84.7	87.4	87.4	87.4
4			84.76	84.76	84.7	87.4	87.4	87.4
$35^\circ$		0.25		104.8	101.4	81.13	110.9	110.7
	0.5		60.12	60.5	59.9	62.8	62.8	62.8
	0.75		53.92	53.92	52.92	54.8	55.8	54.46
	1		51.2	52.8	51.7	52.5	53.7	52.5
	1.25		51.2	51.2	51.2	52.5	52.5	52.5
	1.5		51.2	51.2	51.2	52.5	52.5	52.5
	1.75		51.2	51.2	51.2	52.5	52.5	52.5
	2		51.2	51.2	51.2	52.5	52.5	52.5
	2.5		51.2	51.2	51.2	52.5	52.5	52.5
	3		51.2	51.2	51.2	52.5	52.5	52.5
	3.5		51.2	51.2	51.2	52.5	52.5	52.5
	4		51.2	51.2	51.2	52.5	52.5	52.5
	$30^\circ$	0.25		20	20	22.04	20.7	20.65
0.5			17.83	17.83	17.4	18	18	17.86
0.75			17.69	17.69	17.4	17.75	17.75	17.75
1			17.5	17.5	17.4	17.75	17.75	17.75
1.25			17.5	17.5	17.4	17.75	17.75	17.75
1.5			17.5	17.5	17.4	17.75	17.75	17.75
1.75			17.5	17.5	17.4	17.75	17.75	17.75
2			17.5	17.5	17.4	17.75	17.75	17.75
2.5			17.5	17.5	17.4	17.75	17.75	17.75
3			17.5	17.5	17.4	17.75	17.75	17.75
3.5			17.5	17.5	17.4	17.75	17.75	17.75
4			17.5	17.5	17.4	17.75	17.75	17.75

Table D Database results from FELA analysis for  $\varphi = 40^\circ$ 

$\varphi$	$i$	$S/B_1$	UBC (kN/m <sup>2</sup> ) of new footing in the presence of existing footing						
			LB			UB			
			$B_1/B_2=0.5$	$B_1/B_2=1.0$	$B_1/B_2=2.0$	$B_1/B_2=0.5$	$B_1/B_2=1.0$	$B_1/B_2=2.0$	
$0^\circ$	0.25		1413.3	1185	883.5	1613	1316	971.2	
	0.5		1077	1086	853.8	1202	1200	941.5	
	0.75		890.5	914.6	817.5	1007	1006	920.6	
	1		822.9	791.7	769.7	897.4	897.8	902.5	
	1.25		762.55	760.7	763.8	831	830.9	830	
	1.5		727.3	726.3	723.2	785.9	786.7	785.4	
	1.75		701.7	700	700	757	755.5	756.9	
	2		682.4	683.7	679.3	735.9	735.3	736.1	
	2.5		659.4	660.7	661.3	710.6	711.1	710.2	
	3		650.1	651	649.9	699.4	699.6	699.1	
	3.5		650.1	650.1	649.9	694.3	694.5	694.5	
	4		650.1	650.1	649.9	694.3	694.5	694.5	
	$15^\circ$	0.25		1097	831	541.3	1207	900	589.1
		0.5		480.5	482	523.5	536.2	535	523.2
0.75			301	284.2	302.3	326.1	327	325.5	
1			237.2	237.5	236.1	253.1	253.5	256.2	
1.25			211.1	213.6	211	227.4	226.7	227	
1.5			208.9	207.4	206.1	219.2	219.6	219.4	
1.75			207	206.2	206.1	218	217.9	217.7	
2			203.1	201.7	203.1	215.4	210	214.7	
2.5			201.7	201.7	202.1	210	210	214	
3			201.7	201.7	202.1	210	210	210	
3.5			201.7	201.7	201.82	210	210	210	
4			201.7	201.7	201.82	210	210	210	
$40^\circ$		0.25		653.5	600	397.3	723.9	680.8	435.1
		0.5		208.9	208.2	211.4	229	225.4	229.1
	0.75		147.2	148.5	149	158.6	158.6	158.4	
	1		127	126.8	127.5	133.4	133.2	133.5	
	1.25		121	121	121	126	126	125.9	
	1.5		121	121	121	126	124.2	124.2	
	1.75		121	121	121	124.2	124.2	124.2	
	2		121	121	121	124.2	124.2	124.2	
	2.5		121	121	121	124.2	124.2	124.2	
	3		121	121	121	124.2	124.2	124.2	
	3.5		121	121	121	124.2	124.2	124.2	
	4		121	121	121	124.2	124.2	124.2	
	$20^\circ$	0.25		53.2	53.2	63.54	64.27	64.27	64.2
		0.5		39.4	39.2	37.71	40.5	40.23	40.93
0.75			36.3	36.3	32.5	37.85	37.85	37.85	
1			35.3	35.36	32.5	36	36.8	36.8	
1.25			33.5	33.5	32.5	35	36	35.8	
1.5			32.5	32.5	32.5	33.23	33.23	33.23	
1.75			32.5	32.5	32.5	33.23	33.23	33.23	
2			32.5	32.5	32.5	33.23	33.23	33.23	
2.5			32.5	32.5	32.5	33.23	33.23	33.23	
3			32.5	32.5	32.5	33.23	33.23	33.23	
3.5			32.5	32.5	32.5	33.23	33.23	33.23	
4			32.5	32.5	32.5	33.23	33.23	33.23	
$30^\circ$		0.25		53.2	53.2	63.54	64.27	64.27	64.2
		0.5		39.4	39.2	37.71	40.5	40.23	40.93
	0.75		36.3	36.3	32.5	37.85	37.85	37.85	
	1		35.3	35.36	32.5	36	36.8	36.8	
	1.25		33.5	33.5	32.5	35	36	35.8	
	1.5		32.5	32.5	32.5	33.23	33.23	33.23	
	1.75		32.5	32.5	32.5	33.23	33.23	33.23	
	2		32.5	32.5	32.5	33.23	33.23	33.23	
	2.5		32.5	32.5	32.5	33.23	33.23	33.23	
	3		32.5	32.5	32.5	33.23	33.23	33.23	
	3.5		32.5	32.5	32.5	33.23	33.23	33.23	
	4		32.5	32.5	32.5	33.23	33.23	33.23	