Interference of Two Closely-Spaced Footings on Finite Sand Layer

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ABSTRACT: Bearing capacity of footing is influenced by the presence of adjacent footing. In this study, two closely-spaced strip, square, and circular footings are modelled in finite elements using commercially available software - PLAXIS 2D and 3D. Analysis is done considering both smooth and rough footing bases. The effect of spacing between the footings is examined for footings resting on both semi-infinite and finite sand layers. In addition, angle of shearing resistance of foundation soil is varied from 30° to 40° to investigate its effect on the bearing capacity. Bearing capacity of footings with rough base are found to attain a peak value at a particular spacing indicating the "*blocking effect*". For square and circular footings, interference due to spacing is found to be insignificant compared to strip footing. Interference factors for rough footings are found to be higher than that for smooth footings.

KEYWORDS: Bearing capacity, Interference, Finite element method, Finite layer

1. INTRODUCTION

In the modern world, due to space constraint in the urban areas, tall structures in close proximity to each other have become a common sight. In such cases, the behavior of footings is different from an isolated footing due to inference in the pressures bulbs from adjacent footings. The ultimate bearing capacity of isolated single strip, square, and circular foundations were given by Terzaghi (1943) and expressed as

$$q_u = cN_c + qN_q + 0.5\gamma BN_\gamma \quad (1)$$

$$q_u = 1.3cN_c + qN_q + 0.4\gamma BN_\gamma \quad (2)$$

$$q_u = 1.3cN_c + qN_q + 0.3\gamma BN_\gamma \quad (3)$$

where, q_u = ultimate load carrying capacity of the footing
c = cohesion of soil
q = overburden pressure at the level of footing
γ = unit weight of sandy soil
B = width of the footing

N_c,$N_q$and N_γ are the bearing capacity factors that depend on the angle of shearing resistance of the soil. If the footing is embedded at depth *D*, $q = \gamma * D$. However, the bearing capacity can be much higher when the footings are close and resting on a finite layer of soil. The interference between the pressure bulbs are found to improve the load carrying capacity of the footing which can be economized. Extensive studies have been carried out in the past on the bearing capacity of such footings.

A large number of small-scale model experimental tests have been carried out by many other researchers in studying the interference effect between two closely-spaced strip footings {Mandel, 1963, Murthy, 1970, Singh et al., 1973, Wang and Jao 2002, Kumar and Saran, 2003, Al Tikrity, 2009, Abbas and Hussian, 2013, Lavasan et al., 2015} and few researchers have carried out experimental investigations on footings of other shapes {Saran and Agarwal, 1974, Kumar and Saran, 2003, Basudhar et al., 2007, Lee and Eun, 2009, Reddy et al., 2012}. Some researchers have done numerical analysis using various finite element softwares for studying the interference effect on closely-spaced footings {Khing et al., 1993, Ghazavi and Lavasan, 2008, Lee and Eun, 2009, Mabrouki et al., 2010, Ghosh and Sharma, 2010, Lavasan and Ghazavi, 2012, Abbas and Hussain, 2013}.

Stuart, 1962 was the first to examine the interference effect and proposed theoretical solution to obtain the ultimate bearing capacity of two closely-spaced strip footings on the basis of limit equilibrium method. Stuart, 1962 had proposed charts for efficiency factor of closely-spaced strip footings with different spacing. Das and Larbi-Cherif, 1983 conducted model tests on isolated and two closely-spaced strip footings on sand layer and compared the results with Stuart, 1962. Depth of embedment of footing was considered and design charts were proposed. Verma and Saran, 1987 also conducted experimental studies on interference of strip footings on clay and sand. The study inferred that interference of footings was significant only in sands but not in clays.

Kumar and Ghosh, 2007 investigated the ultimate bearing capacity of interfering two parallel strip footings using method of stress characteristics and efficiency factors were computed. Analysis was performed considering two types of failure mechanisms with quadrilateral wedge and triangular wedge below the base of the footing, the latter mechanism was found to match the results closely with theory of Stuart, 1962 and with the recent solutions using upper bound analysis whereas the former mechanism provides conservative estimate of interference factor merely close to those proposed by Kumar and Saran, 2003. Kumar and Kouzer, 2008 determined the ultimate bearing capacity of interfering rough strip footings by using upper bound analysis in conjunction with model developed using finite difference programming software, FLAC. Results were found to compare well with analytical solution given by Kumar and Ghosh (2007).

Kumar and Bhoi, 2009 conducted small-scale model tests on strip footing for three different angles of shearing resistance of soil (ϕ=37.4^0, 41.8^0 and 44.8^0) with unit weights equal to 16.2, 16.7, and 17.2 kN/m^3. Results were found to compare well with the available theories.

Mandel, 1963 and Graham et al., 1984 studied the interference of three parallel strip footings. Mandel, 1963 observed that there was no significant improvement in ultimate bearing capacity when more than two parallel footings were considered. Graham et al., 1984 calculated failure load using the method of stress characteristics. In addition, they concluded that the footing roughness does not have much effect on load carrying capacity or efficiency of the footing.

Lee and Eun, 2009 investigated the effects of multiple footing configurations on their load carrying capacity using finite element analysis and plate load tests with various diameters of circular footing. Results were verified with experimental results from the literature and load response was analysed for different spacing between the footings and footing widths. Correlation parameters and design equations were also proposed. Ghosh and Sharma, 2010 modelled closely-spaced shallow square and rectangular footings to determine interference factor with various parameters like angle of shearing resistance, aspect ratio and spacing between the footings.

The results obtained were found to compare well with Saran and Agarwal, 1974. Results showed that there is no much interference in the case of square footings. Nainegali and Basudhar, 2011 analysed settlements of closely-spaced rectangular footings for various parameters like width, spacing between the footings, length to width ratio, modulus of elasticity variation with depth, etc. using finite element analysis. They considered uniform and linear varying elastic modulus of foundation soil.

Lavasam and Ghazavi, 2013 conducted numerical analysis to model the interference of square and circular footings using Mohr-Coulomb criteria. Failure mechanism under square footings was compared with the mechanism proposed by Golder, 1941. Numerical results showed that the interference of footings had significant influence on failure mechanism and deformation pattern of the soil layer.

Kumar and Saran, 2003 conducted model tests on both strip and square footings to evaluate the interference effect on both reinforced and unreinforced sand layer for various sizes of reinforcement with both continuous and discontinuous reinforcement layers. They studied the tilting effects, for example the amount and direction of tilting, of closely-spaced footings and quantified the improvement achieved by reinforcing the soil. Lavasam and Ghazavi, 2012 conducted experimental investigation to evaluate the bearing capacity, settlement and tilt of the closely spaced square and circular shaped footings on unreinforced and reinforced soil. They concluded that the degree of tilt and settlement can be reduced by increasing the number of reinforcement layer in foundation soil.

Basudhar et al., 2007 conducted both numerical and analytical analyses to determine load-settlement behaviour and compared the results with the experimental study on the circular footing resting on geotextile reinforced semi-infinite layer. Various parameters have been considered, namely, reinforcement arrangement pattern, number of reinforcement layers, bond length, and the effect of relative density, to study its influence on the ultimate load carrying capacity and settlement behaviour of the footing. Results preferred rectangular reinforcement over circular reinforcement and also stated that the equivalent secant modulus, *Es*, increases with number of reinforcement layers and decreases with size of the footing.

It can be concluded from the above literature that the interference factor increases with the decrease in spacing in smooth footings but attains a peak value at critical spacing in case of rough footings. Further, increase in the spacing between the footings decreases the ultimate bearing capacity and reaches a value equal to that of a single footing after certain spacing. It may be noted that many of the above studies mainly dealt with interference of footings resting on semi-infinite sand layer. However, studies on the interference of closely-spaced footings resting on finite layer of sand deposit are very limited. In this study, a series of numerical analyses have been carried out to evaluate the interference between a pair of closely-spaced strip, square, and circular footings on a homogeneous finite and semi-infinite layer of sand deposit.

2. PROBLEM DEFINITION

The objective of the study is to determine the ultimate bearing capacity of closely-spaced footings on both semi-infinite and finite depth of the soil stratum. Interference factors are provided for footings with various spacing and depth ratios. The effect of angle of shearing resistance of the soil is also studied. Strip, square and circular footings are considered for the present study. Both smooth and rough footings are considered in the study.

Two parallel strip footings of same width *B* resting on the surface of soil layer of thickness, *H,* with center to center spacing, *S*, are modelled (Figure 1). The ultimate load carrying capacity of single footing and combined footings for different thicknesses of sand layer below the surface are to be determined. Figures 2(a) and (b) show the PLAXIS 2D model of the smooth and rough strip footing, respectively. Similarly, both square and circular footings are also considered and the geometrical configuration is as shown in Figures 2(c) and (d). Here the diameter of the circular footing is represented as '*D*'.

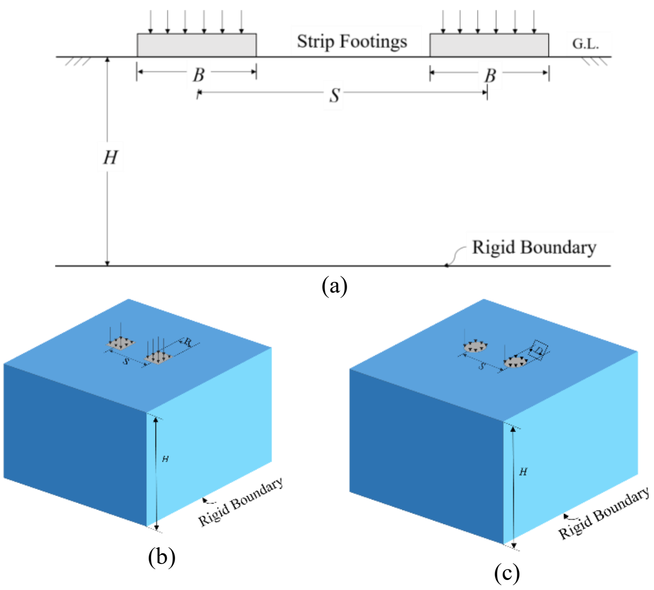


Figure 1: Schematic diagram of the closely-spaced (a) strip (b) square, and (c) circular footings

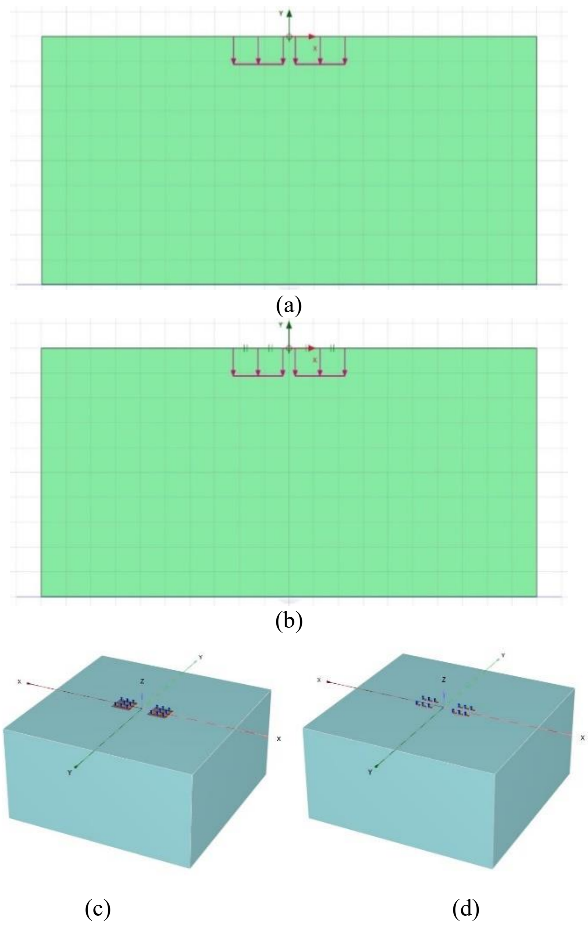


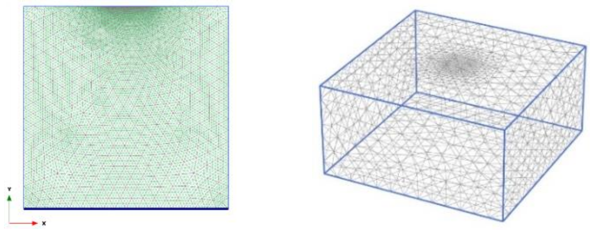
Figure 2: Models of closely-spaced footings: (a) PLAXIS 2D model for the case of smooth strip footings, (b) PLAXIS 2D model for the case of rough strip footing, (c) PLAXIS 3D model for the case of square footings, and (d) PLAXIS 3D model for the case of circular footings

3. MODEL DESCRIPTION

Analysis was carried out using a finite element software PLAXIS 2D and PLAXIS 3D AE (Anniversary Edition). PLAXIS 2D was used to model smooth- and rough-strip footings under plane-strain condition, while PLAXIS 3D was used to model smooth- and rough-square and circular footings.

The default boundary conditions available in PLAXIS, which restrict the horizontal deformations at the side boundaries and both horizontal and vertical deformations at the bottom boundary were used.for the model were activated by fixities in PLAXIS. The extents of boundaries were decided by conducting convergence studies by varying the boundary distances. The model was extended five times the width of the footing in the horizontal direction on both sides so that the boundaries effects on the bearing capacity of the footing are negligible. In the case of semi-infinite depth of soil, the bottom extent of the foundation soil was fixed as five times the width of the footing (5*B*). In the model, sand layer with various depths was simulated. It was observed that with increase of depth of foundation soil beyond 5*B*, the results were not affected. Hence, 5*B* depth was considered as semi-infinite depth. Even the stresses bulbs show that there is negligible stress transferred beyond 5*B* depth.

In order to optimize between the computational time and accuracy, mesh enhancement was used which makes the mesh finer only at the areas of interest. Fine mesh was used in PLAXIS 2D and medium mesh with lower coarseness factor near the footings was used in PLAXIS 3D. Figure 3 shows the mesh configuration of two-dimensional and three- dimensional models.



(a) (b)

Figure 3: Mesh configuration used for (a) PLAXIS 2D model, and (b) PLAXIS 3D model

Convergences for mesh size and boundary distance were firstly carried out. A local coarseness factor of 0.05 was used in PLAXIS 2D with global coarseness as *'Fine'* and for PLAXIS 3D, global coarseness was set to *'Medium'* with local coarseness 0.25. The size of the local mesh was determined by multiplying normal mesh with the local coarseness factor so that it becomes much smaller than the main mesh.

The soil was assumed to follow Mohr-Coulomb model. Table 1 gives the properties of the foundation soil used. The rough footing was simulated by fixing the horizontal movement under the loading area. Footings were loaded simultaneously and were made to settle to the same extent. The effect of tilting was not considered in this study. Loads were applied in displacement-control mode.

Table 1: Properties of foundation soil used

Property	Foundation Soil
Material model	Mohr-Coulomb
Drainage type	Drained
Density, (γ)	16.00 kN/m^3
Elastic modulus (E)	25.00 kPa
Width or diameter of footing (B or D)	2.00 m
Poisson's ratio (υ)	0.30
Cohesion (c)	1.60 kPa
Angle of shearing resistance (ϕ)	30°, 35° and 40°
Overburden pressure (q)	0 kPa

4. RESULTS AND DISCUSSION

4.1 Validation

The present model was validated using Stuart, 1962. Stuart, 1962 had proposed charts of efficiency factors for bearing capacity factors for varying spacing between the foundations. Bearing capacity of the combined footing was calculated using these efficiency factors. Bearing capacity thus obtained was compared with bearing capacity obtained from PLAXIS.

The case of two smooth strip footings resting on semi-infinite soil layer with angle of shearing resistance ϕ=40° was considered. Width of the strip footing was taken as 2m. Figure 4 shows the comparison of results from the present model with Stuart, 1962. The results were found to be in good agreement with Stuart, 1962 with maximum deviation within 7%.

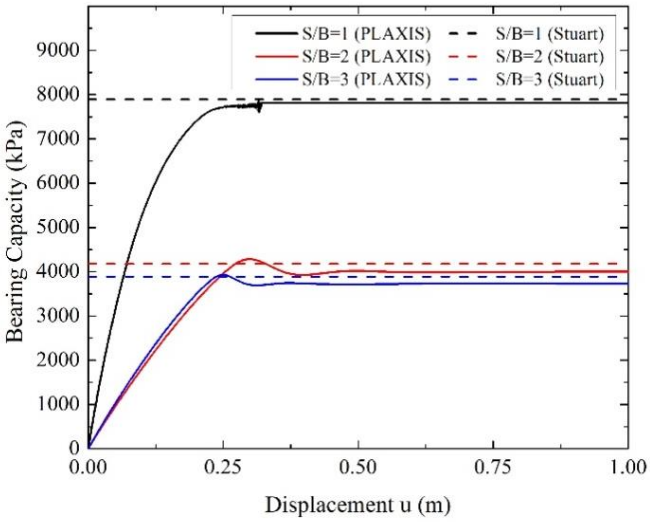


Figure 4: Comparison of bearing capacity of footing from present model with Stuart (1962)

Interference effect on bearing capacity of two closely-spaced strip, square, and circular footings were evaluated for different angles of shearing resistance (ϕ), spacing between the footings (S), and thickness of the finite layer below the footing (H). The results were plotted between interference factors (ξ) and normalized spacing (S/B). Interference factor is defined as the ratio of ultimate bearing capacity of the combined footing $q_{u(combined)}$to twice the ultimate bearing capacity of single footing $q_{u(single)}$for given thickness of foundation soil (H).

$$\text{Interference factor } (\xi) = \frac{q_{u(combined)}}{2 * q_{u(single)}} \quad (5)$$

4.2. Smooth Strip Footing

Figure 5 shows the influence factors for smooth strip footing for various spacing and angles of shearing resistance. In the case of smooth strip footings, interference factors were found to be identical for semi-infinite, and for *H/B*= 3 and 2 for all the angles of shearing resistance of the soil. It was observed that when the depth ratio was decreased from semi-infinite case to *H/B*= 1, the interference factor increases from 1.7 to 1.9 corresponding to angle of shearing resistance ϕ = 40°. This indicates the initiation of interference of adjacent footing on the bearing capacity of the footing for *H/B*=1. Hence, interference effects need to be considered mainly when the depth ratio, *H/B*, is small (of order of one or less). Gradual decrease in interference factors with spacing were observed for all the angles of shearing resistance at all thicknesses of foundation soil.

As the spacing between the footings decreases, the effect of the angle of shearing resistance of foundation soil on the interference factor was found to be significant. A significant reduction in the influence factor was observed when the spacing ratio increases from *S/B*=1 to *S/B*=2. However, the reduction was nominal from *S/B*=2 to *S/B*=3 for all cases. It was observed that rate of reduction in the influence factor was higher for the lower angle of shearing resistance than that for higher angle of shearing resistance of foundation soil.

4.3 Rough Strip Footing

Figure 6 shows the influence factors for rough strip footing for various spacing ratios corresponding to different angles of shearing resistance of the foundation soil. The interference factors for the case of rough footings were found to be much higher than that of smooth footing. In some cases, peak value of interference was observed at *S/B* = 1.25 rather than at *S/B*=1. The results were well compared the results obtained by Mabrouki et al., 2010 with an error of below 10 %. Figure 7 shows the schematic diagram of the failure mechanism at the spacing where the block phenomenon occurs. At this spacing, the footings will act as a single footing. The soil between the footings forms an arch. However, when the spacing between the footing becomes zero, arching effect disappears and act as a single footing with width of 2*B* (Stuart, 1962). This peak was mainly observed in cases of higher angles of shearing resistance of the foundation soil. However, in the cases of lower angles of shearing resistance, the trend was similar to that of smooth footings.

In case of rough footings, the interference factors were found to be same for thickness ratio of foundation soil, *H/B*, higher than 3. However, interference between footings on finite layer was observed from *H/B*=2. After a certain depth ratio, interference due to finite layer dominates the interference due to spacing, not causing the footings to form a *"blocking"* mechanism. The trends for interference factors were similar to that reported by Mabrouki et al., 2010, Das and Labri-Cherif, 1983, Ghazavi and Lavasan, 2008, and Kumar and Kouzer, 2008.

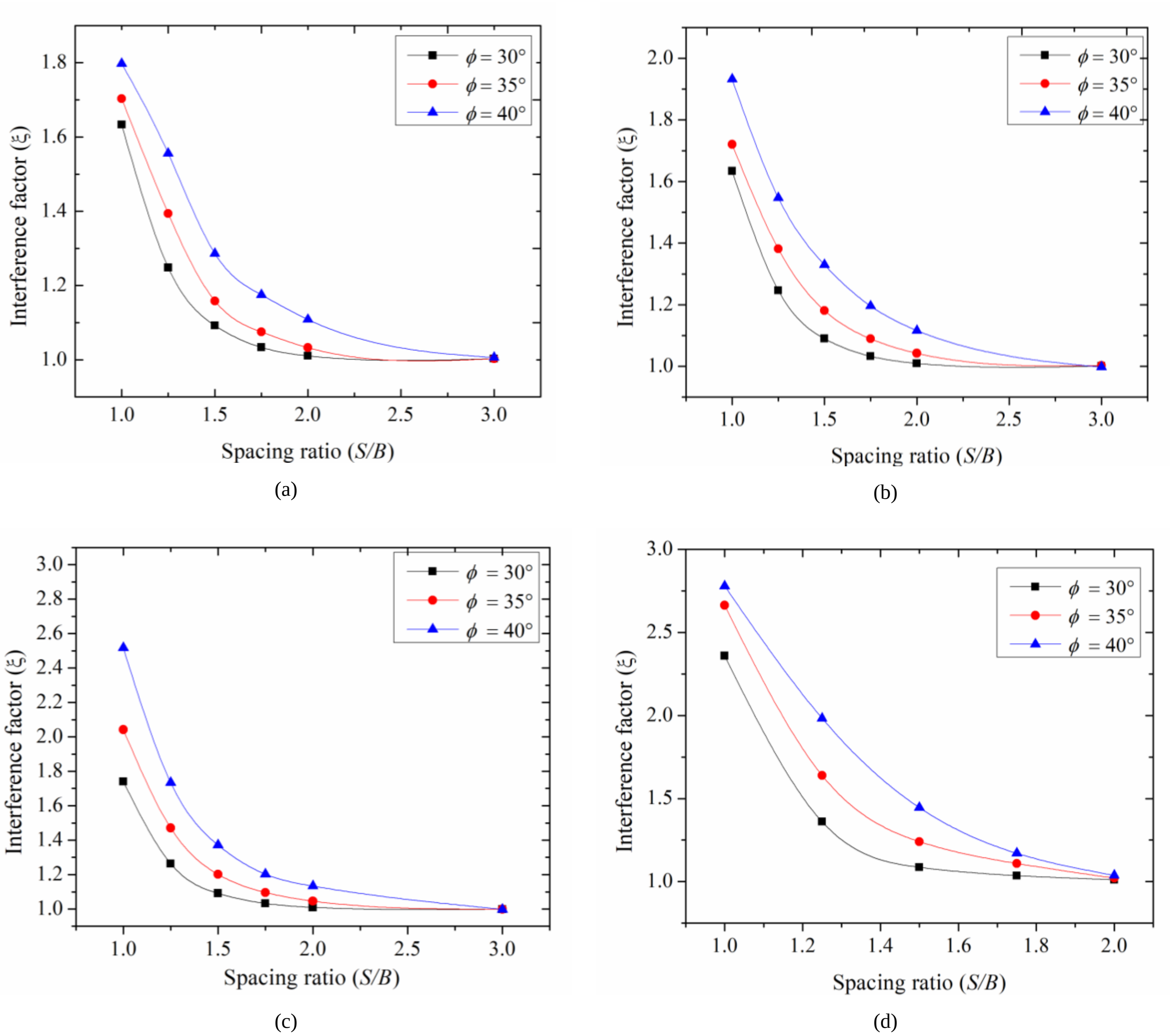


Figure 5: Variation of interference factor with *S/B* ratios for different angles of shearing resistance of sand in the case of smooth footing for (a) semi-infinite, (b) *H/B*=1, (c) *H/B*=0.75, and (d) *H/B*=0.5

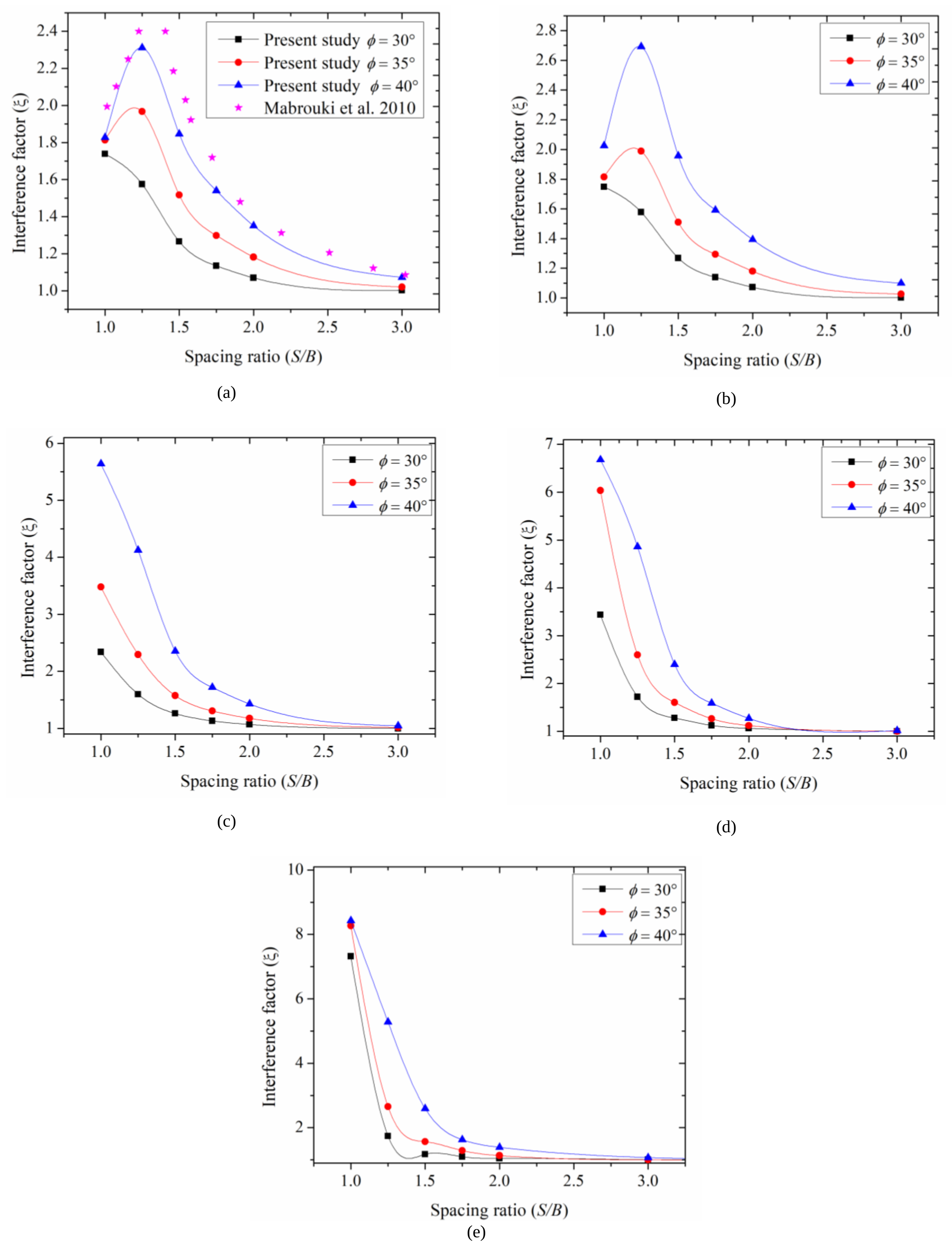


Figure 6: Variation of interference factor with *S/B* ratios for different angles of shearing resistance of sand in the case of rough footing for (a) semi-infinite, (b) *H/B*=2, (c) *H/B*=1, (d) *H/B*=0.75, (e) *H/B*=0.5

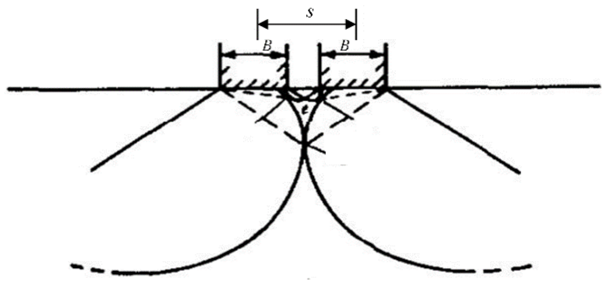


Figure 7: Failure surfaces of closely-spaced rough footings forming "block" (modified after Stuart 1962)

4.4 Mechanism

Figure 8 shows the vertical stress distribution (□$_{yy}$) of two closely-spaced rough footings for spacing ratio *S/B*=1.25 on semi-infinite layer corresponding to footing settlement equal to 20% of *B*. As the spacing between the footings reduces, interference between the footings increases which increases the stress. Interference of stress bulbs was observed to start from *S/B* =2.0. It was observed that at *S/B* = 1.25, the soil was restricted between the footings causing blocking effect, and the increased stress portion can also be observed from the Figure 8. When the spacing between the footings was reduced further less than 1.25, the footings were found to act as single footing.

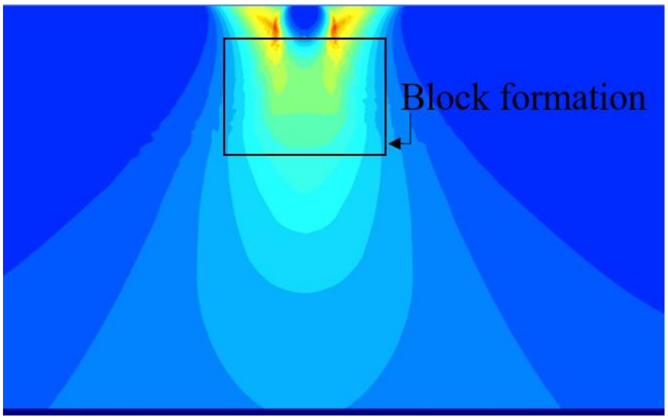


Figure 8: Vertical stress distribution under rough footing for spacing ratio *S/B*=1.25 corresponding to semi-infinite soil layer

Figure 9 shows the contours of vertical stresses for the depth ratio *H/B*=1 corresponding to footing settlement equal to 20% of *B*. The presence of hard stratum at shallow depths increases the stress around it. The stress patterns divert away from the footings. This restricts the formation of *blocking* phenomenon for footings resting on lower depth ratios. Non-formation of the *blocking* phenomenon results in the formation of peak in the interference factor at *S/B*=1 but not at *S/B*=1.25.

4.5 Smooth and Rough Circular Footings

Figure 10 shows the interference factor with *S/B* ratios for different angles of shearing resistance corresponding to smooth and rough circular footings. In circular smooth footing, interference between footings was observed only for *H/B* =0.5 and only for higher angles of shearing resistance of foundation soil. Even in the case of rough footings, interference was significant only for *H/B*=0.5. But the interference factors were higher than that of smooth footing.

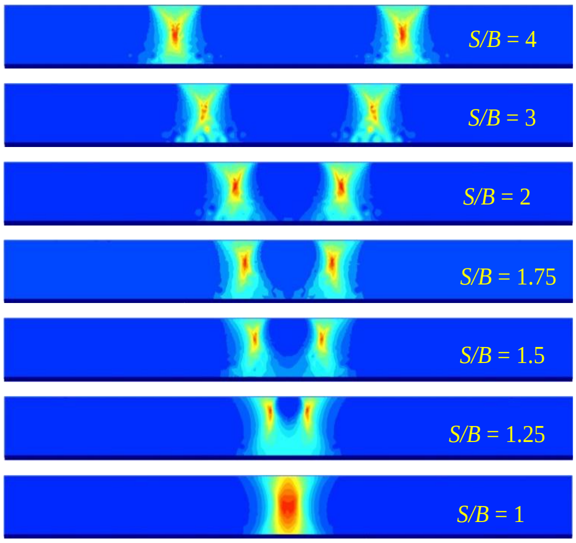


Figure 9: Vertical stress distribution under rough footing for various spacing ratios corresponding to *H/B*=1

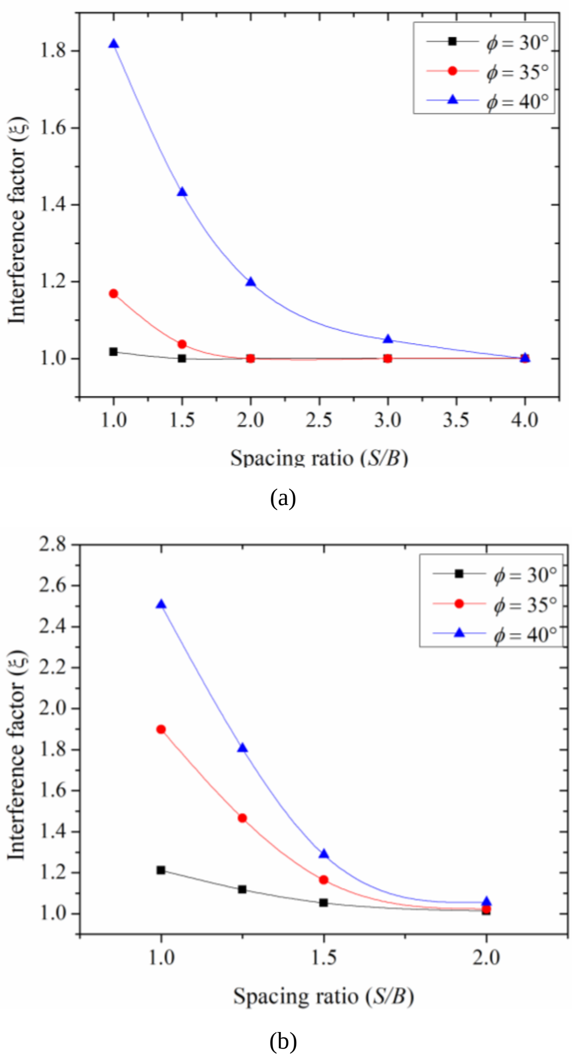


Figure 10: Variation of interference factor with spacing ratios corresponding to *H/B* = 0.5 for (a) smooth, and (b) rough circular footing

4.6 Smooth and Rough Square Footings

Figure 11 shows the interference factor for various *S/B* ratios and angles of shearing resistance in rough square footing. In square smooth footing, interference between footings was insignificant even for small thickness of foundation soil. In the case of rough footing, interference effect was observed only upto the spacing ratio, *S/B*=2.0. Further, there was no interference effect with increase in the spacing.

In the case of strip footing, the stress dispersion is much constrained. However, the stress can be dispersed in all four directions in the case of square and circular footings. This might be reason for the high interference in strip while it is negligible for square and circular footings.

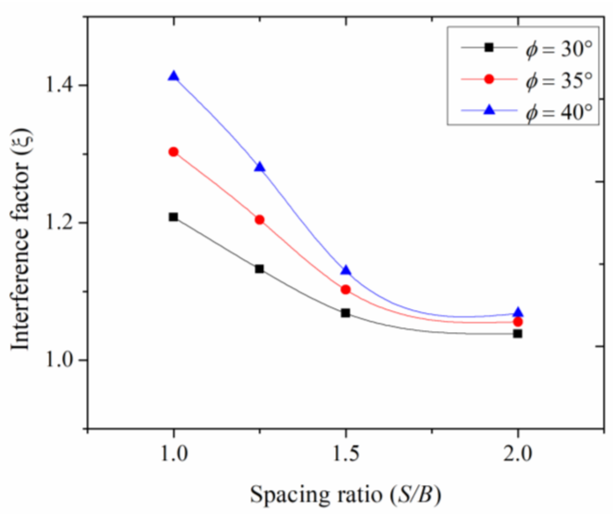


Figure 11: Variation of interference factor with spacing ratio for rough square footing corresponding to *H/B* = 0.5

5. CONCLUSIONS

Interference factors were proposed for various spacings between the footings, and thicknesses of foundation soil. They were proposed for strip, circular, and square footings. Bearing capacity of closely-spaced footing can easily be calculated using the proposed interference factors. The following conclusions can be drawn from the present study.

- Bearing capacity of two closely-spaced footings was more than twice that of individual footing in both smooth and rough strip footings for all the cases considered in the study. However, in the case of circular and square footings, the interference was found to be significant only for low *H/B* ratios (*H/B*<1).
- Interference between the footings was much higher for the case of rough footings compared to that of smooth footings.
- Blocking mechanism was observed for rough strip footings at a spacing ratio, *S/B*, equal to 1.25 where the load carrying capacity of the footing was found to be high.
- Interference factor for various angles of shearing resistance of foundation soil was studied and this factor was found to increase with increase in angle of shearing resistance (ϕ) of the soil.
- Interference between footings was significant for depth ratios less than one (*H/B*<1) and spacing ratios less than two (*S/B*<2) for all the cases studied.
- There was no interference due to spacing in case of square and circular footings resting on semi-infinite layer, but was found to be effective at a depth ratio, *H/B,* equal to 0.5.

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