Indian Geotechnical Journal, 18 (2), 1988

Interference Effect on the Behaviour of Footings

by

G.S. Verma*

Swami Saran**

Introduction

The phenomenon of interference of adjacent footings is of great practical significance as footings in the field are rarely isolated and they interfere with each other to some extent. Due to interference, unequal stress concentrations occur below a footing which cause tilting which changes the behaviour of the footing. A study of interference effect on the bearing capacity, settlement and tilt characteristics of the footings, therefore, acquires importance.

The study of interference between adjacent footings was initiated by Stuart (1962). He developed a theoretical analysis to examine the interference effect of two parallel strip footings placed on cohesionless soil. Mandel (1963) investigated this problem by taking footings on either side of a central footing making it more general. West and Stuart (1965) analysed this problem to find eccentricity and inclination due to interference. Agarwal (1970) investigated experimentally the interference effect for both strip and rectangular footings on cohesionless soil. Singh, Punmia and Ohri (1973) conducted an experimental study on cohesionless soil at relative density of 80 percent to get interference effect of two adjacent smooth square footings. Saran and Agarwal (1974) studied this problem by conducting both two and three dimensional tests on cohesionless soil, at a relative density of 75 percent. In all the above tests both the footings were of equal width and were loaded simultaneously by equal amount. According to these studies the effect of interference of footings is to cause an increase in bearing capacity and decrease in settlement with reduction of spacing. Myslivec and Kysela (1973) conducted model tests on sand for various distances, depths and widths of both foundations. The results show increase in bearing capacity with decrease in spacing and increase in depth. The results also show that if the investigated foundation is deeper than the neighbouring foundation, its

---

*Research Scientist 'B', Deptt. of Civil Engg., University of Roorkee, Roorkee-247667.

**Professor, Deptt. of Civil Engg, University of Roorkee, Roorkee.

(*This modified paper was received in January* 1988 *and is open for discussion till the end of July* 1988)

ultimate load is higher than what it would be if the foundation is separate. On the other hand if the investigated foundation is shallower than the neighbouring foundation, its load bearing capacity is lower than that of the separate foundation. Dash (1982) analysed this problem for surface strip footings on $C-\phi$ soil. He considered one of the footings to be existing and loaded to its safe bearing pressure and then determined the ultimate bearing capacity of the other adjacent newly constructed footing. His results show considerable increase in load carrying capacity of a newly constructed footing due to the presence of an adjacent existing footing.

It was observed that the above investigators, in general, investigated the interference effect on sand in terms of bearing capacity and settlement and not studied the important aspect of the tilt of the footing. Secondly very meagre data is available on interfering footings on clay.

In the present analysis the effect of interference between two adjacent surface strip footings have been studied using constitutive laws of soils. A methodology has been developed to predict the pressure-settlement and pressure-tilt characteristics of such footings resting on sand or clay.

Constitutive Laws

General

Constitutive laws defines the stress-strain behaviour of soil. Since the behaviour of soil over a wide range of stresses is non-linear Kondner's (1963) hyperbolic function as given in equations (1) and (2) has been used in the analysis.

$$\frac{\varepsilon}{\sigma_1-\sigma_3} = a+b\varepsilon \quad \dots (1)$$

or

$$\varepsilon = \frac{a(\sigma_1-\sigma_3)}{1-b(\sigma_1-\sigma_3)} \quad \dots (2)$$

where, ϵ = axial strain

a,b = constants of hyperbola

σ_1, σ_3 = major and minor principal stresses respectively.

For demonstrating the methodology developed in subsequent sections two types of soils have been considered, namely (*i*) Buckshot clay and (*ii*) Ranipur sand.

Buckshot Clay

Some of the important properties of Buckshot clay reported by Carrol (1963) are given below in Table 1.

TABLE 1

Properties of Buckshot Clay

Liquid limit	55 to 70 percent
Plastic limit	20 percent
Moisture content	33.2 percent
Poisson's ratio (μ)	0.375
Undrained shear strength	0.072 N/mm^2

The ratio of the ultimate strength in hyperbolic representation to the actual failure strength was obtained as 1.10. The undrained triaxial test results show negligible influence of confining pressure on tangent modulus E_i $(=1/a)$ and shear strength σ_u $(=1/b)$. The average value of b/a was found to be 142 from the plot of b/a versus moisture content at various confining pressures.

Ranipur Sand

Analysis was done using the characteristics of Ranpur sand, (D_{10} =0.15 mm, C_u = 1.73, D_r = 75 percent, ϕ = 41°), Sud (1984).

Stress-strain relations were obtained at different confining pressures. From these relations it was found that the parameters a and b are dependent on confining pressure and are represented as below

$$\frac{1}{a} = 0.575 + 147.6\ \sigma_3 \qquad \ldots(3)$$

$$\frac{1}{b} = 0.205 + 1.63\ \sigma_3 \qquad \ldots(4)$$

In these relations putting the value of σ_3 in N/mm^2 gives the values of $\frac{1}{a}$ and $\frac{1}{b}$ in N/mm^2.

Theoretical Analysis

Assumptions

The following assumptions are made in the analysis :

1. The soil mass is a semi-infinite, elastic and isotropic medium.
2. Interference is considered between two fully flexible strip footings. Both the footings are loaded with equal load intensities.

3. The whole soil mass supporting the footings is divided into a large number of thin horizontal strips (Figure 1).

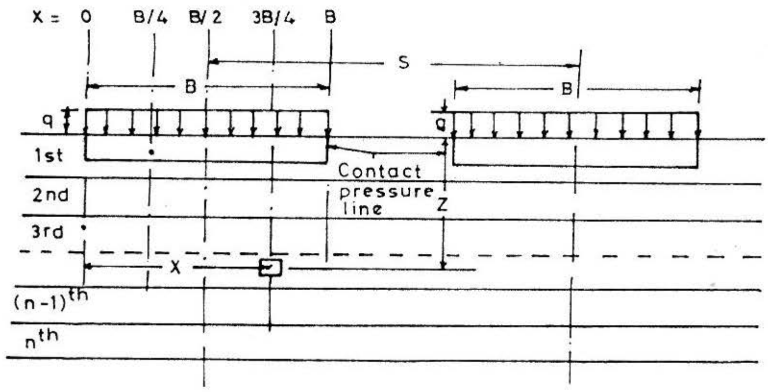

FIGURE 1 Content Pressure Diagrams and Soil Below Footings Divided in Layers

4. The stresses in each layer are computed using Boussinesq's theory since the stress equations for various types of loads are available. The strains are computed from the known stress conditions using constitutive laws.

5. There is no slippage at the interface of layers of the soil mass.

General Procedure

The general procedure for the evaluation of pressure-settlement and pressure-tilt characteristics of two interfering footings is described in following steps:

1. For a given intensity of pressure and spacing of footings, the contract pressure distribution at the interface of footings bases and supporting soil is assumed as shown in Figure 1 which induces stresses in the soil.

2. The soil mass supporting the footings has been divided into large number of thin strips as shown in Figure 1.

3. The horizontal, vertical and shear stresses given by Eqs. (5), (6) and (7) respectively are computed at the centre of each layer, by superimposing the stresses due to both the footings, at five vertical sections through $\times = 0$, B/4, B/2, 3B/4 and B (Figure 1). From these stresses principal stresses and their directions with respect to the vertical z-axis are determined.

$$\sigma_x = \frac{q}{\pi} \{\alpha - \sin \alpha \cos (\alpha + 2\delta)\} \qquad \ldots (5)$$

$$\sigma_z = \frac{q}{\pi} \{\alpha + \sin \alpha \cos (\alpha + 2\,\delta)\} \qquad ...(6)$$

$$\tau_{xz} = \frac{q}{\pi} \{ \sin \alpha \sin (\alpha + 2\delta)\} \qquad ...(7)$$

4. Strip footings representing the plane strain condition, after simplifying the expressions for principal strains, we get.

$$\frac{\varepsilon_3}{\varepsilon_1} = \frac{\sigma_3 - \mu_1 \sigma_1}{\sigma_1 - \mu_1 \sigma_3} = -\mu_2 \text{ (say)} \qquad ...(8)$$

where, ϵ_1, ϵ_3 = major and minor principal strains respectively

$$\mu_1 = \frac{\mu}{1 - \mu} \qquad ...(9)$$

μ = Poisson's ratio

Value of μ was obtained directly through laboratory tests in clays. For sands its value is taken as follows:

$$\mu = \frac{K_o}{1 + K_o}$$

in which $K_o = 1 - \sin \phi$

where, K_o = coefficient of earth pressure at rest

ϕ = angle of shearing resistance of soil

5. The strain in the direction of major principal stress is computed from constitutive relations as given below

$$\varepsilon_1 = \frac{a' (\sigma_1 - \sigma_3)}{1 - b'(\sigma_1 - \sigma_3)} \qquad ...(10)$$

where, $a' = a(1 - \mu^2)$ and $b' = 1.1 \times b$

Values of a and b are taken from constitutive relations. As indicated earlier, computations have been made for Buckshot clay and Ranipur sand by picking the values of a and b from the earlier section. Since in the case of sand, parameters a and b are dependent on confining pressure, an average value of these have been utilized in the analysis. Averaging is done for confining pressure variation upto the depth equal to ten times the width of footing. The strain in the minor principal stress direction is given by

$$\epsilon_3 = -\mu_2 \epsilon_1 \qquad ...(11)$$

6. The strain in the vertical direction (ϵ_z) for each layer is computed using the following expression

$$\epsilon_z = \epsilon_1 \cos^2 \theta_1 + \epsilon_3 \cos^2 \theta_3 \qquad ...(12)$$

where θ_1 and θ_3 are the directions of the principal strains with respect to the vertical axis.

7. The vertical settlement, s, of any layer is computed by multiplying the strain ϵ_z with the thickness of each layer, δ_z.

$$s = \epsilon_z . \delta_z \qquad ...(13)$$

The total settlement (S_t) along any vertical section is computed by numerically integrating the above expression

$$S_t = \sum_{i=1}^{n} \varepsilon_z . dz \qquad ...(14)$$

The total settlement was computed along five vertical sections as stated earlier.

8. The tilt (t) of footing is calculated from the following equation.

$$\text{Sin } t = \frac{S_B - S_o}{B} \qquad ...(15)$$

where, S_B = settlement at section X = B

S_o = settlement at section X = O

and B = width of the footing

9. If the tilt as computed in the above step is negative or zero then the average settlement is computed by dividing the area of settlement diagram by width of the footing.

10. If the tilt as computed in the above step is positive then the analysis is revised for computing average settlement by taking a single footing of equivalent width viz. sum of two footings width plus the clear spacing between the footings, for reduced pressure intensity. This reduced pressure intensity is taken equal to the total load on two footings divided by the equivalent width of footings. Now the average settlement is computed as above. This average settlement is considered equivalent to the above two inrerfering footings with the actual intensity of pressure.

11. The average settlement for various pressure intensities on footings is computed by repeating steps 1 to 10.

12. Steps 1 to 11 are repeated for different centre to centre spacings between the footings.

13. Average surface load intensity versus average settlement curves are drawn.

Interpretation and Results

Footings in Clay

General: Taking both the footings of width 250 mm tilts and average settlements were computed, using the above described analysis, corresponding to different pressure intensitives varying from 0.025 N/mm^2 to 0.20 N/mm^2, for centre to centre spacings of B, 1.5B, 2B, 3B, 4B, 6B and also for isolated footing. Similar exercise was done for footings of widths 500 mm and 1000 mm.

Tilt: Tilt of the footings have been computed using Eq. (15) and are given in Table 2.

It is evident from the table that direction of tilt depends on (*i*) spacing and (*ii*) stress intensities on the footings. As spacing increases, positive tilt occurs at smaller pressure intensities. In this case it was found that the soil between the two footings is stressed in such a way that this soil moves alongwith the two footings. In other words this part of soil acts as a part of footings. This type of phenomenon is termed as 'block action'. Keeping this in view during positive tilting, the analysis is revised by considering the two footings alongwith the part of soil between the footings as the single footing loaded with reduced pressure intensity. This reduced pressure intensity is equal to the total load acting on the two footings divided by the sum of the two footings width plus the clear spacing between the footings. In case of negative tilting both the footings behave independently and hence no revision is made.

Pressure-settlement Curves : For convenience pressure-settlement curves were plotted as ratio of average settlement to width of the footing versus pressure intensity for above mentioned spacings between the footings for footings of width 250 mm, 500 mm and 1000 mm. It was found that for a particular spacing a single curve is obtained for all footing sizes. Figures 2 and 3 show typical pressure-settlement curves for centre to centre spacings of 1, 1.5, 2, 3, 4 and 6 times the width of the footing.

Ultimate bearing capacity : The ultimate bearing capacity has been determined corresponding to the settlement equal to 5 percent (Sharan, 1977) of the width of the footing from pressure-settlement curves. The plot of ultimate bearing capacity versus ratio of spacing to width of footing is shown in Figure 4.

TABLE 2

Tilt (in degree) of Two Smooth Flexible Interfering Strip Footings Resting on Buckshot Clay

Spacing/ Width S/B	Pressure Intensity q(N/mm²)							
	0.025	0.050	0.075	0.100	0.125	0.150	0.175	0.200
1	0.095	0.238	0.448	1.076	5.117	15.273	28.076	44.028
1.5	0.043	0.089	0.129	0.014	−0.856	−4.587	−8.993	−7.200
2	0.025	0.047	0.057	−0.015	−0.758	−3.475	−7.944	−14.04
3	0.012	0.018	0.011	−0.038	−0.410	−1.759	−3.961	−6.940
4	0.006	0.007	−0.0011	−0.034	−0.232	−0.969	−2.198	−3.895
5	0.0002	−0.002	−0.009	−0.028	−0.108	−0.374	−0.860	−1.557

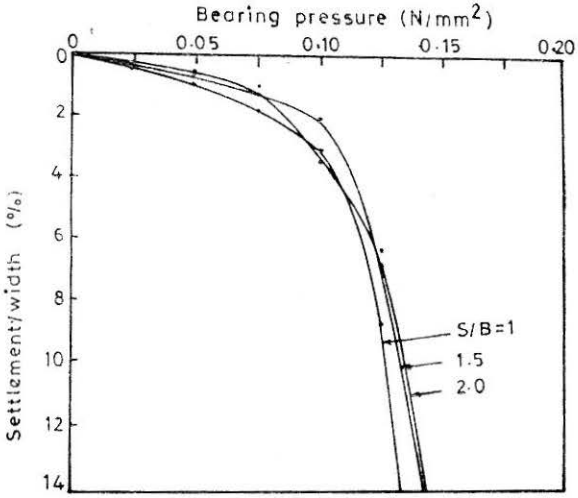

FIGURE 2 Pressure vs Average Settlement/Witdh for Two Smooth Flexible Interfering Footings Resting on Buckshot Clay

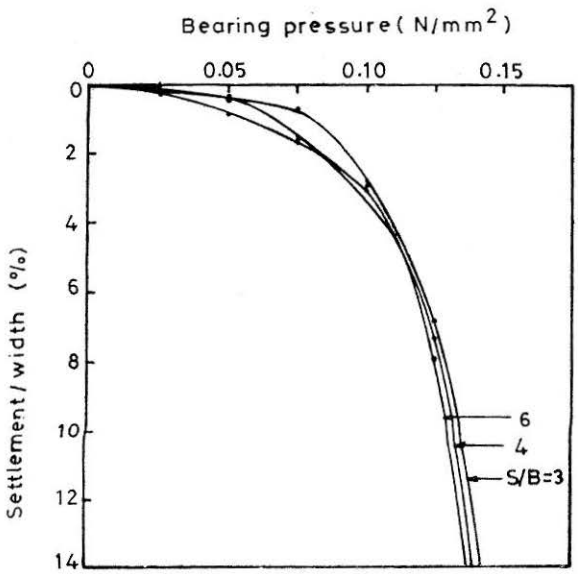

FIGURE 3 Pressure vs Average Settlement/width Curves for Two Smooth Flexible Interfering *Strip Footings* Resting on *Buckshot Clay*

It is observed from Figure 4 that, in general the ultimate bearing capacity of the footing due to interference increases as they come closer. The greatest increase (at S/B = 1.4) amounted to 4.44 percent of the ultimate bearing capacity of an isolated footing. If the spacing is less than 1.4 times the width of the footing then ultimate bearing capacity reduces and finally

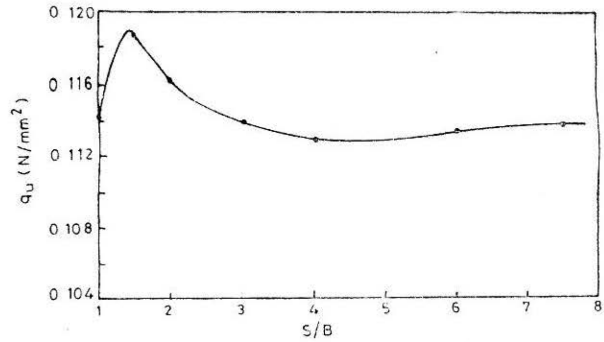

FIGURE 4 Ultimate Bearing Capacity vs S/B for Two Smooth Flexible Interfering Strip Footings Resting on Buckshot Clay

becomes equal to that of an isolated footing when they touch each other. At S/B = 4.2 the lowest value of ultimate bearing capacity is obtained which is about 0.66 percent less than that of an isolated footing. Beyond centre to centre spacing of about five times the width of footing there is no significant effect of interference on the ultimate bearing capacity. It is clear from the above discussion that for strip footings on the surface of clay, the change in ultimate bearing capacity is insignificant as they approach each other. This may be attributed to the fact that no change of void ratio occurs in saturated clays under short term loading.

Tilt at failure : Tilt at failure for different spacing to width ratio is plotted in Figure 5. The curve shows that tilt at failure increases as the footings approach each other and becomes maximum when the spacing is about 1.5 times the width of the footing. As the block action starts at S/B = 1.42 the tilt suddenly drops down to zero at this spacing.

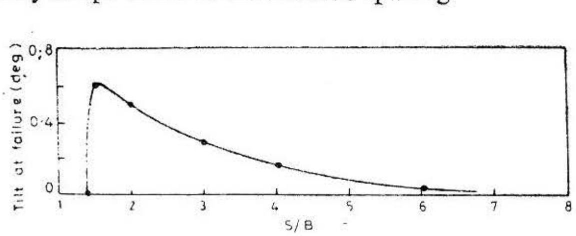

FIGURE 5 Till at Failure vs S/B for Two Smooth Flexible Interfering Strip Footing Resting on Buckshot Clay

Footings in Sand

General : The tilts and average settlements of two smooth flexible interfering strip footings each of width 250 mm resting on Ranipur sand at relative density of 75 percent and for centre to centre distance varying from B to 6B and also for isolated footing were obtained for the range of surface load intensity of 0.1 N/mm² to 1.0 N/mm² in a similar manner as in the case of footings in clay.

Tilt : The tilt of the footings were obtained in a similar manner as described earlier and the trend was also same. Details are given elsewhere (Verma, 1986).

Pressure-settlement curve : Pressure versus average settlement curves for the above footings were plotted for S/B equal to 1, 1.5, 2, 4, 5 and 6 and also for isolated footing. Figure 6 shows typical curves for S/B equal to 1 and 1.5. Details are given elsewhere (Verma, 1986). These curves were utilised for computing ultimate bearing capacity.

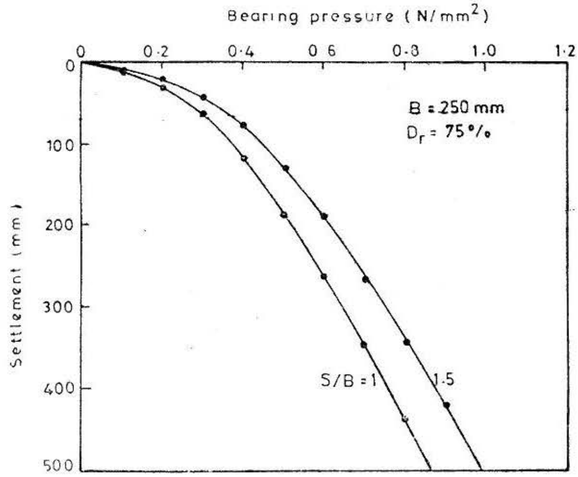

FIGURE 6 Pressure Vs Average Settlement for Two Smooth Flexible Interfering Strip Footings Resting on Ranipur Sand

Ultimate bearing capacity : Taking 50 mm as allowable settlement for footing of width 2000 mm the allowable settlement (S_p) is computed for footings of different width (B_p) from the following relation

$$\frac{S_f}{S_p} = \left[\frac{B_f\,(B_p+300)}{B_p\,(B_f+300)} \right]^2 \qquad \ldots (16)$$

where, S_f = settlement for footing of width B_f

S_p = settlement for footing of width B_p

In Eq. (16) the width B_p is taken as width of individual footing if no block action takes place and equal to equivalent width of the footings i.e. width of two footings plus the clear spacing between the footings if block action takes place. The ultimate bearing capacity was determined corresponding to the allowable settlement (S_p) as computed above from the pressure-settlement curves for different spacings between the footings. Figure 7 shows the variation of ultimate bearing capacity with respect to S/B ratio.

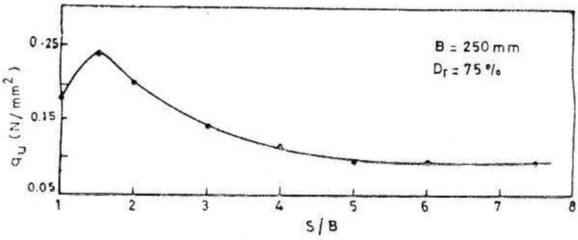

FIGURE 7 Ultimate Bearing Capacity Vs S/B for Two Smooth Flexible Interfering Strip Footings Resting on Ranipur Sand.

It is observed from Figure 7 that ultimate bearing capacity increases as the footings approach each other. The greatest increase of the ultimate bearing capacity of a pair of foundations amounted to 184.44 percent at S/B = 1.5. If the spacing is less than 1.5 times the width of the footing the ultimate bearing capacity reduces and finally becomes equal to twice that of an isolated footing when the footings touch each other. It may be due to the fact that relative density of sand increases on imposition of more stresses. The lowest value of ultimate bearing capacity is obtained at S/B = 5 which is 1.79 percent less than that of an isolated footing. The ultimate bearing capacity value is not significantly affected beyond the centre to centre spacing of about 4.5 times the width of footing.

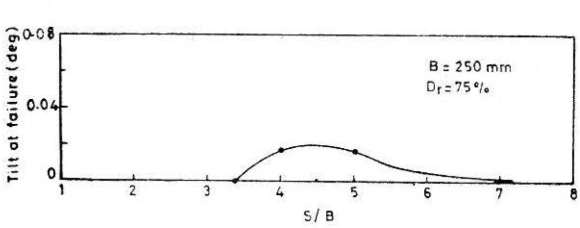

FIGURE 8 Tilt at Failure Vs S/B for Two Smooth Flexible Interfering Strip Footing Resting on Ranipur Sand

Tilt at failure : Tilt at failure was plotted in Figure 8 for different spacings. The curve shows that below S/B = 3.35 the tilt at failure is zero. The reason may be attributed to the block action. If S/B is increased from 3.35 then tilt at failure increases becoming maximum at about S/B = 4.5 and then decreases on further increase in spacing and finally becomes equal to zero.

Comparison

The comparison of predicted ultimate bearing capacity values has been made with the experimental values of Agarwal (1970) by plotting them in nondimensional form in Figure 9. The experimental test data is available only for S/B $\geqslant$ 2.5. It is evident from Figure 9 that the trend of the two curves is the same. There is no experimental data available for clays.

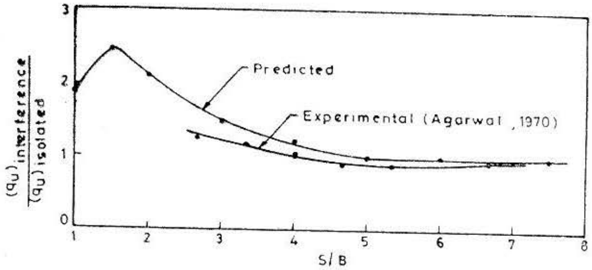

FIGURE 9 Comparison of Predicted Bearing Capacity Values with Agarwal's (1970) Values

Conclusions

Analytical procedures have been given in this paper using non-linear stress-strain behaviour of soil, reflecting more closely the actual behaviour in the field, to predict the behaviour of two smooth interfering surface strip footings resting on clay as well as sand.

The interference does not have significant effect on ultimate bearing capacity of clay while there is significant increase in ultimate bearing capacity of sand due to interference effect of two smooth flexible strip footings as they approach each other. An increase of about 184.44 percent (at S/B =1.5) have been found in case of sand.

Tilt at failure increases due to interference with decrease in spacing both in case of clay as well as sand upto certain spacing and then decreases and becomes equal to zero at spacing at which block action starts taking pla ce.

One of the significant findings from the present studies is that the *allowable load on interfering footings should not* be based on shear and settlement considerations alone, but, also on allowable tilt.

References

AGARWAL, V.C. (1970), "Effect of Surface Footings on Sand", *M.E. Thesis*, University of Roorkee, Roorkee.

CARROL. W.F, (1963) : Dynamic Bearing Capacity of Soils, *Technical Report No.* 3-599, *U.S. Army Engineers, Waterways Experiment Stations*, Corps of Engineers, Vicksburg, Mississippi.

DASH, P.K., (1982) : "Effect of an Existing Footing on the Load Carrying Capacity of a Foundation", *Ind. Geotech. Jr.*, 12 : 2 : 160-165.

KONDNER, R.L., (1963), : ("Hyperbolic Stress-Strain Response of Cohesive Soils," *Proc.* of ASCE, *Journal of* SMFE, 89; SM 3; 115-143.

MANDEL, J., (1963) : "Interaction Plastique de Foundations Superficielles," *Proc. Int. Conf.* on SMFE, Budapest.

MYSLIVEC, A. and KYSELA, Z., (1973): Interaction of Neighbouring Foundations, *Proc. of 8th Int. Conf.* on SMFE, Mockba, USSR, 1: 3 : 181-184.

SARAN, SWAMI and AGARWAL, V.C., (1974) : "Interference of Surface Footings in Sand," *Ind. Geotechnical Journal.*, 4 : 2 : 129-139.

SHARAN, U.N., (1977) : "Pressure Settlement of Characteristics of Surface Footings from Constitutive Laws", Ph D. *Thesis,* University of Roorkee, Roorkee.

SINGH, A., Punmia, B.C. and OHRI, M.L., (1973): "Interference Between Adjacent Square Footings on Cohesionless Soil", *Indian Geotechnical Journal.* 3 : 4: 275-284.

STUART, J.G., (1962): "Interference Between Foundations, With Special Reference to Surface Footings in Sand." *Geotechnique* 12: 1 : 15-22.

SUD, V.K., (1984): "Behaviour of Shallow Foundations Adjacent to Slopes." Ph. D. *Thesis,* University of Roorkee, Roorkee.

VERMA, G.S., (1986): "Interference Effect on the Behaviour of Footings," M.E. *Thesis,* University of Roorkee, Roorkee.

West, J.M. and Stuart, J,G, (1965); "Oblique Loading Resulting from Interference Between Surface Footings on sand," *Proc. of the Sixth Int. Conf.* on SMFE, Canada (Montreal), II : 214-217.

Notations

a = Constant of hyperbola

a' = A constant

B = Width of footing, mm

b = Constant of hyperbola

b' = A constant

c = Cohesion, N/mm²

E_i = Initial tangent modulus, N/mm²

K_o = Coefficient of earth pressure at rest

q = Load intensity, N/mm²

S = Centre to centre spacing between the two footings, mm

S_B = Settlement at section $\times$ = B, mm

S_o = Settlement at section $\times$ = O, mm

S = Total settlement of 'n' layers, mm

t = Tilt

α = Angle subtended at depth Z by the footing

γ = Unit weight of soil

θ_1 = Inclination of major principal stress with respect to Z axis

θ_3 = Inclination of minor principal stress with reference to Z axis

δZ = Thickness of horizontal layer of soil , mm

ϕ = Angle of shearing resistance of soil, degree

σ_1 = Major principal stress, N/mm^2

σ_3 = Minor principal stress, N/mm^2

σ_u = Ultimate compressive strength in hyperbolic representation, N/mm^2

ϵ = Strain

ϵ_z = Strain in the vertical z direction

ϵ_1 = Major principal strain

ϵ_2 = Intermediate principal strain

ϵ_3 = Minor principal strain

μ = Poisson's ratio

μ_1, μ_2 = Ratios