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BEARING CAPACITY AND SETTLEMENT OF TWO INTERFERING FOOTINGS ON SAND

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Abstract

Calculation of the bearing capacity and settlement of a foundation is usually carried out by conventional methods, only applicable to isolated footings. In practice, footings are rarely isolated, thus the phenomenon of foundation interference is of great practical interest.

The investigation reported herein envisaged experimental study of the interference effect of two adjacent footings, subjected to vertical concentric loads, and resting on cohesionless soil. The test results show significant effect of the spacing between footings on the bearing capacity of these footings. In addition, remarkable influences of the foundation shape, the aspect ratio of the footing, restraining footing against tilting, and soil density were explored.

1. Introduction

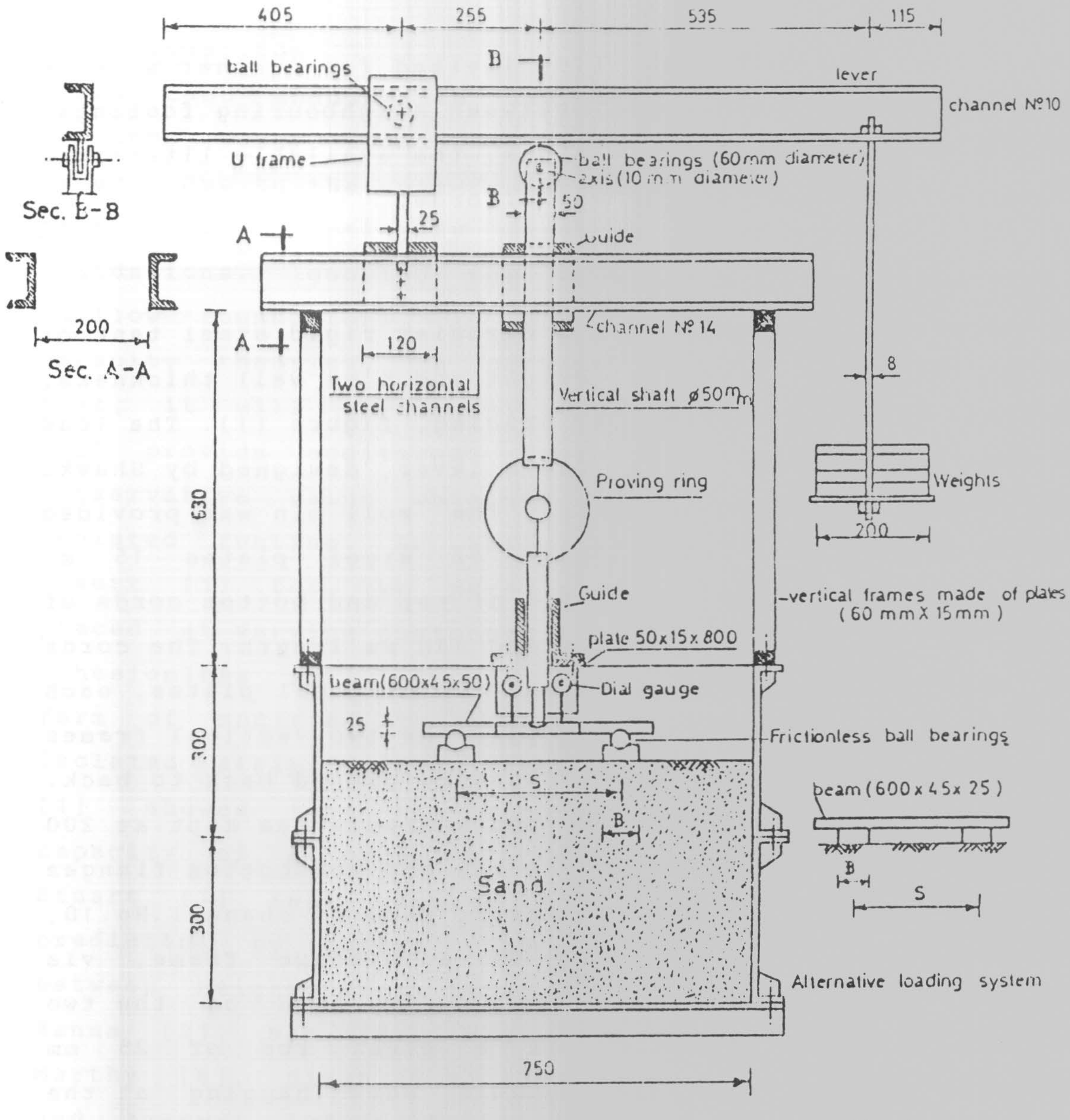
Significant changes in the ultimate bearing capacity of footings occur when they are placed at close spacing in a group, due to the soil-foundation interaction process. This problem is practically important in both deep and shallow foundations. Ignoring the phenomenon of interference of shallow foundations, in most of the conventional bearing capacity theories, is perhaps due to the understanding that, it will give results on the safe side and therefore will provide additional factor of safety on the already conservative value obtained by applying the theory of an isolated footing. An analytical study was first done by Staurt [1] for two parallel interfering strip footings placed at varying distances from each other, and resting on cohesionless soil. Stuart [1] obtained his theory in the form of modified Terzaghi's bearing capacity equation for isolated strip footings. However Stuart's experimental work [1] showed that his theory overestimates the bearing capacity of a group of two strip footings. Nevertheless Stuart [1] test results follow a simillar trend as that predicted by theory. The problem of the interference between neighbouring foundations was studied further by Hanna [2], Rao [3], West and Stuart [4], Agarwal [5], Murthy [6], Singh et al [7], Myslivec and Kysea [8], Swami and Agarwal [9], Deshmukh [10], and Abdrabbo [11]. Most of these authors have studied the problem, experimentally, with reference to a strip footing. Few of them used rectangular and square footings. Some of these investigations concerned simultaneous loading of the neighbouring footings, Murthy [6].

Stuart [1] and Deshmukh [10] invited for further work on the interaction phenomenon between neighbouring footings; but in spite of these invitations, the available literature indicates that no attention was afforded.

2. Test equipment

The tests were performed in a circular rigid steel tank of 750 mm diameter, 600 mm height and 5 mm wall thickness, provided with circumferencial bracing, figure (1). The load was applied incrementally via a lever, designed by Shawki [12], using standard weights. The soil bin was provided with two vertical frames made of steel plates 15 mm thick. Each frame consisted of top and bottom cords of 15 mm by 60 mm cross section and 530 mm length. The cords were attached to two vertical and two diagonal plates, each of 15 mm by 60 mm cross section. The two vertical frames carried two horizontal steel channels placed back to back. The clear distance between the two channels was kept at 200 mm using steel strips welded to the top and bottom flanges of the channels. The loading lever, made of channel No.10, was supported at one end on a u-shape frame, via frictionless ball bearings, seated in turn on the two horizontal steel channels via a steel rod of 25 mm diameter, whereas standard weights were hanging at the other end.

The load was transmitted to the footing via a vertical circular steel rod, 50 mm diameter, guided at two levels. The top guide was fixed on the two horizontal steel channels, whereas the bottom guide beared on two steel plates, 50 mm x 15 mm cross section, fixed to the edge of the soil bin. The internal diameter of the two guides was



Dim in mm.

Figure (1) Layout of the test apparatus, after shawki (1988)

50.0125 mm. To minimize the friction effects, the lever was attached to the vertical shaft via frictionless ball bearings. To measure the applied load, the vertical shaft was provided with a calibrated proving ring of 25.74 N/Division accuracy. The load was transmitted to the interfering footings through a horizontal steel beam of 600 mm length and 45 mm by 25 mm cross section, the horizontal steel beam in turn was placed in complete contact directly to the surface of the footings. In this case of loading, the footings are restrained against rotation, and exhibited only vertical displacements. Therefore, the loading tests simulate the case of two interfering footings connected together with a rigid ground beam. In few loading tests, on strip footings, the footings were allowed to rotate by providing frictionless ball bearings between the footings and the horizontal steel rigid beam. The loads were applied centrally with respect to the two footings within an accuracy of ± 0.5 mm.

The vertical steel rod used for transmitting the load from the lever to the footings through the guide system was kept, always, precisely vertical using a spirit level. The clearance between the guide holes and the loading rod is 0.0125 mm. The top and bottom guides have the facilities to move laterally to ensure, precisely, the verticality of the applied loads. Also, the two horizontal steel channels were erected horizontally on the top of vertical frames using shim.

The footing models which were machined from mild steel plates, 25.4 mm thick, were circular with diameter of 100 mm, square and strip of 45 mm width; the length of strip footing was 300 mm. The error in measuring the footing dimensions did not exceed ± 0.5 mm. The two footings were placed, perpendicular to the direction of the loading beam i.e. plane of loading using a steel ⊥ square. The spacing between the two footings was measured to an accuracy of ± 0.5 mm.

The settlements of the two interfering footings were observed using four dial gauges of 0.002 mm accuracy fixed rigidly to a rigid reference beam with the tips of each two of them resting on one of the two footings.

Table 1 - characteristics of the sand

Mean grain size	$d_{50} = 0.48$ mm
Degree of uniformity	$\frac{d_{10}}{d_{50}} = 0.375$
	$\frac{d_{15}}{d_{85}} = 0.35$
Effective grain size	$d_{10} = 0.18$ mm
Specific gravity of solids	$Gs = 2.67$
Minimum unit weight	$\gamma_d = 14.62$ KN/m^3
Maximum unit weight	$\gamma_d = 17.85$ KN/m^3

The angle of shearing resistance of sand was measured using both triaxial and shear box apparatus. Unconsolidated undrained triaxial tests were performed at different relative densities. Triaxial tests were run with three different cell pressures and a common tangent was drawn as nearly as possible through the origin. Triaxial test results indicated that, the angle of shearing resistance was 44° at a relative density of 92%, whereas an angle of

33.5^{o} was obtained at a relative density of 38%. Angles of shearing resistance of 40.5^{o} and 32^{o} were obtained, using direct shear box apparatus, at sand relative densities of 68% and 38% respectively. This confirmed Hanna's results [13] reporting that the angle of shearing resistance measured in a shear box apparatus was 10.4% higher than the one obtained from triaxial test for the dense sand (Dr=69%); whereas, the two values were almost equal in the case of loose sand ($Dr \leq 46.5$). The sand beds were prepared by laying air-dried silica sand in layers, each 50 mm thick, compacted manually utilizing a hammer weighing 35 N. The grain size of the sand varied between 1.14 mm and 0.08 mm; 60% by weight of the sand grains were of medium size according to British specifications. The maximum and minimum void ratios of the used sand were found to be 0.792 and 0.467 respectively. The void ratios were obtained from the measured maximum and minimum unit weights of dry sand. The maximum unit weight was obtained in accordance with ASTM specifications No. D698-70-A, whereas the minimum density was obtained in accordance with ASTM specification No. D2049-69. The specific gravity of solids was also determined in accordance with ASTM specification No. D854-58. The principal characteristics of the sand used are given in Table (1). The global unit weight of the sand was controlled by weighing the used sand in the bin, whereas the homogeneity of the sand bed was observed using 6 small wooden boxs, 60 cm^{3} in volume, placed at different depths in the sand bed. The sand bed was accepted if it satisfied the following two conditions: the difference in the measured local unit weights, at different places in the sand bed did not exceed 1%, and the

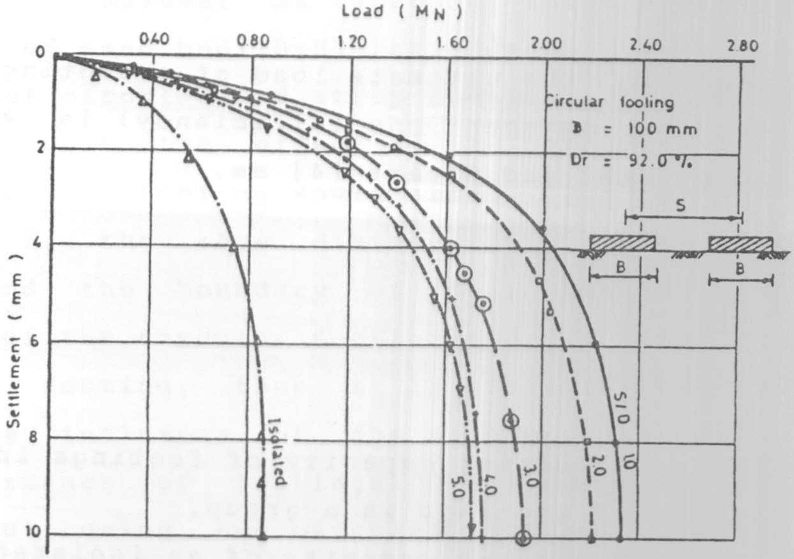


Figure (2) Load settlement curves

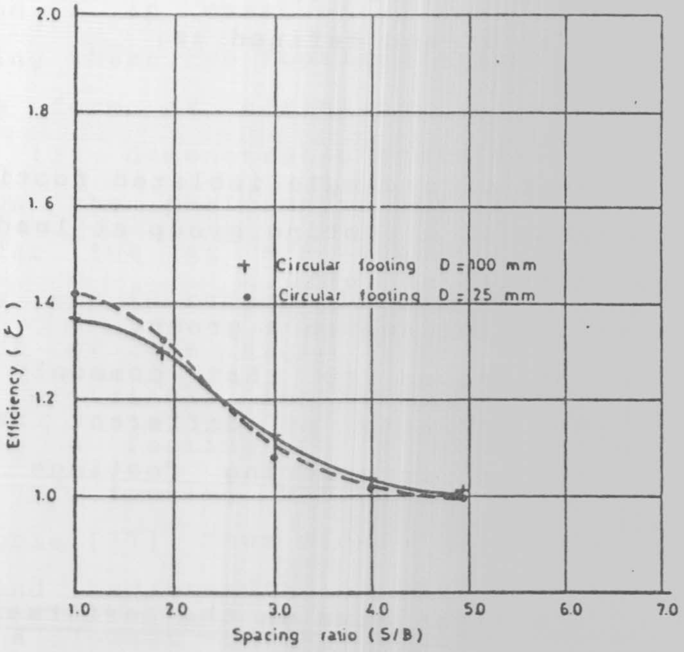


Figure (3) Effect of tank boundary on the efficiency as the load corresponding to a settlement ratio (ρ/B) of 10%.

The increase in the ultimate load of a footing due to the presence of an adjacent one (efficiency) is calculated as recommended by West and Stuart [4] as,

$$\varepsilon = \frac{q_G}{n\, q_I} \tag{1}$$

In which,

q_G = ultimate bearing capacity of footings in a group.

n = number of footings in a group.

q_I = ultimate bearing capacity of an isolated footing.

ε = efficiency.

Another term was introduced here which is the group settlement ratio (S_r), and defined as;

$$S_r = S_G/S_s \tag{2}$$

In which,

S_s = settlement of a single isolated footing at load (P).

S_G = settlement of a footing group at load (nP).

S_r = group settlement ratio.

n = number of footings in a group.

This term is analogous to that commonly used in pile foundation. The effects of different factors on the performance of two interfering footings are explained herein below.

3.1. Effect of container size on the performance of footing

At a spacing ratio S/B=1, of two-footing group, the depth of sand bed/twice of the footing width ratio, varied between 3 and 6.6, in case of circular and strip footings respectively. However at spacing ratio S/B equal to 5.0, the depth of sand bed/(S+B) ratio decreases to 1.0 and 2.2, in case of circular and strip footings, respectively. Thus suspicion about the effect of the base of soil bin on the performance of footing would arise. At a spacing ratio S/B equal to 5, the edge distance between the center of the footing and the boundary of soil bin is 1.25 times the diameter of the circular footing and 5.8 times the width of the strip footing, thus it is believed that, there is no appreciable influence of the side boundary of soil bin on the performance of footings. Some comparative tests were carried out using two circular footings of diameter 25 mm and 100 mm placed on the surface of sandy soil in the same container. In case of the small size footing, 25 mm diameter, the depth of sand bed/(S+B) ratio is 24 in case of S/B=1 and 8 in case of S/B=5.0. The test results, obtained using these two footings are illustrated in figure (3), in the form of efficiency (ε) versus spacing ratio s/B. Figure (3) demonstrates that, the effect of soil bin boundaries on the performance of footing group is of maximumn order 10% at s/B equal to 1.0. This effect decreases as s/B increases. It should be noted that, there is no effect of the rigid base of soil bin on the performance of single isolated footings , of similar dimensions as a footing in a group, since the depth of sand/breadth of footing was 6 in case of large size footing, Hubble [17]. Thus figure (3) confirms that, as the depth of sand bed/breadth of footing decreases (i.e. two footings at a closest spacing) a deficient effect increases (i.e. more divergence from the actual value). These results agree with those obtained by Hubble [17].

3.2 Effect of footing restrain against rotation

Figure (4) illustrates the effect of spacing ratio S/B, between two strip footings, on the efficiency of these footings in two conditions; firstly, the footings are completely restrained against rotation; secondly, the footings were allowed to rotate in plane of loading. The ultimate load of the two interfering footings was obtained from load-displacement relationship as the load corresponding to a settlement ratio $\rho/B=10\%$, whereas the ultimate load of a single isolated footing was considered as the load corresponding to zero slope of the load-settlement curve. The settlement ratio ρ/B at this load was 5%. Thus the efficiency of the two interfering footings was calculated at a settlement ratio differing from that of a single isolated footing. From figure (4), it is evident that, the efficiency of the completely restrained footings increased, by up to 80% depending upon S/B ratio, and that rotating footings experienced less efficiency. Thus, it is preferable to tie up closely spaced footings with ground beams. At the first sight to figure (4) it can be realized that, the efficiency changes inversely proportional to the spacing and reaches a maximum value when the footings touch each other. This is in agreement with the experimental results reported by the available literature (for instance, West and Stuart [4], Swami and Agarwal [9] and Deshmukh [10]), while it differs from those reported theoretically and experimentally by Stuart [1] in which he found that, a substantial increase in the efficiency has been found when the two footings are placed at a spacing of 1.5 B centre to centre, that is to say at S/B=1.5. Figure [4] also confirms that, the interaction effect between the two footings on

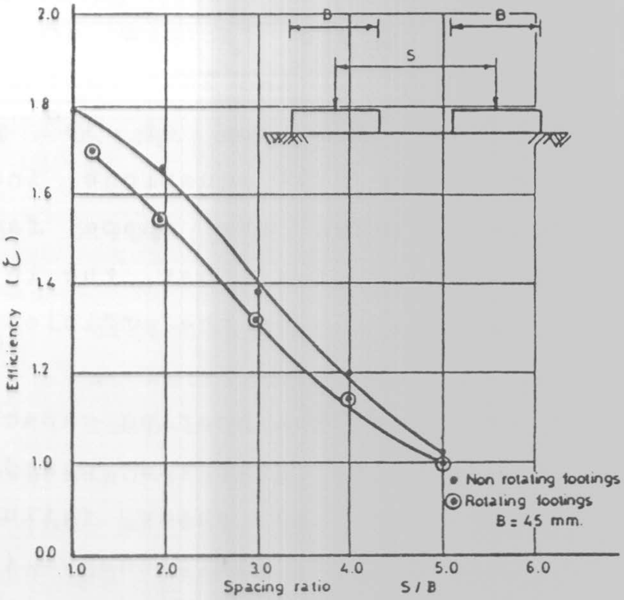


Figure (4) Efficiency versus spacing ratio
(at failure)

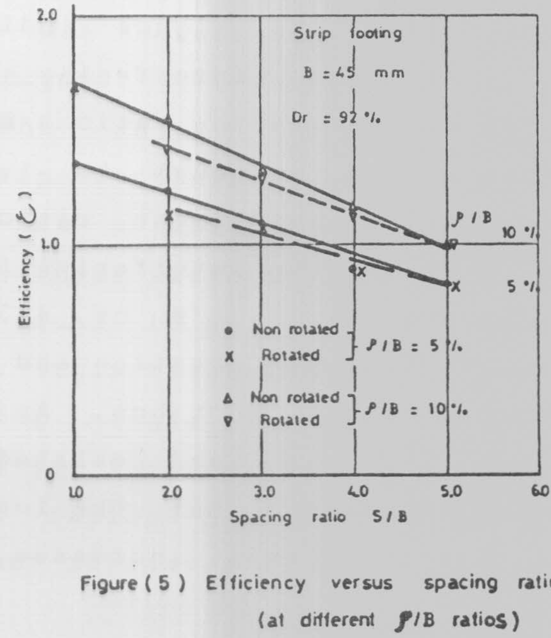


Figure (5) Efficiency versus spacing ratio
(at different ρ/B ratios)

efficiency becomes negligable at S/B=5.

But one can argue about the interfering effect of the shape factor of the footing on the efficiency of these footing. Calculation of the shape factors of single isolated footings of dimensions BxL and 2BxL resting on sand having an angle of internal friction of 33^{o} and 44^{o}, using Hansen [18] and Meyerhof [19] equations, indicates that the maximum difference between the shape factors in the two cases is 7%. Thus it is clear that, the influence of shape factor of the two footing on the efficiency is of a minor effect.

It is well known that the bearing capacity of a shallow foundation on a granular soil is based on a specified displacement rather than on shear failure. Thus, it is interesting to obtain the efficienecy (ε_s) of the two interfering strip footings, at a displacement equal to that of a single isolated footing; and also, to obtain the efficiency at working load range of the two interfering footings, figure (5). The figure indicates that the efficiency (ε_s) of two interfering strip footings, linearly decreases as the spacing ratio S/B between the two footings increases, and is equal to 1.0 at S/B=5.0 and ρ/B=10%. However, at a settlement ratio ρ/B equal to 5%, the efficiency of the two interfering footings is equal to 1.0 at a spacing ratio S/B of 4.3 in the case of footings restrained against rotation and at S/B of 4.5 in the case of nonrestrained footings. As the displacement ratio ρ/B exceeds 5%, the load resisted by the group of the two footings increases, but the load carried by the single isolated footing never increases, because of the footing failure (isolated footing failure at $\rho/B=5\%$). Thus, an increase in efficiency is expected as the settlement ratio ρ/B increases. In conditions similar to the strip footing tests, the efficiency of the two interfering strip footings, restrained against rotation, may be expressed as;

$$\varepsilon_{10\%} = 1.72 - 0.144\ (S/B) \qquad (3)$$

and,

$$\varepsilon_{5\%} = 1.36 - 0.104\ (S/B) \qquad (4)$$

In which,

$\varepsilon_{5}\%$ and $\varepsilon_{10}\%$ = efficiencies of restrained footings at settlement ratios (ρ/B) 5% and 10% respectively.

Figure (5) shows also that, at a spacing ratio S/B equal to 5.0, there is no effect of the restraining condition against rotation on the efficiency of the two interfering strip footings.

The group settlement ratio S_r of the two interfering strip footings was calculated at different values (ρ/B), as shown in figure (6). The figure illustrates that, the group settlement ratio S_r of the two restrained interfering strip footings, increases as the spacing ratio S/B increases. At a settlement ratio ρ/B equal to 10%, the group settlement ratio is less than unity; wheares the efficiency is equal to unity, at S/B equal to 5, as shown in figure (5). This situation represents the condition of post failure for single isolated footings and prefailure for the group of two interfering footings.

At settelement ratios ρ/B less than 4.6%, still the settlement ratio increases as the spacing ratio increases,

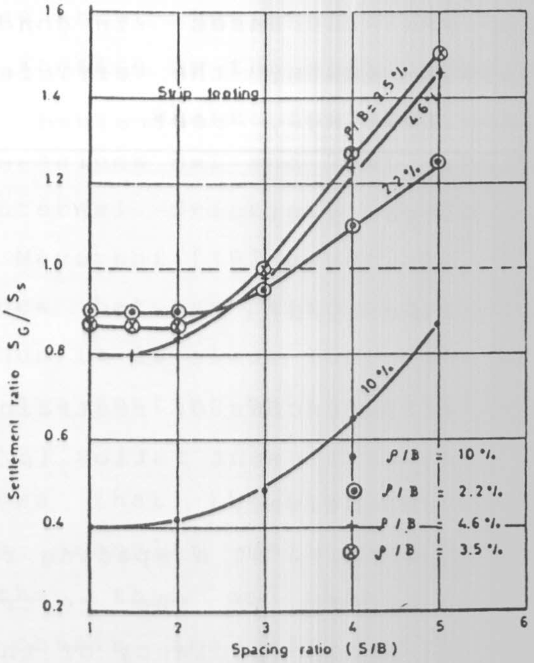


Figure (6) Settlement ratio versus spacing ratio

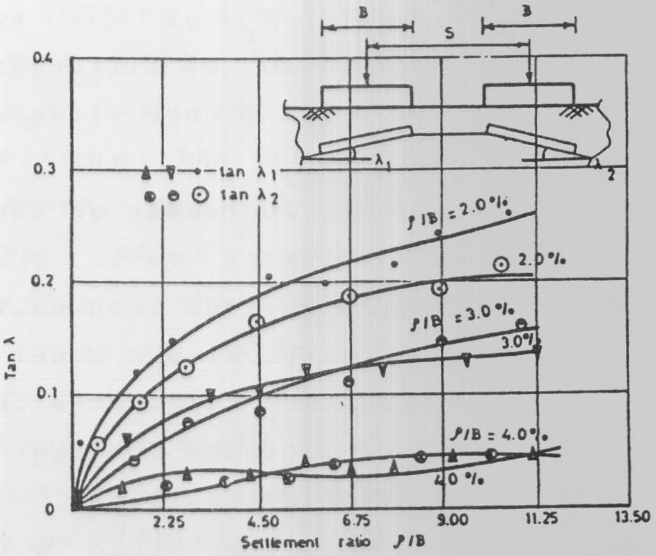


Figure (7) Variation of tan λ with average settlement ratio but attains values greater than unity at a spacing ratio greater than 3.0 depending upon the settlement ratio ρ/B. Now it is clear that one should separate between the minimum spacing between two interfering footings at which the efficiency is equal to 1.0, and the spacing at which the displacement of the two interfering footing, loaded by (2P), is equal to that of single isolated footing loaded by a load (P), that is to say $S_r=1.0$. Figure (6) indicates $S_r=1.0$ at two values of s/B ratios, the figure clarifies one of these ratios of ρ/B. For settlement ratio ρ/B less than 4.6%, whereas the size of soil bin becomes an obstacle for obtaining the second ratio. The other value of ρ/B is expected at a widerspacing ratio ρ/B and a higher settlement ratio ρ/B.

To extract the benefit of figure (6), the following example is given. Suppose a single isolated strip footing of width 1.00 m is constructed in sand bed with an average SPT values of 20 blows. The allowable bearing capacity of this footing corresponding to a displacement of 25.4 mm (ρ/B=2.5%) is 250 KN/m^2, Terzaghi and Peck [14]. Consequently the allowable load acting on this footing is 250 kN/m'. Now if two identical strip footings, having the same dimensions as the single isolated footing are loaded by 250 kN/m' each, the displacement of the two footings will be less than 25.4 mm as long as the spacing ratio S/B is less than 3.3, consequently the allowable bearing capacity of these footing may be increased to ensure a displacement of 25.4 mm. On the other hand, the displacement of the two footings will be bigger than 25.4 mm when the spacing ratio S/B is greater than 3.3, a typical displacement value of 31 mm occurs at a spacing ratio s/B equal to 5, and consequently the allowable bearing pressure should be reduced to ensure a displacement of 25.4 mm, this confirms the finding illustrated in figure (5). Consequently the efficiency term introduced by Stuart [1] is really invaluable in case of footings resting on sandy soil.

Figure (6) also indicates that the displacement of two interfering strip footings loaded with load equal to twice the load causing a displacement of 0.1B of the single isolated footing, increases as the spacing between the two footings increases and never attains the displacement of a single isolated footing although at a spacing ratio equal to 5, the efficiency is equal to 1.0. Thus the efficiency term of footing groups in sand gives misleading results.

Figure (7) demonstrates the variation of the footing tilt $\tan\lambda$ against the average settlement ratio ρ/B of the two interfering rotating strip footings. The footing tilt graph shown in figure (7) reveals that, unsymmetrical behaviour does occur. This finding was reported also by West and Stuart [4] and Andrawes [20]. This suggests that the contact stress below these footings becomes unsymmetrical resulting in eccentric reaction on the footing. This confirms the results of West and Stuart [4] and Swami and Agarwal [9] in which they demonstrated that due to the blocking and arching in the soil between the two footings, oblique contact stresses beneath the footings has been developed. Thus the failure in soil beneath the footings takes place at one side of the footing (the side close to the neighbouring footing), that is to say one side failure surface.

3.3 Effect of soil density

In spite of the unvalidity of Stuart efficiency term, the effects of soil density and footing shape on the performance of two interfering footings were discussed using this term. Figure (8) shows the influence of relative density of soil on the efficiency of the two interfering strip restrained footings. The efficiencies were based on the failure load of the footing group at a settlement ratio of 10% and the ultimate load of the single isolated footing at a settlement ratio of 5%. The loading tests were conducted on strip footings (L/B=6.7) at different soil densities. The soil density varied between 15.6 to 17.6 kN/m^3, the corresponding relative densities are 34% and 92% respectively. Figure (8) indicates that, in the case of dense sand, the interference between the two footings has a remarkable effect on the efficiency of these footings. This effect decreases significantly as the soil relative density decreases and the interference has less effect when the soil becomes loose. This may be attributed to the change in the mechanism of failure from a general shear failure in case of dense sand to a local shear failure in case of loose sand. General shear failure is, always, associated with interference between the plane of failure underneath the footings, whereas in local shear failure, the extent of the plane of failure is limited with less interference. Neverthless the interaction between the two footings becomes ineffective at S/B=5 irrespective to the relative density of sand.

3.4 Effect of footing shape

Figure (9) shows the effect of footing shape on the

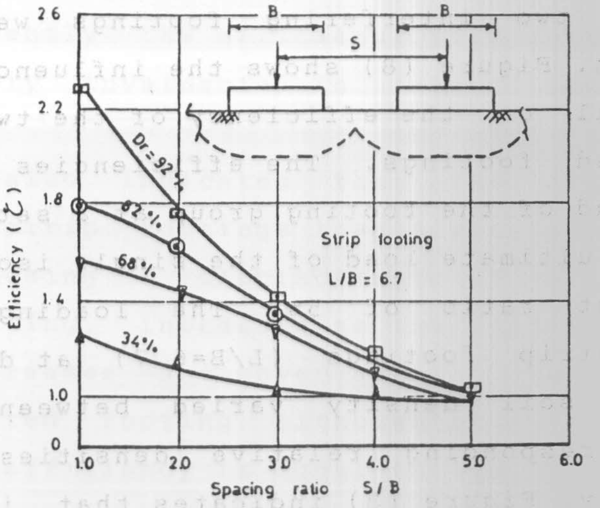


Figure (8) Variation of efficiency with relative density

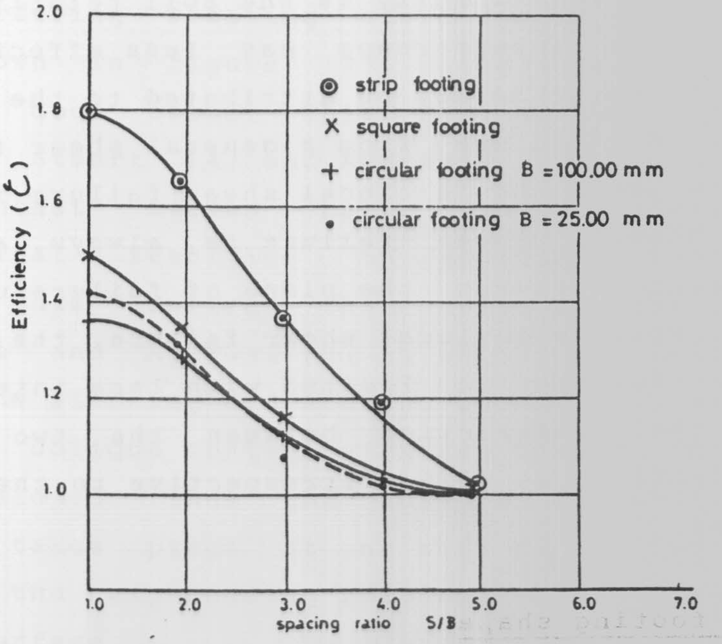


Figure (9) Effect of footing shape on efficiency

efficiency of a group of two footings, the efficiencies were based on the failure load of the footing group at a settlement/footing width ratio of 10%, and the failure load of the single footing is at a settlement ratio of 5%. The figure indicates that, the footing efficiency is critically affected by the footing shape, and a group of two strip footings is more efficient than square and circular groups. However the effect of shape of footings in case of square and circular shapes is not prenounced at a spacing rotio S/B greater than 4.0. This may be attributed to the fact that part of the failure planes in case of square and circular footings occurs without any interference; but still the interaction effect between the two footings becomes ineffective at S/B=5, irrespective of the footing shape. Figure (10) illustrates again the effect of footing shape on the efficiency calculated at equal displacements. The figure indicates that, there is inappreciable effect of footing shape on the effeciency calculated at a displacement ratio equal to 5%, and at a spacing ratio S/B less than 3.0.

3.5 Comparison with previous experimental work

Figure (11) illustrates the efficiency of two interfering square footings at different spacing ratio S/B. The efficiency was based on loads of footing group and single isolated footing at the same settlement ratio ρ/B. The figure, also, illustrates the efficiency of two interfering square footings achieved by Singh et al [7]. The figure confirms the same finding of the effect of relative density of sand on the efficiency of footing group.

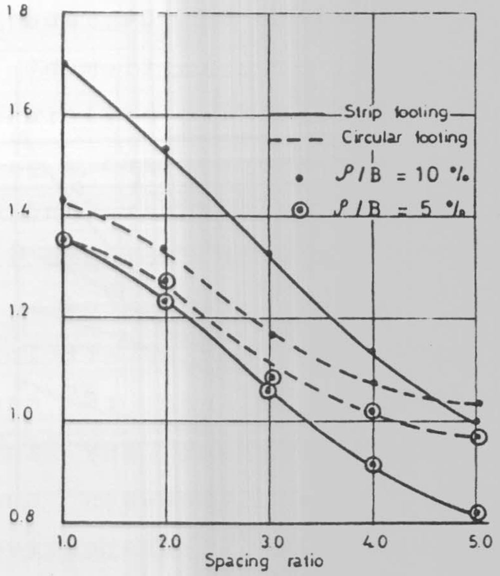


Figure (10) Variation of efficiency with spacing ratio at different settlement ratios

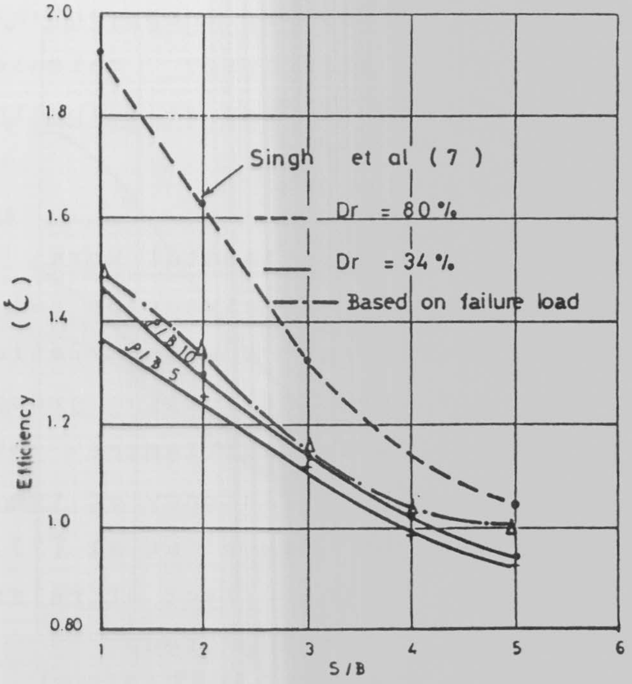


Figure (11) Efficiency of square footing vs. spacing ratio

4. Conclusions

The following are the main concluded points extracted from this course of investigation;

1- The interaction effect between two interfering rotating footings causes unsymmetrical shear failure planes in soil beneath the footings. The failure in soil beneath each footing is one sided failure surface.

2- Rotating footings in a group experience less efficiency than those of completely restrained footing, and thus it is perferable to tie up closely spaced footings with a rigid ground beam.

3- The efficiency of a footing in a group should be based on the settlement ratio rather than on the ultimate load ratio and consequently the efficiency term proposed by Staurt [1] gives misleading results.

4- The spacing between two interferring footings in a group is not only the most significant factor affecting the behaviour of these footings but also, soil density, footing shape, and restraining condition of footings are other vital factors.

References

[1] Stuart,J.G. (1962), Interference between foundations, with special reference to surface footings in sand. Geotechnique, Vol.12, pp.15-22.

[2] Hanna,T.H. (1963), Model studies of foundation groups in sand. Geotechnique, Vol.13, pp.3345-3351.

[3] Rao,P. (1965), Effect of spacing on settlement and ultimate bearing capacity characteristics of footings. M.E. Thesis, I.I.T, Bombay, India.

[4] West,J.M. and Stuart,J.G. (1965), Oblique loading resulting from interference between surface footings on sand. proc. 6th Conf., ICSMFE, Vol.II, pp.214-217.

[5] Agarwal,V.C. (1970), Interference of surface footings on sand. M.E. Thesis, University of Roorkee, Roorkee.

[6] Murthy,S.S.N. (1970), Interference in surface footings on clean sands. proc. of the Symposium on shallow foundations. Indian Nat. Soc. of SMFE, pp.109.

[7] Singh,A. and Punmia,B.C, and Ohri,M.L. (1973), Interference between adjacent square footings on cohesionless soil. Indian Geotechnical Journal, Vol.3 No.4, pp.275.

[8] Myslivec,A. and Kysea,Z. (1973), Interaction of Neighbouring foundations. proc. of 8th Conf. ICSMFE, Moscow, Vol.1, 3, pp.181.

[9] Swami,S. and Agarwal,V.C. (1974), Interference of surface footings in sands, Indian Geotechnical Journal, Vol.4, No.2, p.129.

[10] Deshmukh,A.M. (1978), Interaction of different types of footings on sand. Indian Geotechnical Journal, Vol.8, pp.130-204.

[11] Abdrabbo,F.M. (1985), Contact stresses beneath two interfering strip foundations. The bulletin of the Faculty of Engineering, Alexandria University, Vol.XXIV.

[12] Shawki,A. (1988), Bearing capacity for shallow footing under inclined load. M.Sc. Thesis, Alexandria University, Egypt.

[13] Hana,A.M. (1981), Foundations on strong sand overlying weak sand. Journal of Geat. Engineering Division, proceedings ASCE Vol. 107, No. GT7.

[14] Terzaghi, K. and Peck, R.B. Theoretical soil mechanics, John Wiley and Sons, 1943.

[15] Vesic A.S. (1973), Analysis of ultimate loads of shallow foundations, Journal of Soil Mechanics and Foundation Engineering Division ASCE Vol.99, No SM1.

[16] DeBeer, E.E. and Vesic, A.B. (1958), Etude Experimentale de la capacite portante du sable sous des foundations directes etablies en surface, Annales des Travaux Publics de Belgique, Brusses, Belgium, vol. 59, No.3, pp.5-53.

[17] Hubble,D.W. (1979), Effect of depth to a firm base on the bearing capacity of small footings on sand. M.Sc. Thesis, Department of Civil Engineering, Queen's University at Kingston, Ontario, Canada.

[18] Hansen, J.B. (1961), A general formula for bearing capacity, Bulletin No.11, Danish Geotechnical Institute, Copenhagen, pp.38-46.

[19] Meyerhof, G.G. (1953), The bearing capacity of foundation under eccentric and inclined loads, Proc. 3rd Int. Conf. on Soil Mechanics and Foundation Engineering, Zurich, Vol.I, pp.440-445.

[20] Andrawes, K.Z. (1970), A contribution to plane strain model testing of granular materials. Ph.D. Thesis, University of Southhampton, England.