A STUDY ON INTERFERENCE OF SURFACE MODEL FOOTINGS RESTING ON SAND

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ABSTRACT

A model study has been conducted on the effect of interference of footings on bearing capacity and settlement of surface square, circular and strip footings resting on sand. One footing was loaded to its safe bearing capacity and increments of load were applied to an adjacent footing till complete failure of sand occurred. The efficiency of interfering footings have been compared to that of the isolated footings having the same size from the considerations of bearing capacity and settlement characteristics. The interference between footings was observed to cause an increase in bearing capacity and decrease in settlement with reduction in spacing.

Keywords: *Circular Footing and Strip Footing, Interference of Footings, Model Footings, Square Footing*

1. INTRODUCTION

All the structures, which exist on the earth, are ultimately supported by the earth. The loads of a structure are transmitted to the ground through its lowest structural element called the foundation. In addition to the foundation material, the destiny of a structure also depends on the properties of the patch of the earth, rock or soil, on which the structure stands. So a foundation engineer is concerned with the twin problems of evaluating the ability of the earth to support the loads and designing the proper transition members to transmit the superstructure loads to the ground. The foundation design is aimed at providing a means of transmitting the loads from a structure to the underlying soil without causing any shear failure or excessive settlement of the soil under the imposed loads. Thus the choice of a suitable bearing capacity of soil becomes the most important point to be considered in any project. Bearing capacity, the supporting power of a soil or rock, may be determined by analytical methods, conducting field and laboratory tests and from the building codes. Soil characteristics, position of water table, types of foundation and their location are some of the factors which affect the bearing capacity and the performance of a foundation.

The conventional theories on bearing capacity deal with ideal situation. Inadequacies of these theories have been experienced by many when met with situations, which deviate from those assumed in these theories. When a locality is under-developed and the foundation units are farther apart, the adoption of conventional methods for computing the bearing capacity is quite justified. But as the area goes on developing, the proximity of the buildings to each other has a definite influence on the bearing capacity and settlement characteristics of footings. The interaction of pressure bulbs and failure surfaces in closely placed footings change their bearing capacity and settlement. This has provided the direction for research on behaviour of interfering (adjacent) footings.

Model studies conducted on purely cohesionless soil by Stuart [1] showed an increasing trend of bearing capacity with decreasing spacing when pair of footings were brought closer from large distance achieving a maximum at a spacing of about 1 to 1.5 times width of the footing. The failure surfaces were also drawn and ultimate capacity for the pair was worked out. The results of this theoretical investigation were not in close agreement with the observed. Stuart [1] presented the results in the form of non-dimensional charts. Stuart [1] was concerned only with the interference between two footings. Mandel [2] investigated a more general problem with structures on either side of a footings. He developed the solution for an ideal soil considering it as a weightless material. It is evident from his curves that as the spacing between the footings decreases, the bearing capacity increases. This is in general agreement to the work of Stuart [1]. Amir [3] obtained the tilt in case of hinged footings and moments in the case of restrained footings from the theoretical investigations on a pair of strip footings. Saran and Aggarawal [4] conducted tests on sands and found that bearing capacity of two interfering footings decreases rapidly with the increase in spacing up to a spacing of 4.5 times width of the footing beyond which it decreases slowly and attains value of the bearing capacity of isolated footings. The extent of failure surface decreases with the increase in spacing. Amir [5], Kumar [6], Kumar and Saran [7], Kumar and Saran [8], Bohra [9], Khan [10] and other investigators have also studied the effect of interference between footings. Significant improvement in bearing capacity computations have been made through investigations on the effect of various factors including interference of footings, which is not considered in the conventional theories of bearing capacity. In practice, footings may not be isolated due to the proximity of a nearby footing leading to interference between them. In such cases effect of interference should be taken into account. However, this fact is usually not taken into consideration in design of foundations.

In brief it may be said that important changes in bearing capacity and settlement characteristics occur when a footing is placed in close proximity of a loaded footing. The centre to centre spacing is the most significant parameter influencing the interference of footings. Other parameters that affect the performance of adjacent footings are: type of soil, density of soil, type of footing, roughness of footing and depth of footing.

In this study one footing was loaded to its safe bearing capacity and increments of load were applied to an adjacent footing till complete failure of sand occurred. The ultimate bearing capacity and settlement characteristics of this adjacent footing has been compared to that of the isolated footings having the same size. Performance of the adjacent footings has also been referred as performance of group of footings.

2. DEVELOPMENT OF TEST PROGRAMME

2.1 Soil Used

Dry sand was used for the study. Salient properties of the sand are: 100% passing through 2 mm sieve, coefficient of uniformity $c_u = 1.5$, coefficient of curvature $c_c = 0.87$, specific gravity G = 2.66, proctor's density = 16.57 kN/m^3, minimum density = 14.68 kN/m^3, maximum density 17.2 kN/m^3, optimum moisture content = 11.63%, density achieved for the study = 16.5 kN/m^3, angle of internal friction (dry) = 36°, angle of internal friction (submerged) = 33.5°, permeability of sand = 0.453 x 10^{-3} mm/s and was classified as poorly graded sand (SP), according to the classification system of the Bureau of Indian Standards [11,12].

2.2 Footings

Rough model footings of size 4 cm x 4 cm, 5 cm x 5 cm, 7 cm x 7 cm, 15 cm x 6 cm and circular footings of diameter 5 cm, 6 cm and 7 cm were selected for the study. Model footings were moulded from aluminium alloy. An emery cloth of extra-fine grade J298-EA was pasted on the base of the footing to make it rough. Arrangements were made for normal transmission of the load.

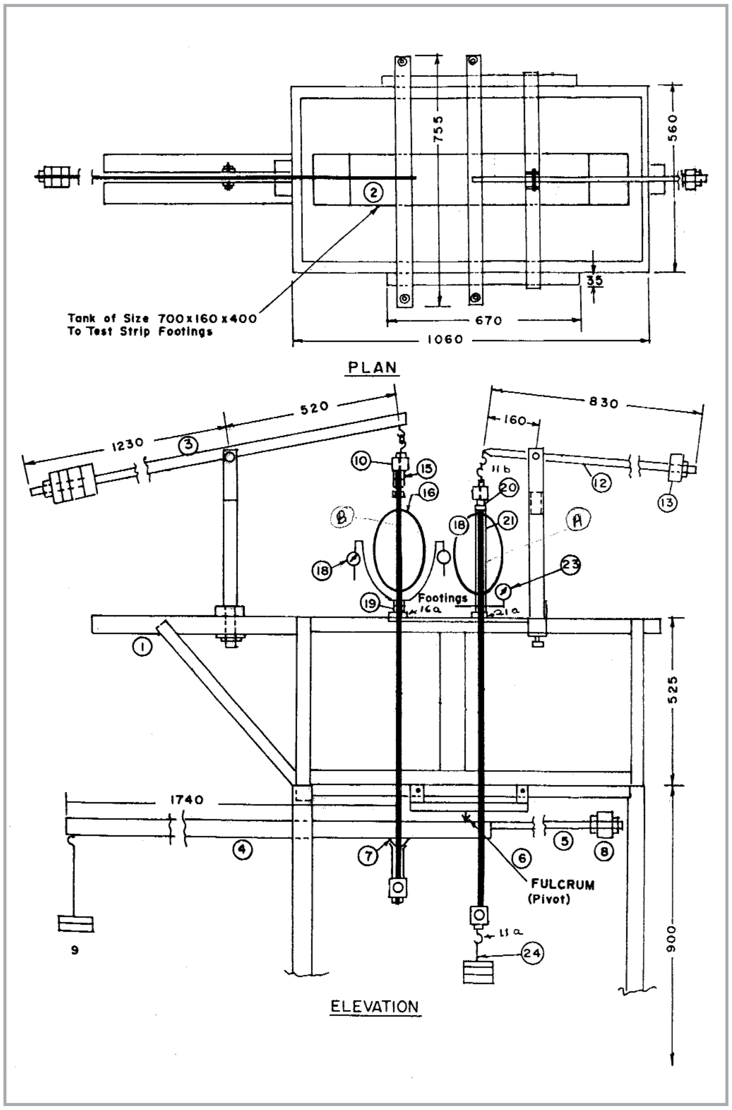

Figure 2: Experimental Setup (Loading Tank)

2.3 Tank

The size of tank was 100 cm x 50 cm in plan and 50 cm in depth. The tank was made of angle iron and wooden planks (Figure 1). The tank was designed to be used for circular footings, square footings and strip footings. When the tests were required to be conducted on strip footings, another tank of size 70 cm x 16 cm x 40 cm was kept inside the bigger tank (Figure 2) to facilitate the use of 15 cm x 6 cm size footings in plane strain condition. Details of tank are given elsewhere such as by Khan [10].

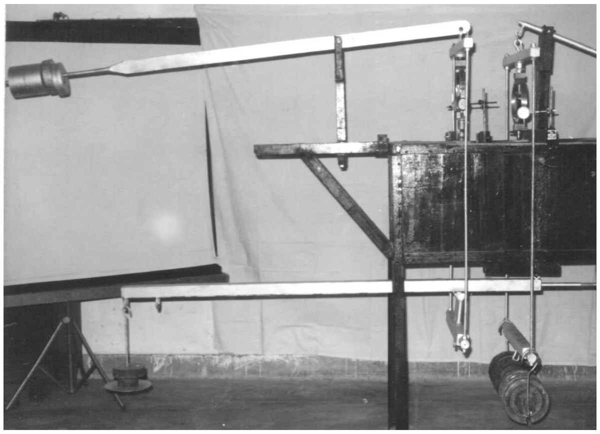

Figure 1: Setup of apparatus

2.4 Loading System

Dead load system of loading was used. One frame was used to load the footing, which represented existing footing, to safe bearing capacity of footing. Another frame was used to apply increments of load to adjacent footing till complete failure of sand occurred.

2.5 Tests Performed

Tests were performed on isolated footing and in group at four S/D ratios; as shown in Table 1, where *S* is the spacing between footings, *B* is the width of footings and *D* is the diameter of the footings.

Table 1: Tests performed on model footings

S. No.	Size of Footing	S/B or S/D Ratio
1	4 cm x 4 cm	1.75, 2.5, 3, 4
2	5 cm x 5 cm	1.4, 2, 3, 4
3	7 cm x 7 cm	1, 2, 3, 4
4	15 cm x 6 cm	1, 2, 3, 4
5	5 cm diameter	1.4, 2, 3, 4
6	6 cm diameter	1.16, 2, 3, 4
7	7cm diameter	1, 2, 3, 4

2.6 Test Procedure

Dry sand was compacted in layers of 15 cm thickness with simultaneous working of two form vibrators fitted on a mild steel plate for one minute, which gave a density of 16.5 kN/m^3. After compacting and levelling the sand, frames were fixed in desired position and model footings were placed under the proving ring suspended from the loading frames. A seating load of 7 kN/m2 was applied and then released to ensure the contact between the base of footing and surface of sand, which was in accordance with the methods of Bureau of Indian Standards [13]. Load was applied through steel ball and settlement of footing for each load increment was recorded using dial gauges. Load was applied on the footings in increments till failure of sand occurred. Each test was repeated for at least three times and average load intensity-settlement curve was plotted for the tests.

3. TEST RESULTS

Load intensity was plotted against the corresponding settlement of the footings and an average curve was obtained for each set. The curves, in general, show a linear variation in the initial portion and become non-linear thereafter. Figure 3 shows average load intensity-settlement curve for isolated square footings. Load intensity-settlement curve for group of square footings placed at different S/B ratios are given in Figures 4, 5 and 6. Figure 7 shows average load intensity-settlement curve for isolated strip footing and group of strip footings placed at different S/B ratios. Figure 8 shows average load intensity-settlement curve for isolated circular footings. Load intensity-settlement curve for group of circular footings placed at different S/D ratios are given in Figures 9, 10 and 11. These plots were used for interpretation and deriving conclusions. Three ultimate load criteria i.e. tangent-intersection method, log-log plot method and collapse load criteria, have been used. All these criteria require that loading tests should be carried out to large displacements. The ultimate bearing capacity for square, strip and circular footings obtained by the above methods have been presented in Tables 2, 3 and 4 respectively, where *S* is the spacing between footings, *B* is the width of footings and *D* is the diameter of footings.

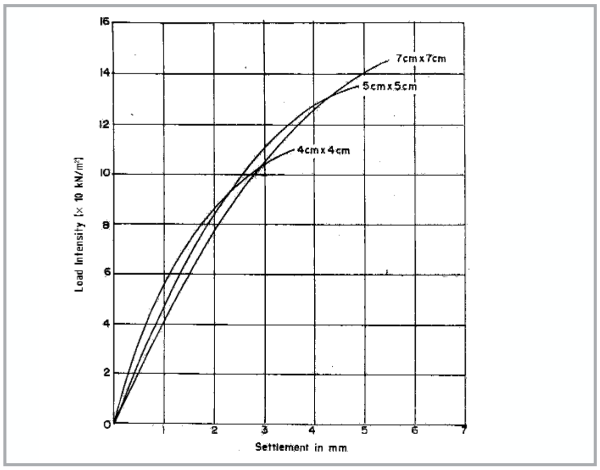

Figure 3: Load Intensity (x 10 kN/m^2) v/s Settlement (mm) for Isolated Square Footings

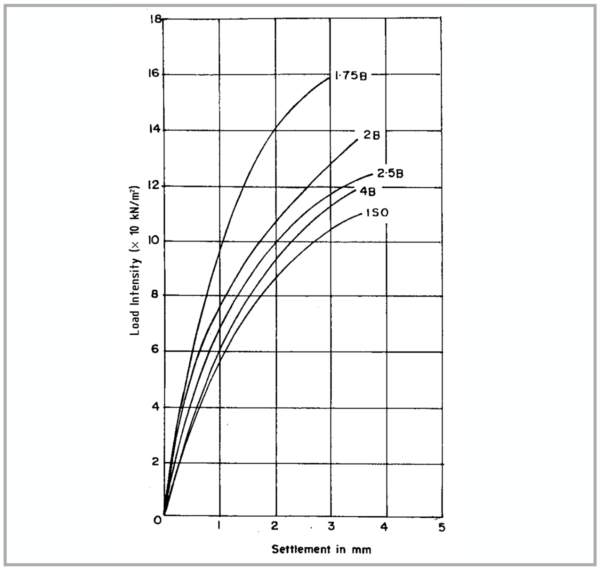

Figure 4: Load Intensity (x10 kN/m^2) versus Settlement (mm) for 4 cm x 4 cm Square Footings

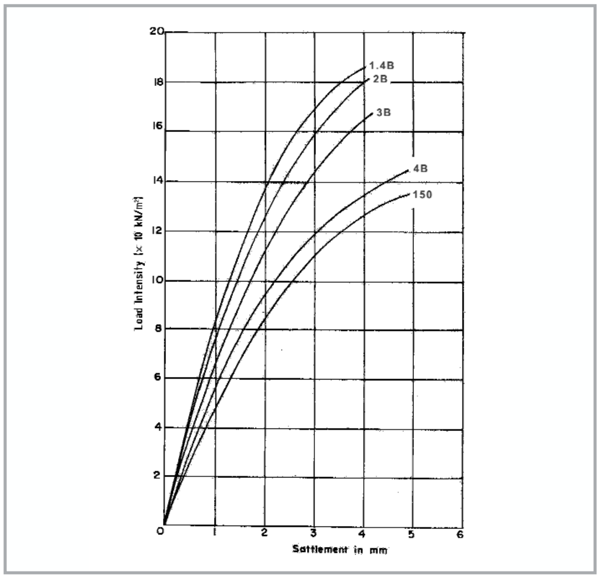

Figure 5: Load Intensity (x10 kN/m^2) versus Settlement (mm) for 5 cm x 5 cm Square Footings

The ultimate bearing capacity obtained using tangent intersection method, which is quite common in use due to convenience, was adopted for evaluating interference factors.

The failure surfaces formed on sand at the time of collapse of the footing were extended to about 2 to 3 times the width (diameter) of isolated footings. The footings failed by general shear failure mode as witnessed by the sudden collapse of

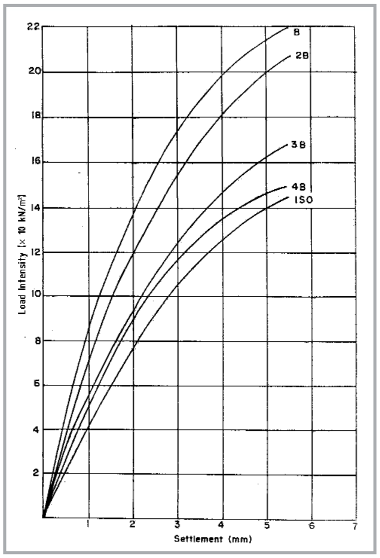

Figure 6: Load Intensity (x10 kN/m^2) versus Settlement (mm) for 7 cm x 7 cm Square Footings

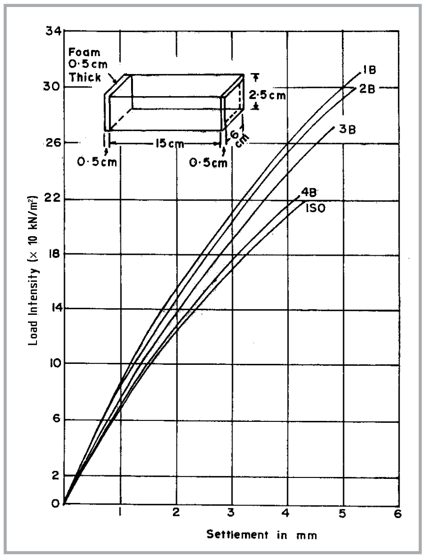

Figure 7: Load Intensity (x10 kN/m^2) versus Settlement (mm) for 15 cm x 6 cm Strip Footing

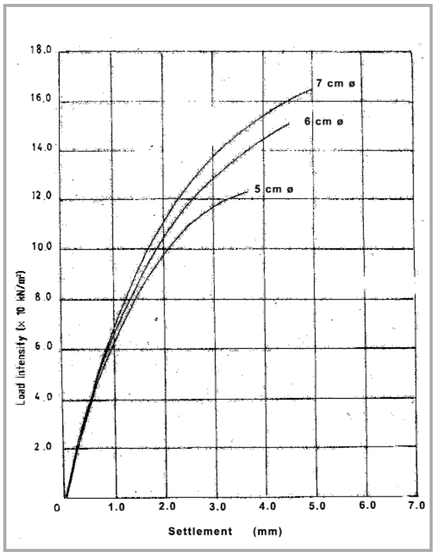

Figure 8: Load Intensity (x10 kN/m^2) versus Settlement (mm) for Isolated Circular Footings

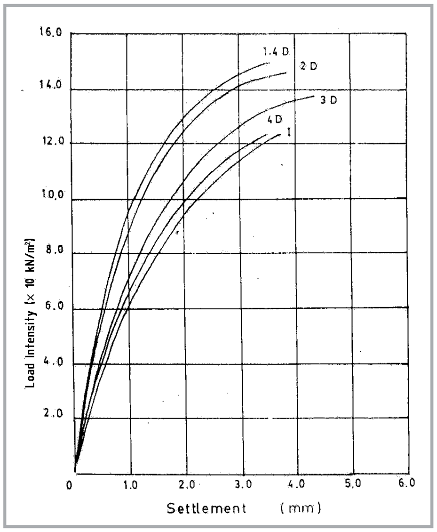

Figure 9: Load Intensity (x10 kN/m^2) versus Settlement (mm) for 5 cm Diameter Footings

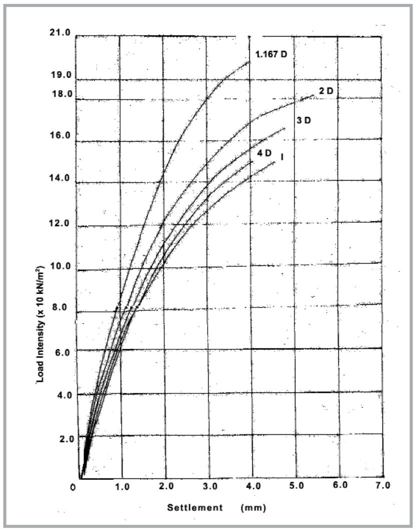

Figure 10: Load Intensity (x10kN/m^2) versus Settlement (mm) for 6 cm Diameter Footings

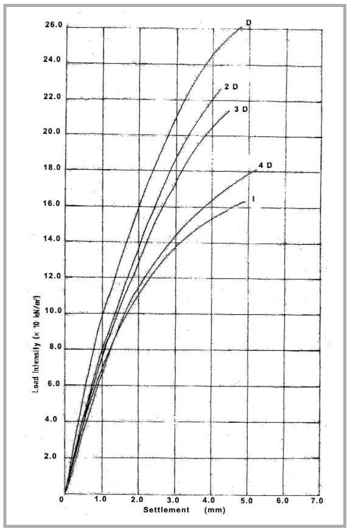

Figure 11: Load Intensity (x10 kN/m^2) versus Settlement (mm) for 7 cm Diameter Footings

footing into the soil at the time of failure. More amount of heave was observed between the footings and less amount of heave was observed towards non-interfering edges of footings.

4. DISCUSSIONS AND INTERPRETATION OF RESULTS

The ultimate bearing capacity increases as the size of footing increases. This fact has been supported by all investigators. The increase in the ultimate bearing capacity with the corresponding increase in the size of footing has been presented in Figures 12 and 13. It is also evident from Tables 2 and 4.

The footings failed by general shear failure mode as witnessed by the sudden collapse of footing into the soil at the time of failure. More amount of heave was observed between the footings and less amount of heave was observed in non-interfering edges of footings.

An examination of Figures 4, 5, 6, 7, 9, 10 and 11 indicates a significant effect on bearing capacity and settlement characteristics of footings when the centre to centre spacing is varied from *B* to 4B, in the case of circular footing, *D* to 4D. Bearing capacity of interfering (group) footing decreases rapidly with the increase in spacing up to a spacing of 4B and becomes almost equal to the bearing capacity of an isolated footing. The increase in the ultimate bearing capacity may be due to: (a) existing footing acts as a surcharge for the adjacent footing and (b) at wider spacing no interference takes place and each footing acts as an individual (isolated) footing [Figure 14(a)]. As spacing is reduced, a condition shown in Figure 14(b) arises, where the passive zones just

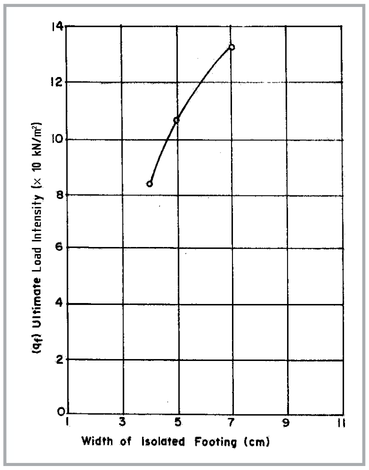

Figure 12: Load Intensity (x10 kN/m²) versus Width of Square Footings (cm)

penetrate, however there is no apparent change in bearing capacity value. If spacing is further reduced, passive zones between the footings start curtailing one another which results in changes in stress value and increase in ultimate bearing capacity of the group of footings [Figure 14(c)].

Figures 15(a) to 15(c) show Interference Efficiency Factor 'F$_\gamma$'(q_{ultg}/q_{ulti}) versus S/B (or S/D) ratio for square, strip and circular model footings respectively. Figures 16(a) to 16(c) show the average curve between Interference Efficiency Factor 'F$_\gamma$'(q_{ultg}/q_{ulti}) and S/B (or S/D) ratio for square, strip and circular model footings respectively. Where q_{ultg} is the ultimate bearing capacity of a footing placed in close proximity of an already loaded footing to its safe bearing capacity and q_{ulti} is the ultimate bearing capacity of an isolated footing, S is the centre to centre spacing between the footings of width B or diameter D. The ratio q_{ultg}/q_{ulti} may be called as Interference Efficiency Factor 'Fg' for bearing capacity. In order to predict the increased bearing capacity of a square, strip and circular footings placed in a group, the Interference Efficiency Factor 'F$_\gamma$' can be introduced in the Terzaghi's bearing capacity equation (surface footings) as below:

$q_{ult} = 0.5\,\gamma\,B\,N_\gamma\,F_\gamma$ (strip footing)

$q_{ult} = 0.4\,\gamma\,B\,N_\gamma\,F_\gamma$ (square footing)

$q_{ult} = 0.3\,\gamma\,B\,N_\gamma\,F_\gamma$ (circular footing)

Table 2: Failure load tables for square footings
table 2a: collapse load criterion

4 cm x 4 cm		5 cm x 5 cm		7 cm x 7 cm	
S/B Ratio	Collapse Load (kN/m²)	S/B Ratio	Collapse Load (kN/m²)	S/B Ratio	Collapse Load (kN/m²)
1.75	157	1.4	186	1.0	220
2.0	135	2.0	180	2.0	200
2.5	123	3.0	165	3.0	167
4	116	4.0	145	4.0	150
Isolated	110	Isolated	135	Isolated	146

Table 2b: Log-log criterion

4 cm x 4 cm		5 cm x 5 cm		7 cm x 7 cm	
S/B Ratio	Ultimate Load (kN/m²)	S/B Ratio	Ultimate Load (kN/m²)	S/B Ratio	Ultimate Load (kN/m²)
1.75	130	1.4	151	1.0	190
2.0	107	2.0	140	2.0	155
2.5	98	3.0	130	3.0	150
4	92	4.0	109	4.0	133
Isolated	90	Isolated	107	Isolated	126

Table 2c: Tangent intersection criterion

4 cm x 4 cm		5 cm x 5 cm		7 cm x 7 cm	
S/B Ratio	Ultimate Load (kN/m²)	S/B Ratio	Ultimate Load (kN/m²)	S/B Ratio	Ultimate Load (kN/m²)
1.75	128	1.4	155	1.0	180
2.0	93	2.0	134	2.0	153
2.5	91	3.0	124	3.0	126
4	85	4.0	108	4.0	122
Isolated	82	Isolated	107	Isolated	116

Table 3: Failure load table for 15cm x 6 footings

S/B Ratio	Failure Load (kN/m²)		
	Collapse Load Criterion	Log-log Criterion	Tangent Intersection Criterion
1.0	310	215	208
2.0	296	210	196
3.0	272	180	168
4.0	223	150	150
Isolated	220	145	147

Table 4: Failure load table for circular footings
Table 4a: Collapse load criterion

5 cm diameter		6 cm diameter		7 cm diameter	
S/D Ratio	Collapse Load (kN/m²)	S/D Ratio	Collapse Load (kN/m²)	S/D Ratio	Collapse Load (kN/m²)
1.4	148.0	1.16	198.0	1.0	245.0
2.0	142.0	2.0	169.0	2.0	220.0
3.0	131.0	3.0	155.5	3.0	205.0
4.0	123.0	4.0	149.0	4.0	165.0
Isolated	121.0	Isolated	142.0	Isolated	155.0

Table 4b: Log-log criterion

5 cm diameter		6 cm diameter		7 cm diameter	
S/D Ratio	Collapse Load (kN/m²)	S/D Ratio	Collapse Load (kN/m²)	S/D Ratio	Collapse Load (kN/m²)
1.4	140.0	1.16	190.0	1.0	230.0
2.0	136.0	2.0	170.0	2.0	192.0
3.0	122.0	3.0	147.5	3.0	180.0
4.0	96.0	4.0	135.0	4.0	147.0
Isolated	105.0	Isolated	121.0	Isolated	150.0

Table 4c: Tangent intersection criterion

5 cm diameter		6 cm diameter		7 cm diameter	
S/D Ratio	Collapse Load (kN/m²)	S/D Ratio	Collapse Load (kN/m²)	S/D Ratio	Collapse Load (kN/m²)
1.4	124.0	1.16	149.0	1.0	164.5
2.0	116.0	2.0	127.0	2.0	139.0
3.0	100.0	3.0	118.0	3.0	130.0
4.0	97.0	4.0	109.0	4.0	118.0
Isolated	89.0	Isolated	106.0	Isolated	115.0

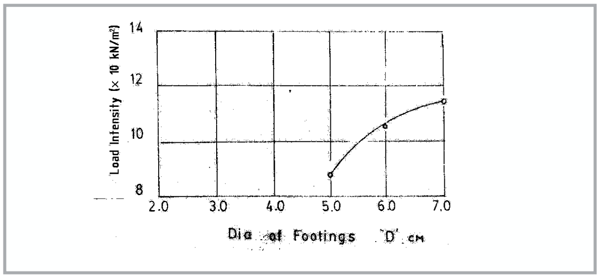

Figure 13: Load intensity (x10 kN/m²) versus diameter (cm) of footings

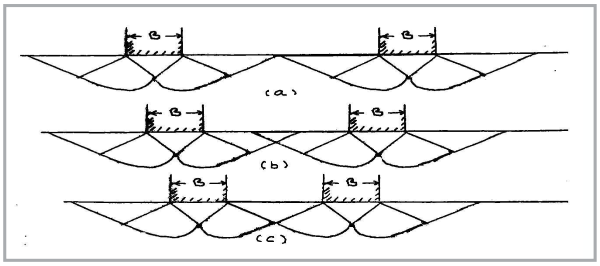

Figure 14: The development of the failure surfaces as two rough based foundations approach each other on the surface of a cohesionless soil

Where,

q_{ult} = Ultimate bearing capacity of adjacent footing (kN/m²),
γ = Density of soil (kN/m³),
B = Diameter (width) of footing (m),
N_γ = Terzaghi's bearing capacity factor and
F_γ = Interference Efficiency Factor.

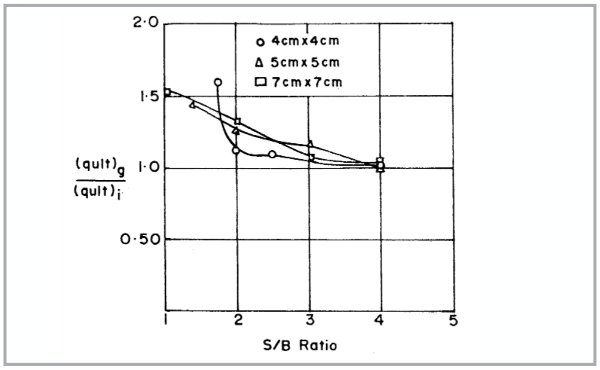

Figure 15(a): Interference efficiency factor 'F_γ' versus S/B ratio (square footings)

Figures 17(a), 17(b) and 17(c) show the plots between non-dimensional settlement ρ_g/ρ_i and S/B ratio at 30 kN/m² load intensity for square, strip and circular model footings, where ρ_g/ρ_i is the ratio of the settlement of the adjacent footing at a given load intensity to an identical isolated footing at the same intensity of pressure; it may be referred as interference efficiency factor for settlement F_ρ. Figures 18(a), 18(b), and 18(c) show an average curve between non-dimensional settlement ρ_g'/ρ_i' (Fr) and S/B ratio at 30 kN/m² load intensity for square, strip and circular footings.

The settlement behaviour of footing resting on sand shows that the closely spaced footings stiffen the soil response and reduces the settlement at a given load intensity.

The relationship between ρ_g'/ρ_i' and S/B ratio for 1.0 mm, 2.0 mm and 3.0 mm settlement for average value of square footings have been presented in Figure 19, where q_g' is pressure intensity of

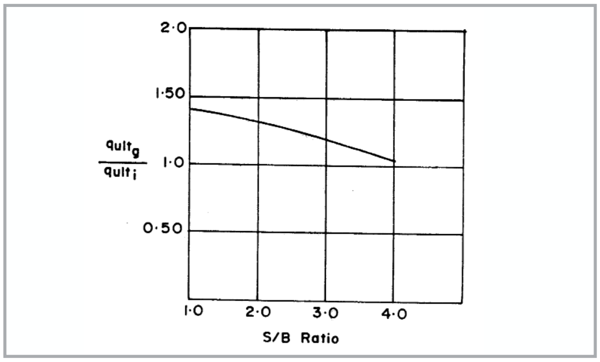

Figure 15(b): Interference efficiency factor 'F_γ' versus S/B ratio (strip footings)

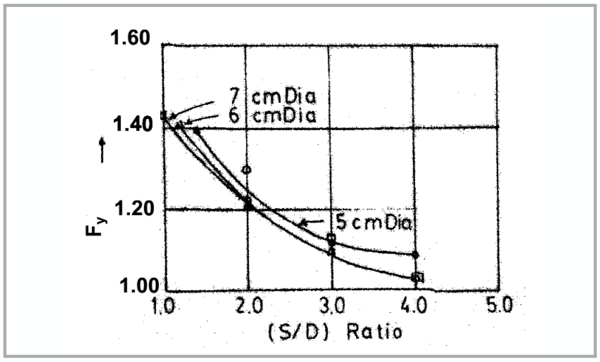

Figure 15(c): interference efficiency factor 'F_γ' versus S/D ratio (circular footings)

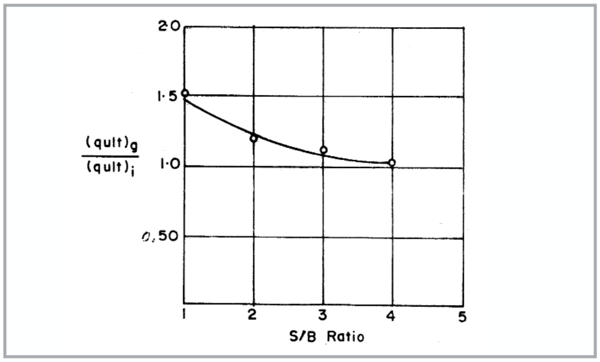

Figure 16(a): Average interference efficiency factor 'F_γ' versus S/B ratio (square footings)

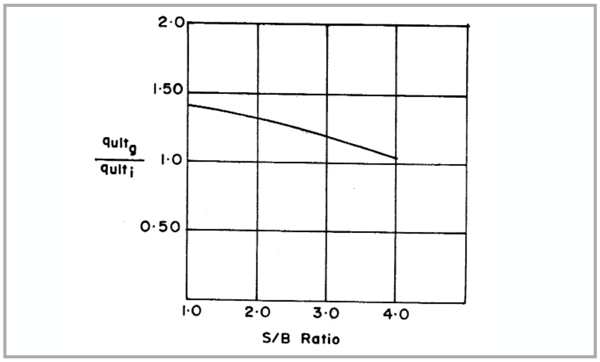

Figure 16(b): Average interference efficiency factor 'F_γ' versus S/B ratio (strip footings)

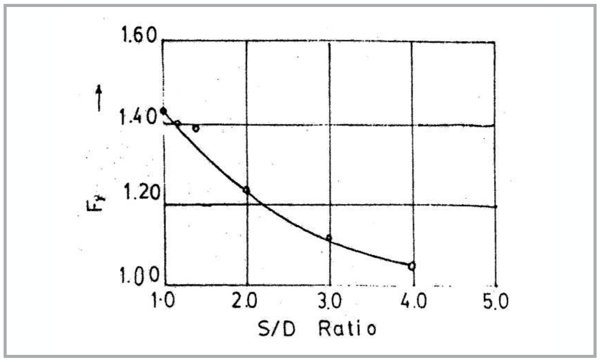

Figure 16(c): Average interference efficiency factor 'F_γ' versus S/D ratio (circular footings)

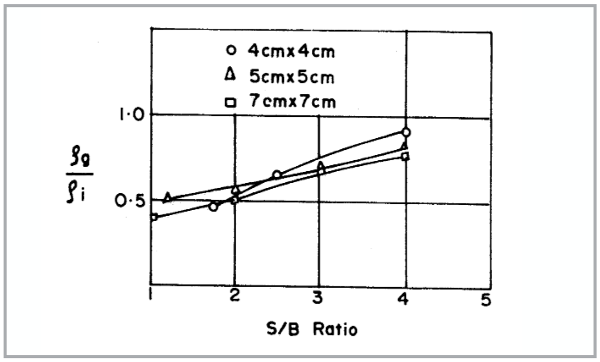

Figure 17(a): F_ρ ($\rho_g/\rho i$) versus S/B ratio at 30 kN/m^2 intensity for square footings

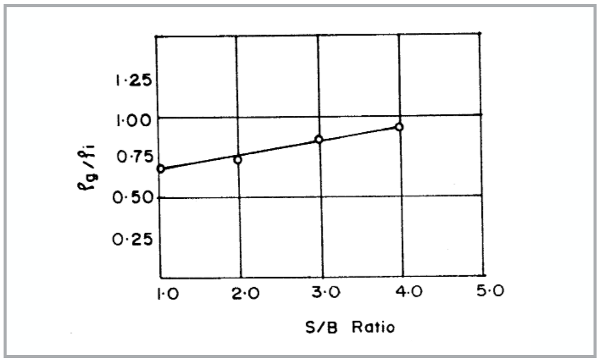

Figure 17(b): F_ρ ($\rho_g/\rho i$) versus S/B ratio at 30 kN/m^2 intensity for strip footings

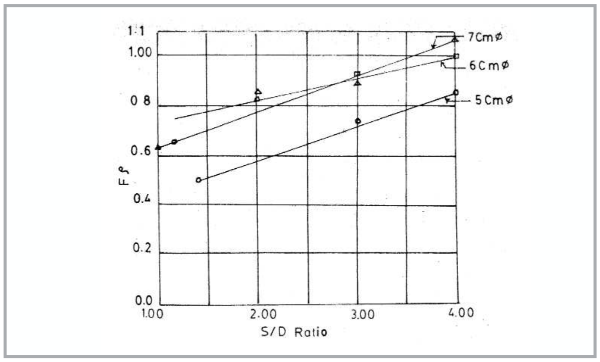

Figure 17(c): F_ρ ($\rho_g/\rho i$) versus S/B ratio at 30 kN/m^2 intensity for circular footings

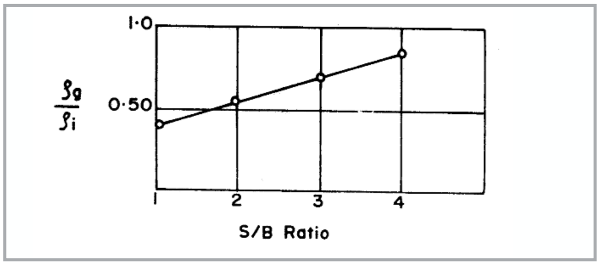

Figure 18(a): Average F_ρ ($\rho_g/\rho i$) versus S/B ratio at 30 kNm^2 intensity for square footings

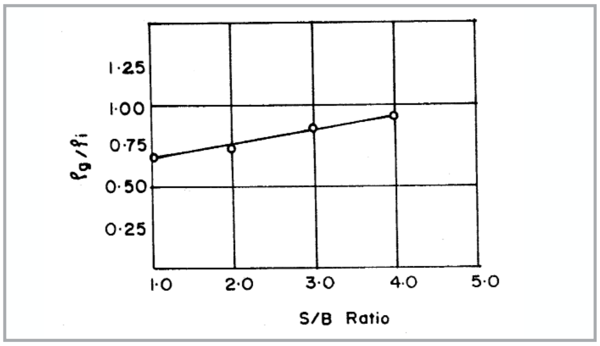

Figure 18(b): Average F_ρ ($\rho_g/\rho i$) versus S/B ratio at 30 kNm^2 intensity for strip footings

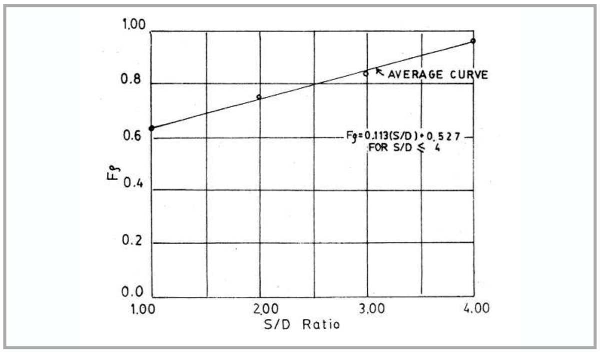

Figure 18(c): Average F_ρ ($\rho_g/\rho i$) versus S/B ratio at 30 kNm^2 intensity for circular footings

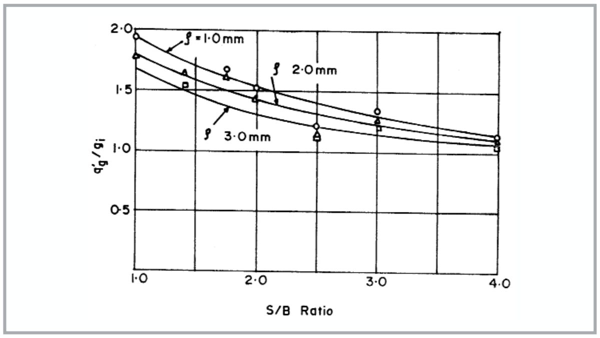

Figure 19: qg/qi versus S/B Ratio for Average Value of Square Footings

group of footings at constant settlement and q_i' is the pressure intensity of isolated footing at same settlement. For constant value of settlement, the pressure intensity ratio q_g'/q_i' decreases as S/B ratio increases. Similar trend was observed for strip and circular model footings.

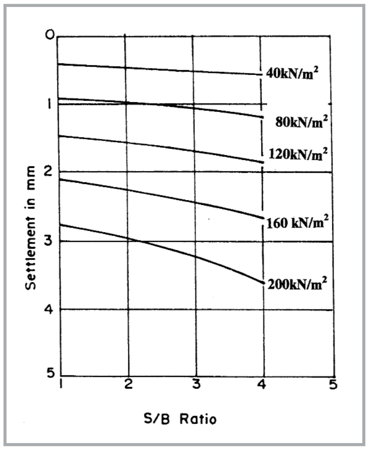

Figure 20: Settlement versus S/B Ratio at Equal Load Intensity for Strip Footings

Figure 20 shows settlement versus S/B ratio at equal load intensity for strip footings. It is clear from the figures that for equal loading intensity, settlement of footing decreases with decrease in spacing and for equal settlement, the loading intensity was found to increase with a decrease in spacing of the footings. Similar trend was observed for square and circular model footings.

5. CONCLUSION

1. Bearing capacity of model footings increases as the size of footing increases.
2. Bearing capacity of interfering footing is more than that of isolated footing of the same size.
3. Bearing capacity of interfering footing increases as spacing between them decreases.
4. For equal settlement, the loading intensity was found to increase with decrease in spacing of the footings.
5. Settlement for a given load intensity decreases as the spacing between the footings decreases.
6. In order to predict the increased bearing capacity of a square, strip and circular footings placed in a group, the Interference Efficiency Factor 'Fg' can be introduced in the Terzaghi's bearing capacity equation as under:

$$q_{ult} = 0.5\,\gamma\,B\,N_\gamma\,F_\gamma \qquad \text{(strip footing)}$$
$$q_{ult} = 0.4\,\gamma\,B\,N_\gamma\,F_\gamma \qquad \text{(square footing)}$$
$$q_{ult} = 0.3\,\gamma\,B\,N_\gamma\,F_\gamma \qquad \text{(circular footing)}$$

Where, qult = Ultimate bearing capacity of adjacent footing (kN/m^3),
γ = Density of soil (kN/m^3),
B = Diameter (width) of footing (m),
N_γ = Terzaghi's bearing capacity factor and
F_γ = Interference Efficiency Factor. ■

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