Behaviour of Footings Subjected to Two-way Eccentric Load

by

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Introduction

A foundation engineer generally comes across the problems of foundations subjected to two-way eccentric load e.g. the foundations of an abutment, retaining wall, columns and chimneys etc. In general, foundations of such structures are subjected to vertical load and moments about both the axes of foundation. Moments at the base of foundation are caused due to the horizontal forces acting on the structure. Horizontal forces may be due to earth pressure, wind pressure, seismic force, water current force etc. depending on the type of structure. The vertical load and moments may be replaced by an eccentric vertical load.

For satisfactory action of an eccentrically loaded footing, the following criterion need be satisfied.

(*i*) The footing must be safe against shear failure.

(*ii*) The footing must not settle excessively i.e. the settlement of the footing must be smaller than the permissible settlement.

(*iii*) The footing must not tilt excessively i.e. the tilt of the footing should be smaller than a permissible value.

In the past it was usual to design such footings by conventional theory. According to conventional theory, maximum base pressure below an eccentrically loaded footing is compared with the bearing capacity of centrally loaded footing of the same width.

Meyerhof (1953) was the first investigator who studied the problem of eccentrically loaded footings with the help of model tests. On the basis of test results, he developed a method for computing the bearing capacity of footings subjected to one-way eccentric load and two-way eccentric load respectively.

Model tests on footings were also reported by Eastwood (1955) Dhillon (1961), Zaharescu (1961), Prakash and Saran (1971) and Lee (1965). Of these investigators, only Dhillon Studied the problem of two-way eccentric load, while Eastwood, Zaharescu, Lee, and Prakash and Saran conducted

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The paper is open for discussion till the end of December, 1976.

model tests on footings subjected to one-way eccentric loads. Dhillon found that his model test results did not agree with Meyerhof's theory, whereas Eastwood, Zaharescu and Lee, found their results to be in good agreement with Meyerhof's theory. Prakash and Saran (1971) supported their theory which they developed for the computation of bearing capacity of eccentrically loaded footing.

Most of the above investigators studied only bearing capacity criteria. Only Dhillon (1961) and Prakash and Saran (1971) have paid attention to the determination of settlement and tilt. Prakash and Saran (1971) gave non-dimensional correlations for predicting settlement and tilt of footings subjected to one-way eccentric load, while Dhillon (1961) gave correlations which hold good for both one-way and two-way eccentric load.

It is evident from the brief introduction of the pertinent literature on the topic that a very meagre data is available on footings subjected to two-way eccentric loads.

In the present investigation it was proposed to study bearing capacity, settlement and tilt characteristics of footings subjected to two-way eccentric load with the help of model tests.

Development of Test Programme

Sand used

The test were performed on uniform, dry Ranipur Sand at relative density of 72 per cent.

Ranipur sand (d_{10}=0.11 mm, C_u=1.70, C_s=2.66) has angle of shearing resistance of 41° at 72 per cent relative density.

Footings

The tests were conducted on box type square footings (10 cm × 10 cm, 15 cm × 15 cm) and rectangular footings (10 cm × 20 cm, 10 cm × 40 cm) made of mild steel. In order to simulate the roughness of actual footings the bottom of footings were knurled. Rectangular steel strip of 3 cm width were placed on two perpendicular sides of each footing for fixing tilt meters (Figure 1). Every footing was marked at the centre and along the width such that eccentricity-width ratio (e_x/B) became 0, 0.1, 0.2 and 0.3. Similar marking was done along the length of the footing so that eccentricity-length ratio become 0, 0.1, 0.2 and 0.3.

Tank

Tests were conducted in box of 115 cm × 115 cm × 49 cm deep made of wooden planks stiffened with angle sections provided at bottom, top and all corners. Size of tank was selected according to the size of largest footing to be tested in it (Ghumman 1966).

Loading Device

Loads were applied to the footing by means of a screw jack acting through a calibrated proving ring. The screw jack was fitted in the web of a horizontal beam and was designed for the load carried by the largest footing tested. The horizontal beam (I Section) was bolted to the two

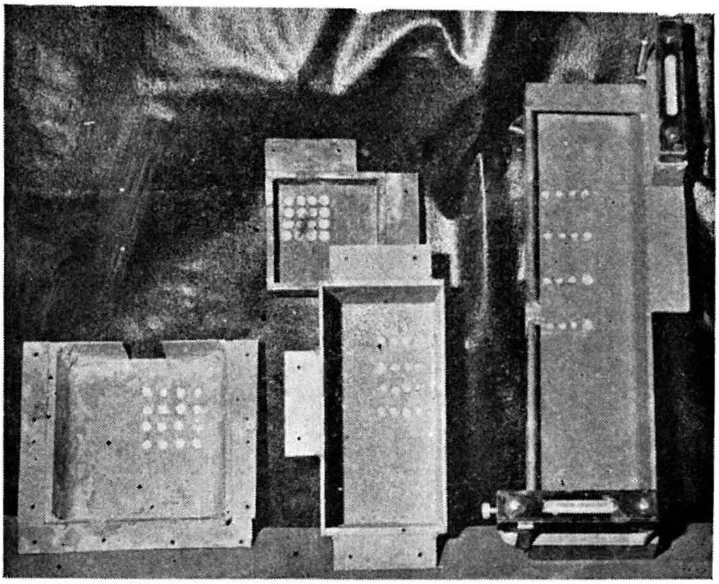


FIGURE 1. Footings and arrangement of tiltmeters on a footing

vertical posts. Posts were attached to the two parallel sides of the tank so that the horizontal beam was placed across the middle of the tank (Figures 2 and 3).

Settlement Measurement

The settlement of the point of load applications were measured with Baty dial gauges with a least count of 0.01 mm. These dial gauges were fixed through magnetic base to the rigid beam placed across the tank. For each footing two dial gauges were used (Figures 2 and 3).

Tilt Measurement

The tilts were measured by two tilt meters mounted on the top of the footing. These were placed in two perpendicular directions so as to give the tilts of the footing along length and width separately. The least count of these tilt meters was 20 seconds.

Sand Placing Technique

Sand was filled in the tank by the method of Rain-fall. The sand was allowed to fall through the holes of 3 mm diameter spaced by 2.54 cm distance from centre to centre. Preliminary investigations showed that there is no significant change in density of sand if the height of fall of sand was kept at 1.5 m above the top of the tank. In all tests the height of the mesh was kept 1.5 m above the top of the tank.

The relative density so obtained was 75 per cent. The uniformity of compaction was checked by penetration tests.

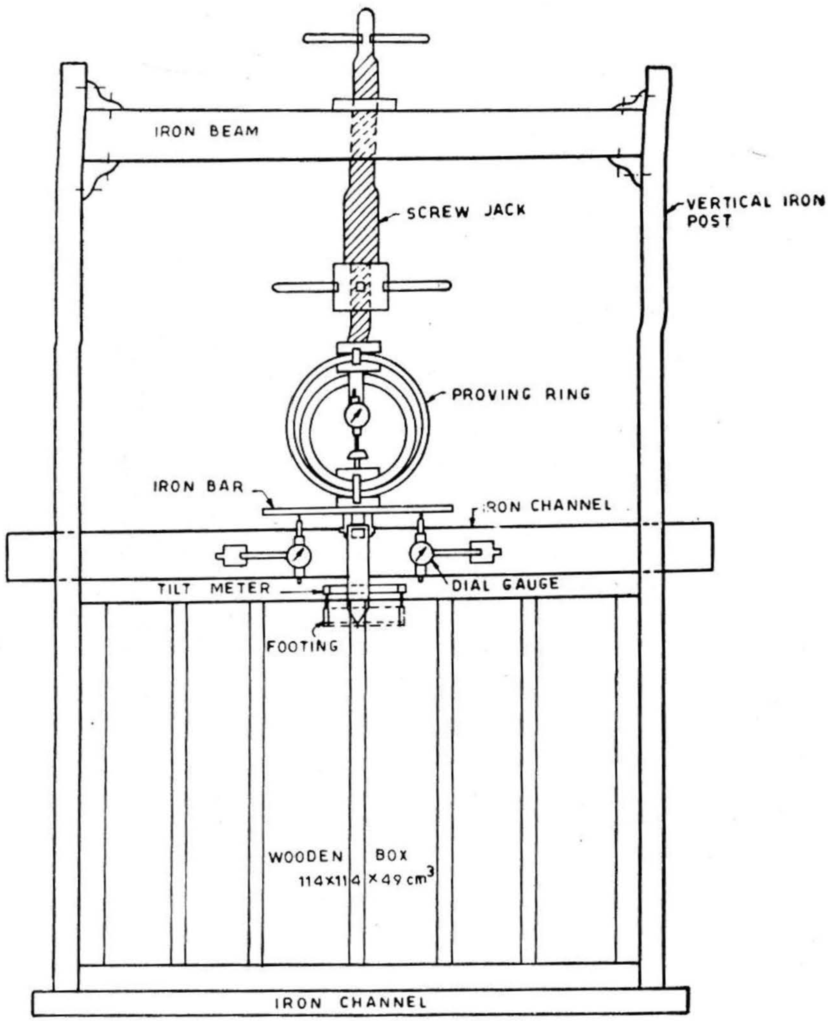


FIGURE 2. Details of the loading arrangement

Test Procedure and Test Results

Firstly the sand was placed in the tank to the desired depth by rainfall technique. The top surface of sand was then made plain and a grid was made in the centre of the tank with the help of coloured Ranipur Sand to facilitate the study of rupture surface and taking the photograph of the same. After this the footing was positioned at the centre with all the devices for settlement and tilt measurements. The end of tapered loading rod was then just touched to the groove of the footing corresponding to the desired eccentricity. The load on the footing was then applied in small increments and the next increment was applied only when the settlement and tilt readings become sensibly constant.

For each increment of the load, the following four reading were taken:

(*i*) Load: It is obtained from the reading of proving ring. (Figure 3)

(*ii*) Settlement of the point of load application: It is taken as the average of the settlements observed on the two dial gauges (Figure 3).

(*iii*) Tilt about *YY*-axis (t_{yy}): It is obtained from the reading of the tilt meter mounted on the footing along its longitudinal axis.

(*iv*) Tilt about *XX*-axis (t_{xx}): It is obtained from the reading of tilt meter mounted on the footing along its transverse axis.

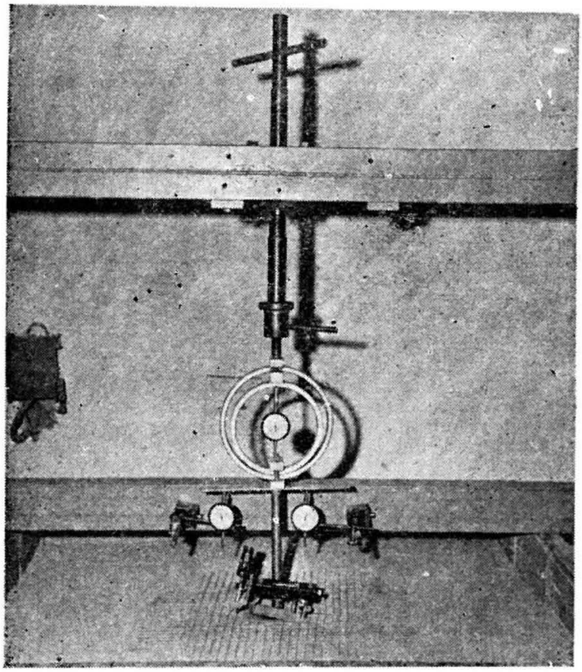


FIGURE 3. Test set up

Adopting the procedure discussed above, 64 tests as listed in Table 1 were performed. For each test, unit load versus S_e, unit load versus t_{xx}, unit load versus t_{yy} were plotted. For tests 5 to 8, these curves are shown respectively in Figures 4a, 4b and 4c. For other tests, similar plots were prepared and are not included here due to limitation of space.

Discussion of Test Results

Ultimate bearing capacity

Ultimate bearing capacity is defined as the maximum load per unit area that a footing can take without causing shear failure. It is obtained from load versus settlement (S_e) curve as the peak load (i.e. load corresponding to the points A, B, C, X and D for tests 5 to 8 (Figure 4a). For other tests ultimate bearing capacity is obtained from similar curves (not shown).

Values of ultimate bearing capacities have been plotted in Figure 5. Figure 5(a) represents the effect of e_x/B on failure keeping the eccentricity e_y/L as zero. This Figure indicates that bearing capacity decreases with the increase in e_x/B.

TABLE I

Statement of Tests Performed

(Relative density of soil = 72%)

Test No.	$\frac{e_y}{L}$	$\frac{e_x}{L}$	Test No.	$\frac{e_y}{L}$	$\frac{e_x}{B}$	Test No.	$\frac{e_y}{L}$	$\frac{e_x}{B}$	Test No.	$\frac{e_y}{L}$	$\frac{e_x}{B}$
Square Footing, 10 cm × 10 cm											
1	0	0.0	5	0.1	0.0	9	0.2	0.0	13	0.3	0.0
2	0	0.1	6	0.1	0.1	10	0.2	0.1	14	0.3	0.1
3	0	0.2	7	0.1	0.2	11	0.2	0.2	15	0.3	0.2
4	0	0.3	8	0.1	0.3	12	0.2	0.3	16	0.3	0.3
Square Footing, 15 cm × 15 cm											
17	0	0.0	21	0.1	0.0	25	0.2	0.0	29	0.3	0.0
18	0	0.1	22	0.1	0.1	26	0.2	0.1	30	0.3	0.1
19	0	0.2	23	0.1	0.2	27	0.2	0.2	31	0.3	0.2
20	0	0.3	24	0.1	0.3	28	0.2	0.3	32	0.3	0.3
Rectangular Footing, 10 cm × 20 cm											
33	0	0.0	37	0.1	0.0	41	0.2	0.0	45	0.3	0.0
34	0	0.1	38	0.1	0.1	42	0.2	0.1	46	0.3	0.1
35	0	0.2	39	0.1	0.2	43	0.2	0.2	47	0.3	0.2
36	0	0.3	40	0.1	0.3	44	0.2	0.3	48	0.3	0.3
Rectangular Footing, 10 cm × 40 cm											
49	0	0.0	53	0.1	0.0	57	0.2	0.0	61	0.3	0.0
50	0	0.1	54	0.1	0.1	58	0.2	0.1	62	0·3	0.1
51	0	0.2	55	0.1	0.2	59	0.2	0.2	63	0.3	0.2
52	0	0.3	56	0.1	0.3	60	0.2	0.3	64	0.3	0.3

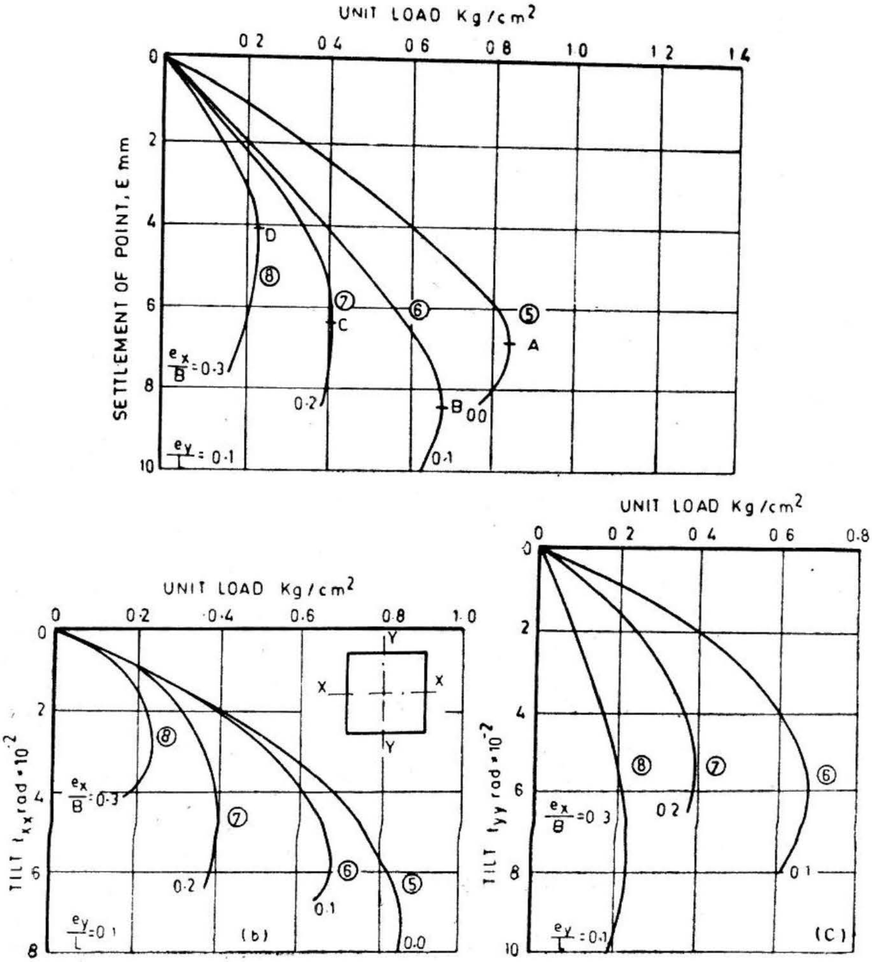


FIGURE 4. Unit Load versus settlement and tilt curves

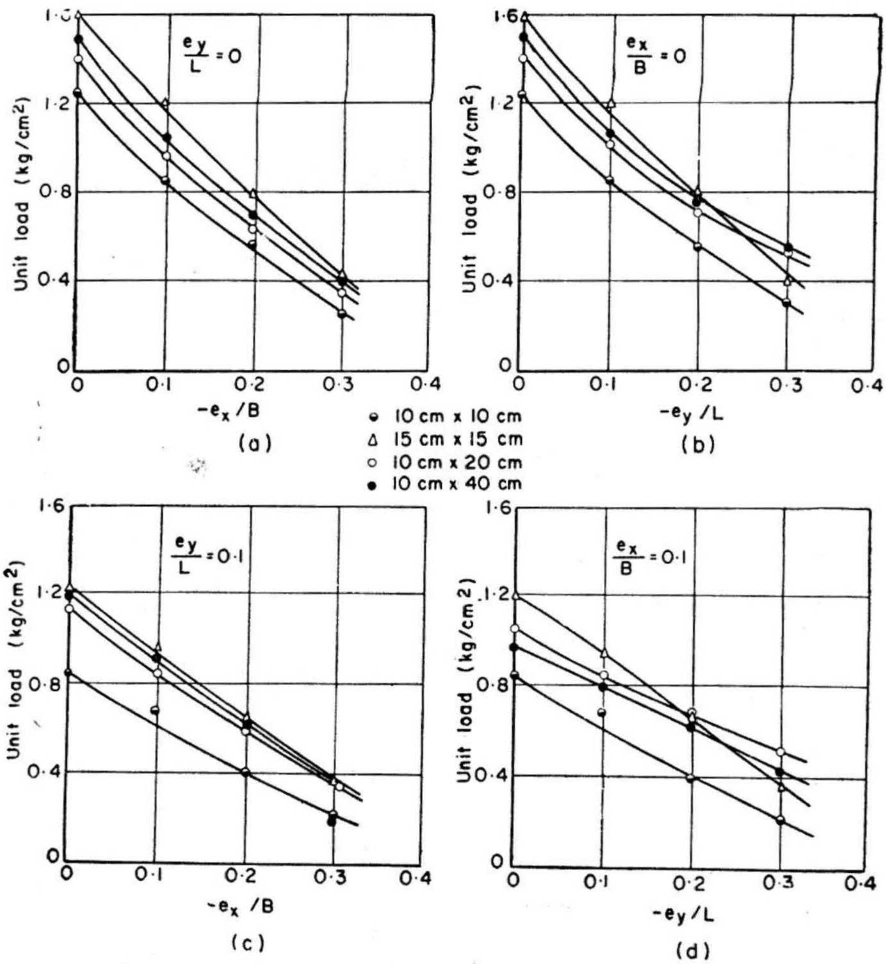


FIGURE 5. Unit Load versus eccentricity—width/length ratio

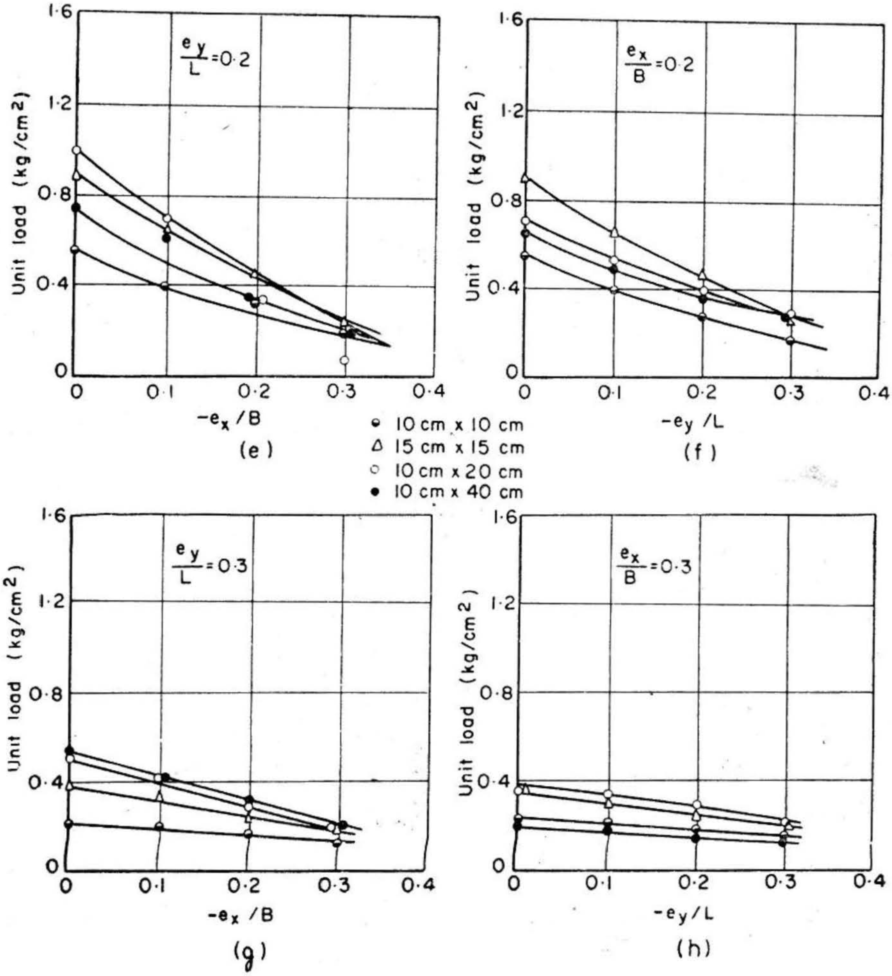


FIGURE 5 (contd). Unit Load versus eccentricity—width/length ratio

Figure 5(b) represents the effect of e_y/L on bearing capacity when $e_x/B=0$. The trend of variation of bearing capacity with e_y/L ratio is same as its trend with e_x/B ratio. However, a careful examination of these two figures indicates that the effect of e_x/B is more than the effect of e_y/L i e. the bearing capacity of footing at particular e_x/B is lesser than the bearing capacity of the footing having equivalent e_y/L. Figure 5(c), (e) and (g) represent the plots of unit load versus e_x/B for $e_y/L=0.1$, 0.2 and 0.3 respectively. Their trend is same as that of Figure 5(a). The trend of Figure 5 (d), (f) and (h) which are the plots between unit load and e_y/L is same as that of Figure 5(a). It can be concluded from these Figures that the eccentricities in both the directions have accumulative effect of reducing the bearing capacity.

Comparison of Results with Previous Investigators

As mentioned in introduction that only two investigators Meyerhof (1953) and Dhillon (1961) studied the problems of footings subjected to two-way eccentric load. Here, therefore, attempt is made to compare our results with the work of these investigators.

Figure 6 shows a comparison between the observed results and the results computed by Meyerhof's theory. It is evident from the Figure that an excellent agreement is there. However, there is significant scatter in very few points.

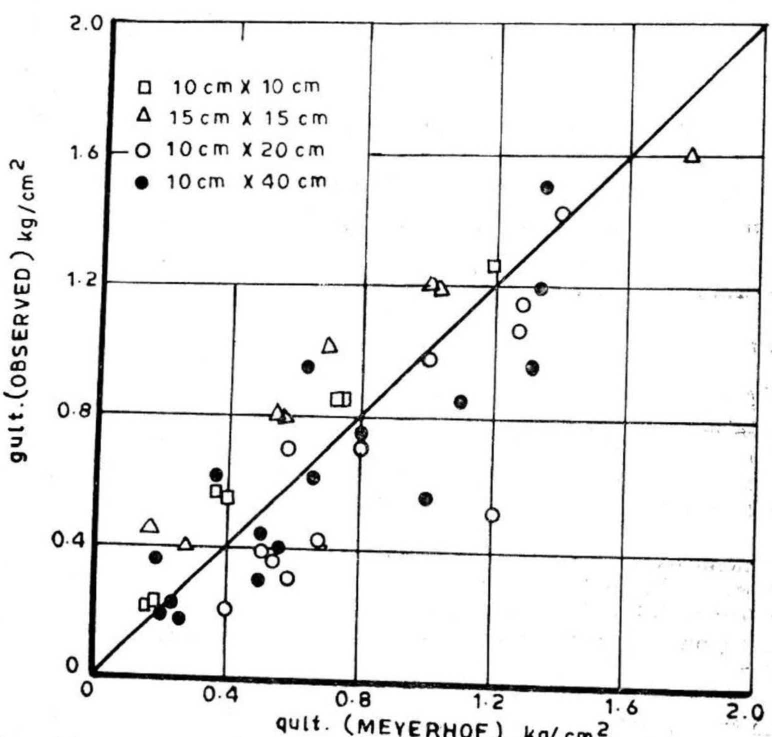


FIGURE 6. Comparison of bearing capacity (observed and Meyerhof's theory)

Figure 7 shows the comparison with the results of Dhillon. A good agreement between the two can be observed from this Figure. In most of the cases it is found that observed values are slightly higher than those computed by Dhillon's formula.

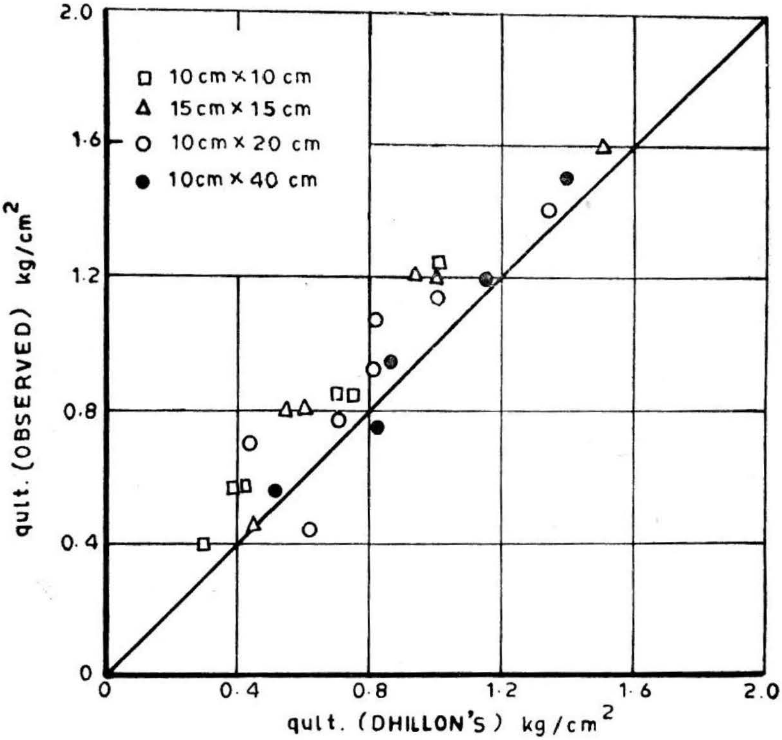


FIGURE 7. Comparison of bearing capacity (observed and Dhillon's theory)

Settlement and Tilt Characteristics

General

Figure 4a shows the load versus settlement curves. Settlements corresponding to points F, G, H and I represent the settlement of footings at pressure 0.1 kg/cm² for tests 5 to 8. It shows that for the same pressure settlement of footing increases with the increase in eccentricity value. Similar trend was obtained for other tests.

Settlements corresponding to points A, B, C and D represents the settlement at failure loads (Figure 4). It is evident from this figure that settlement at failure load decreases with increase in eccentricity. It means that it follows a reverse trend as discussed for the settlement at uniform pressure.

An examination of unit load versus t_{xx} and unit load versus t_{yy} curves (Figures 4b and 4c) indicates that trends of variation of tilt with respect to eccentricities are the same as of the settlement.

Maximum settlement of footing

As discussed earlier, observations were taken for settlement at the point of load application. Maximum settlement will occur at the corner of the footing nearest to eccentric load and it can be obtained by considering the deformation of a rigid footing as shown in Figure 8. Consider two points '*a*' and '*b*' on the two adjacent edges *ad* and *ab* of the footings *abcd* such that $a'a = Eb' = Ea' = ab'$.

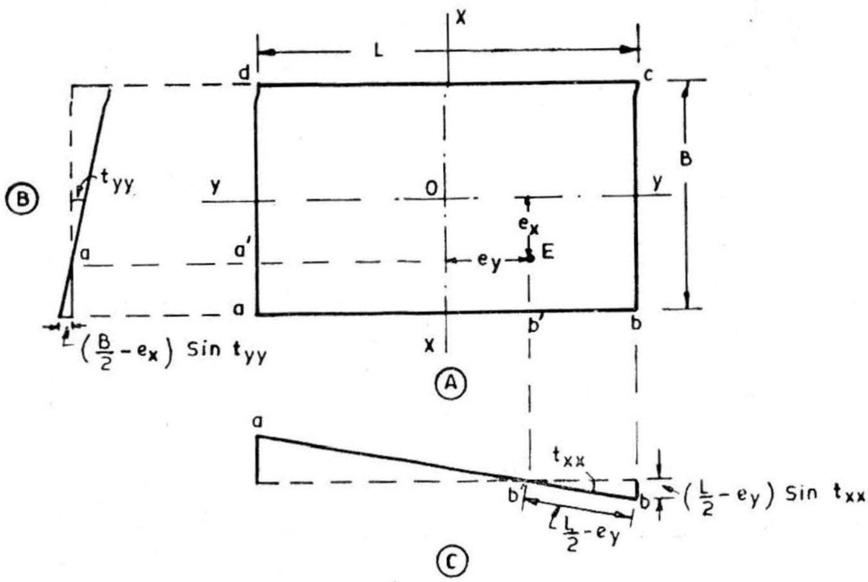


FIGURE 8. Computation of settlements caused by tilts about major and minor axis

As *E* point has eccentricities about both the axis (e_x and e_y.), the point b settles due to tilt t_{yy} of footing about *yy*-axis and tilt t_{xx} about XX-axis.

Settlement of point a w.r.t. $a' = a'a \sin tyy$

$$\text{or } S_1 = (\tfrac{1}{2}B - e_x) \sin t_{yy} \quad \ldots \quad (1)$$

As footing is rigid, the settlement of point b' with respect to E will be the same as that with respect to a'.

Settlement of b' with respect to $E = (\tfrac{1}{2}B - e_x) \sin t_{yy}$

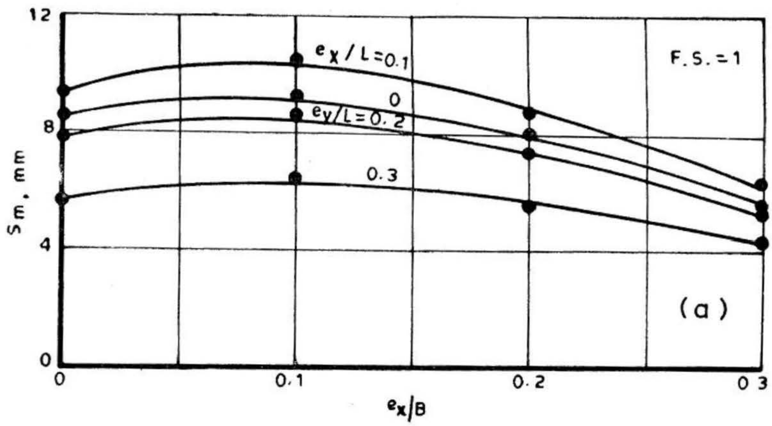
Settlement of *B* with respect to $b' = bb' \sin t_{xx}$

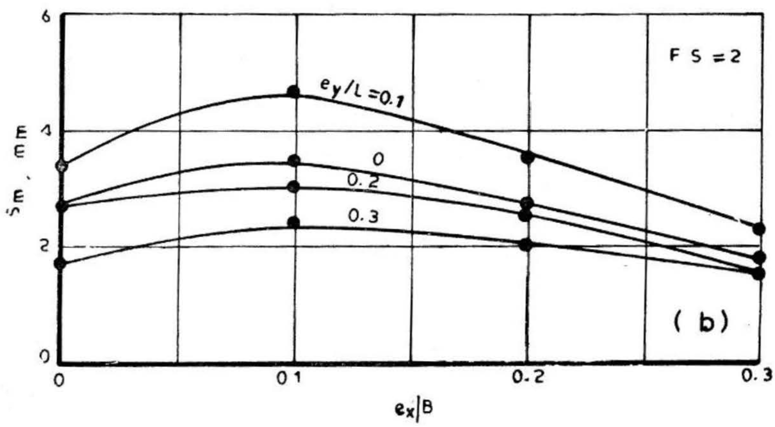
$$S_2 = (\tfrac{1}{2}L - e_y) \sin t_{xx} \quad \ldots \quad (2)$$

If S_e be the settlement of the point *E*, with respect to the centre O, the settlement of the point b' with respect to *C* will be $(S_e + S_1 + S_2)$

$$\text{Therefore } S_m = S_e + (\tfrac{1}{2}B - e_x) \sin t_{yy} + (\tfrac{1}{2}L - e_y) \sin t_{xx} \quad \ldots \quad (3)$$

Values of S_e, t_{xx} and t_{yy} were obtained for $F.S. = 1.2$ and 3 using curves shown in Figure 4 and similar curves (not shown) for each test. The details of procedure for computation are given elsewhere (Singh (1973), Prakash and Saran (1971)). Using the computed values of S_e, t_{xx} and t_{yy}, S_m





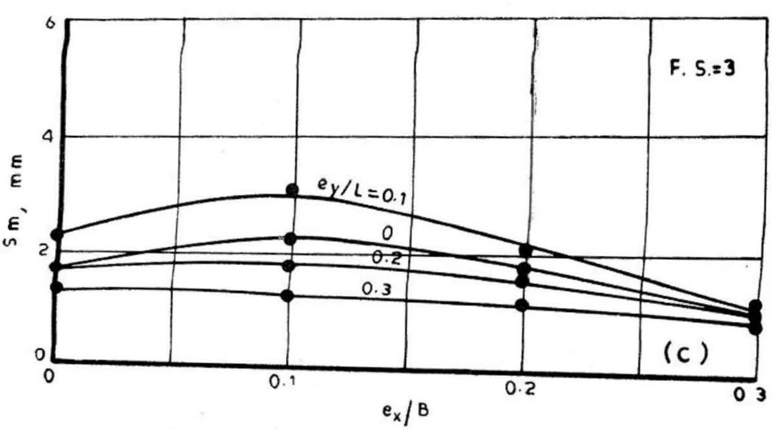


FIGURE 9. Maximum settlement versus eccentricity—width ratio for different factor of safety (Footing 10 cm × 10 cm)

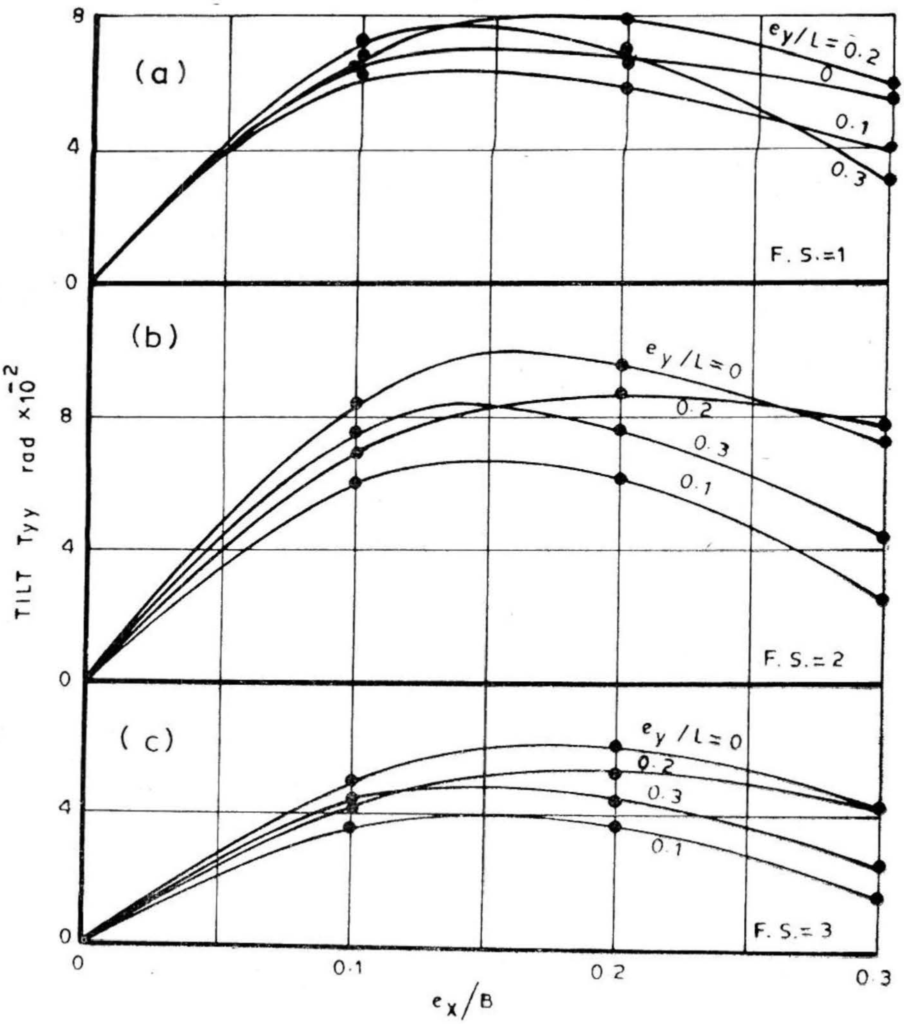


FIGURE 10. Tilt versus eccentricity – width ratio footing (10 cm × 10 cm)

is obtained from Equation (3). Values of S_m so obtaind are given in Figure 9 for footing 10 cm × 10 cm size. It is evident from these curves that S_m attains maximum value when $e_x/B=0.1$ and $e_y/L=0.1$ at all factor of safety. Exactly similar trend was obtained for other size of footings tested in this investigation.

Tilt of footing

Values of tilt obtained at various F.S. for 10 cm × 10 cm size footing are shown in Figure 10. It is evident from this figure that tilt attains maximum value when $e_x/B=e_y/L=0.167$. This trend may be explained with the help of Figure 11 having a plot of moment versus e_x/B. Moment is obtained as the product of vertical load and corresponding eccentricity. This figure indicates that moment attains maximum value at $e_x/B=0.167$. Same value of e_x/B has been obtained for other footings and factors of safety. Curves have been plotted in moment and e_y/L and it is found that moment attains maximum value when $e_y/L=0.167$. These plots are not shown here. As the tilt of footing is caused by the moment only, therefore tilt will be maximum at the eccentricity at which maximum moment occurs. This explains the reason of maximum tilt at $e_x/B=e_y/L=0.167$.

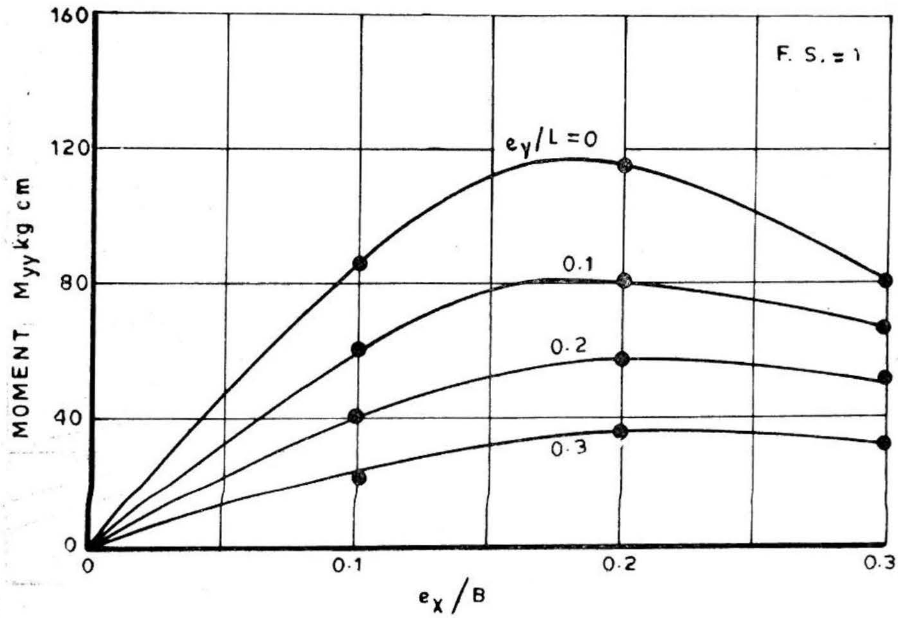


FIGURE 11. Moment versus eccentricity—width ratio (Footing 10 cm × 10 cm

Exactly similar trends were obtained in the cases of rectangular footings. The details are given elsewhere (Singh 1973).

Conclusions

1. Bearing capacity of footing decreases with the increase in e_x/B and e_y/L ratios, e_x and e_y being the eccentricties along the width and the length of footing.

2. For the same pressure settlement and tilts of eccentrically loaded footings increase with the increase in e_x/B and e_y/L. At failure settlement and tilts follow reverse trend i.e. the value decreases with the increase in eccentricities.

3. Maximum settlement of the footing occurs at $e_x/B = e_y/L = 0.1$.

4. Maximum tilts of the footing occurs at $e_x/B = e_y/L = 0.167$.

5. Observed data is found to agree reasonably with the results of previous investigators (Dhillon 1961)), (Meyerhof 1953).

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