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# Behaviour of Eccentrically Loaded Shallow Foundations on Granular Soils

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**ABSTRACT:** The conventional method of footing design requires sufficient safety against failure and the settlement must be kept within the allowable limit. These requirements are dependent on the bearing capacity of soil. To have the safe design, the bearing pressure on the underlying ground has to be kept within the safe allowable limit. Thus the estimation of load carrying capacity of footing is the most important step in design of foundation. All the bearing capacity estimation methods may be classified into the following four categories: (1) the limit equilibrium method; (2) the method of characteristics; (3) the upper-bound plastic limit analysis; (4) slip line method and (5) the numerical methods based on either the finite-element method or finite-difference method. Footings are very often subjected to eccentric loads. This problem has been studied in detail by few investigators. The effective width method by Meyerhof (1953) is widely used for calculating the bearing capacity of eccentrically loaded footings. A stability analysis based on a slip surface derived from experimental results is presented by Purkayastha and Char (1977) for eccentrically loaded strip footings resting on sand.

**KEYWORDS:** HDMR, Fragility Curve, Cornell's Method, Latin Hypercube Sampling, MCS, Probability of exceedance

## I. INTRODUCTION

### Bearing Capacity of Shallow Foundations on granular soil

The stability of a structure depends upon the stability of the supporting soil. For that the foundation must be stable against shear failure of the supporting soil and must not settle beyond a tolerable limit to avoid damage to the structure. For a given foundation to perform its optimum capacity, one must be ensured that it does not exceed its ultimate bearing capacity. Since the publications of Terzaghi's theory on the bearing capacity of shallow foundations in 1943, numerous studies have been made by various investigators. Most of these studies are related to footings subjected to vertical and central loads. Meyerhof (1953) developed empirical procedures for estimating the ultimate bearing capacity of foundations subjected to eccentric vertical loads. Researchers like Prakash and Saran (1971) and Purkayastha and Char (1977) also studied on the eccentrically loaded footings. An extensive review of literature based on bearing capacity of shallow foundations under eccentric loading conditions is presented below.

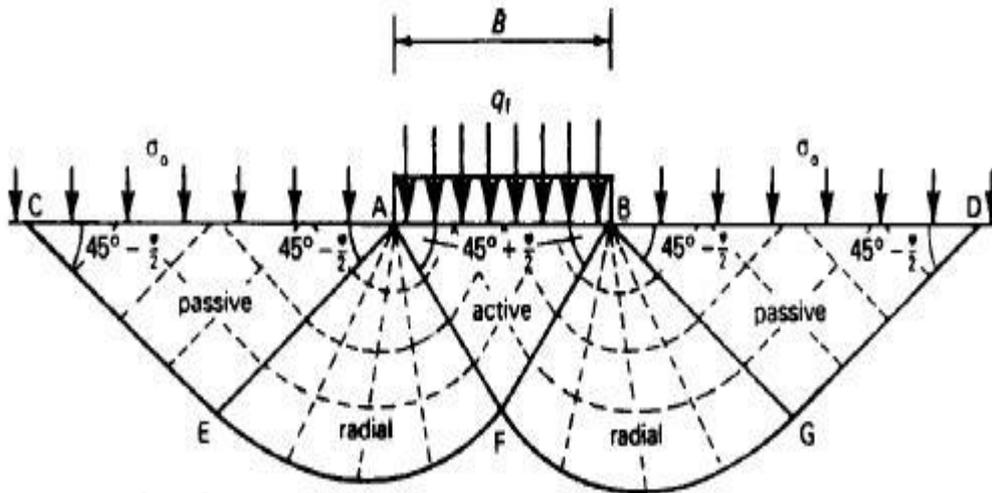
### Centric vertical condition

**Terzaghi (1948)** proposed a well-conceived theory to determine the ultimate bearing capacity of a shallow, rough, rigid, continuous (strip) foundation supported by a homogeneous soil layer extending to a great depth with vertical loading. Terzaghi suggested the following relationships in soil

The failure area in the soil under the foundation can be divided into three major zones:

1. Zone AFB. This is a triangular elastic zone located immediately below the bottom of the foundation. The inclination of sides AF and BF of the wedge with the horizontal is  $\alpha$  (soil friction angle).
2. Zone BFG. This zone is the Prandtl's radial shear zone.

3. Zone BGD. This zone is the Rankine passive zone. The slip lines in this zone make angles of  $(45^\circ - \Phi/2)$  with the horizontal as given in below figure 2.1.

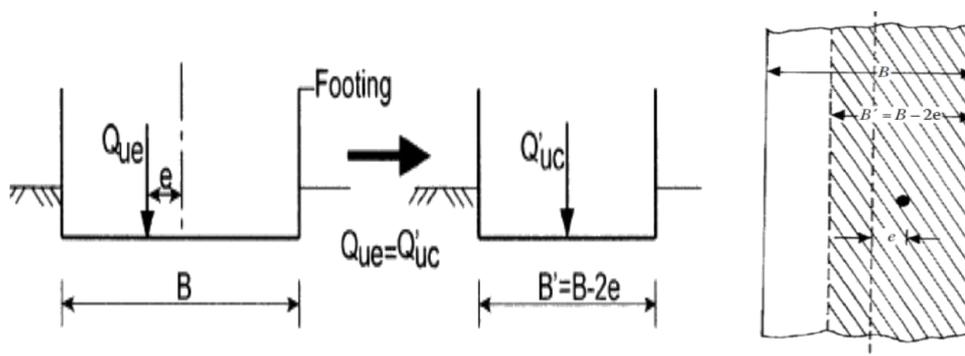


2.2.2 Eccentric vertical condition

Meyerhof (1953) developed an empirical concept by which an eccentrically loaded footing may be regarded as a centrally loaded footing of reduced width. When a shallow foundation is subjected to an eccentric load, it is assumed that the contact pressure decreases linearly from the toe to the heel because at ultimate load, the contact pressure is not linear. The effective width  $B'$  suggested by Meyerhof (1953) defined as

$$B' = B - 2e$$

where  $e$  = load eccentricity



II. MATERIAL USED AND EXPERIMENTAL PROCEDURE

Introduction

The experimental program was designed to study the bearing capacity of eccentrically loaded rectangular footing on granular soil (sand). For this purpose, the laboratory model tests were conducted on rectangular footings in 69% relative density, load eccentricity  $e$  was varied from 0 to  $0.15B$  ( $B$  = width of rectangular footing) at an increment of  $0.05B$ , and the depth of embedment ( $D_f/B$ ) was varied from 0 to 1.0 at an increment of 0.5. The ultimate bearing capacity was interpreted from each test and analyzed.



**Material Used**

**Sand**

The sand used in the experimental program was collected from the river bed of Koel River. It is made free from roots, organic matters etc. by washing and cleaning. The above sample was then oven dried and properly sieved by passing through 710 micron and retained at 300 micron IS sieve to get the required grading. Dry sand is used as soil medium for the test as it does not include the effect of moisture. The geotechnical properties of the sand used is given in Table 3.1. The grain size distribution curve is plotted in Figure 3.1. All the tests were conducted in 69% relative density. The unit weight for 69% relative density is 14.36 kN/m<sup>3</sup> and the friction angle at 69% relative is 40.8° which are found out from direct shear tests.

Table 3.1: Geotechnical property of sand

Property	Value
Specific gravity ( <i>G</i> )	2.64
Effective particle size ( <i>D10</i> )	0.33mm
particle size ( <i>D30</i> )	0.43mm
particle size ( <i>D60</i> )	0.47 mm
Uniformity Coefficient ( <i>Cu</i> )	1.42
Coefficient of Curvature ( <i>Cc</i> )	1.19
Maximum unit weight ( ( ))	15.09 kN/m <sup>3</sup>
Minimum unit weight ( ( ))	13.00 kN/m <sup>3</sup>

Figure 3.1: Grain-size distribution curve of sand

**2.3.1 Surface Footing at Eccentric Loading Conditions**

The ultimate bearing capacity of square footings (10cm x 10cm) with eccentric loading of (*e/B* = 0.05, 0.1, and 0.15) has been found out. The values obtained are presented in Table 5.5 (col.2) and shows in Fig.5.10. Similarly, for surface rectangular footing with load eccentricities the ultimate bearing capacities have been computed and shown in Figure 5.12. It is found that for eccentric loading of 10cm x 20 cm size rectangular footing i.e. *e/B*=0.05, 0.1, 0.15 the ultimate bearing capacities are 114 kN/m<sup>2</sup>, 100 kN/m<sup>2</sup> and 90 kN/m<sup>2</sup> respectively. It is observed that the Ultimate Bearing Capacity decreases with increase in eccentricity both in square as well as rectangular footing.



Table 5.4: Model test parameters for the case of Eccentric Loading condition

B/L	Sand type	Unit weight (kN/m <sup>3</sup> )	Relative Density of sand %	Friction angle - direct shear test (degree)	D <sub>f</sub> /B	e/B	
1	Dense	14.36	69	40.8	0	0	
					0.5	0.05	
					1.0	0.1	
						0.15	
0.5	Dense	14.36	69	40.8	0	0	
							0.05
							0.1
							0.15

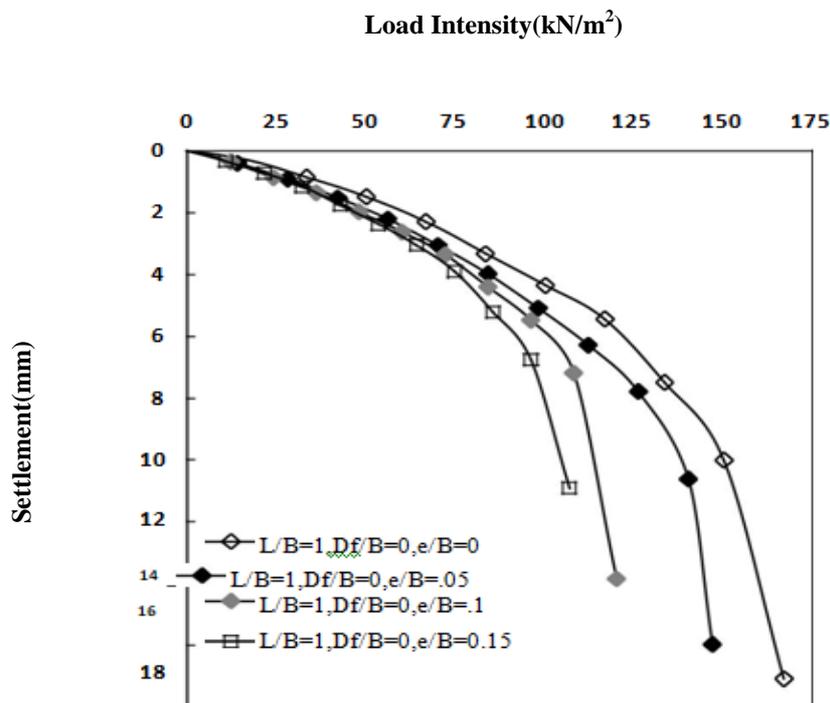


Figure 5.11: Comparison of ultimate bearing capacities of Present experimental results with different available theories



Table 5.5: Calculated values of ultimate bearing capacities ( $q_u$ ) by different theories for eccentric condition along with Present experimental values at surface condition

e/B	present Experiment; $q_u$ (kN/m <sup>2</sup> ) (1)	Terzaghi (1943); $q_u$ (kN/m <sup>2</sup> ) (3)	Meyerhof (1953); $q_u$ (kN/m <sup>2</sup> ) (4)	Hansen (1970); $q_u$ (kN/m <sup>2</sup> ) (5)	Vesic (1973); $q_u$ (kN/m <sup>2</sup> ) (6)	Is code 6430-1981; $q_u$ (kN/m <sup>2</sup> ) (7)
0	121	77.81	116.2	39.5	54.164	72.219
0.05	102	70.03	101.24	37.927	48.748	64.997
0.1	78	62.25	86.97	35.820	43.3315	57.775
0.15	67	54.5	73.423	33.186	37.915	50.553

Figure 5.12: Load Intensity vs. Settlement for Footing size 10cmx20cm with  $e=0, 0.05B, 0.1B$  and  $0.15B$

### 2.3.2 Embedded Footing at Eccentric Loading Conditions

Load-settlement curves have been plotted for the case of eccentrically embedded footing to show the effect of embedment and effect of eccentricity. These are shown in Figs. 5.13 through 5.17. It is seen from the Figs. 5.13 and 5.14 that at depth of embedment equal to 0.5B or 1.0B, the bearing pressure at any settlement level decreases with increase in eccentricity like surface footing. Similarly, Figs. 5.15 through 5.17 indicate that at any eccentricity, the bearing pressure increases with increase in depth of embedment at any level of settlement. The ultimate bearing capacities of eccentrically loaded square footings (10cm x 10cm) at 0.5B and 1B depth of embedment have been found out. The values obtained are presented in Table 5.6 (col.3). The same has been shown in Figs.5.13 and 5.14. It is seen that the ultimate bearing capacity of footing increases with the increase in depth of embedment at any eccentricity. Similarly, at any depth of embedment, the ultimate bearing capacity decreases with increase in eccentricity.



Figure 5.23: Comparison of Present experimental results with Purkayastha and Char (1977) with  $D_f/B=1$

Table 5.8: Calculated values of  $R_k$  by Purkayastha and Char (1977) for eccentric vertical condition along with Present experimental values

$D_f/B$	$e/B$	Present Experiment; $R_k$	Purkayastha and Char (1977); $R_k$
0	0	1	1
	0.05	0.84	0.79
	0.1	0.64	0.65
	0.15	0.54	0.53
0.5	0	1	1
	0.05	0.83	0.84
	0.1	0.74	0.72
	0.15	0.60	0.62
1	0	1.00	1
	0.05	0.87	0.87
	0.1	0.76	0.76
	0.15	0.67	0.66

#### 5.4 Analysis of Test Results

The ultimate bearing capacities of square foundations determined from experimental model tests in the laboratory are given in Table 5.9 (Col. 3). As discussed in section 5.1, in order to quantify certain parameters like  $e/B$ ,  $D_f/B$  all the model test results have been analyzed using Nonlinear Regression Analysis (NLREG). NLREG performs statistical regression analysis to estimate the values of parameters for linear, multivariate, polynomial, logistic, exponential, and general nonlinear functions. The regression analysis determines the values of the coefficients that cause the function to best fit the observed data that is being provided. The reduction factor concept as discussed in section 5.1 use the proposed Eqs. 5.2 and 5.3 to predict the ultimate bearing capacity of square foundation subjected to eccentric load. The following procedure is adopted to analyze the test results and develop the reduction factor.



**Step 1:**

for a given  $D_f/B$  regression analyses is performed to obtain the magnitudes of  $b$  and  $n$ . Regression analysis has been done to determine the values of  $b$  and  $n$  for each depth of embedment ( $D_f$ ).

**Step 2:**

The values of  $b$  and  $n$  obtained from analyses in step 1 are shown in Table 5.10. It can be seen from Table 5.9 that the variations of  $b$  and  $n$  with  $D_f/B$  are very minimal. The average values of  $b$  and  $n$  are 1.954 and 0.84 respectively. We can assume without loss of much accuracy. The experimental values of RF defined by Eq. (5.2) are shown in Col. 4 of Table 5.9. For comparison purposes, the predicted values of the reduction factor RF obtained using Eqs. (5.4), (5.5) and (5.6) are shown in Col. 5 of Table 5.9. The deviations of the predicted values of RF from those obtained experimentally are shown in Col. 6 of Table 5.9. It is seen in most cases the deviations are  $\pm 10\%$  or less; except in one case where the deviation is about 20%. Thus Eqs. (5.4), (5.5) and (5.6) provide a reasonable good and simple approximation to estimate the ultimate bearing capacity of square foundations ( $0 \leq D_f/B \leq 1$ ) subjected to eccentric loading.

Table 5.10: Variation of  $b$  and  $n$  [Eq. (5.4)] along with  $R^2$  values

$D_f/B$	$b$	$n$	$r^2$
0	2.354	0.8558	0.9863
0.5	1.888	0.8297	0.9927
1	1.62	0.8357	0.9996

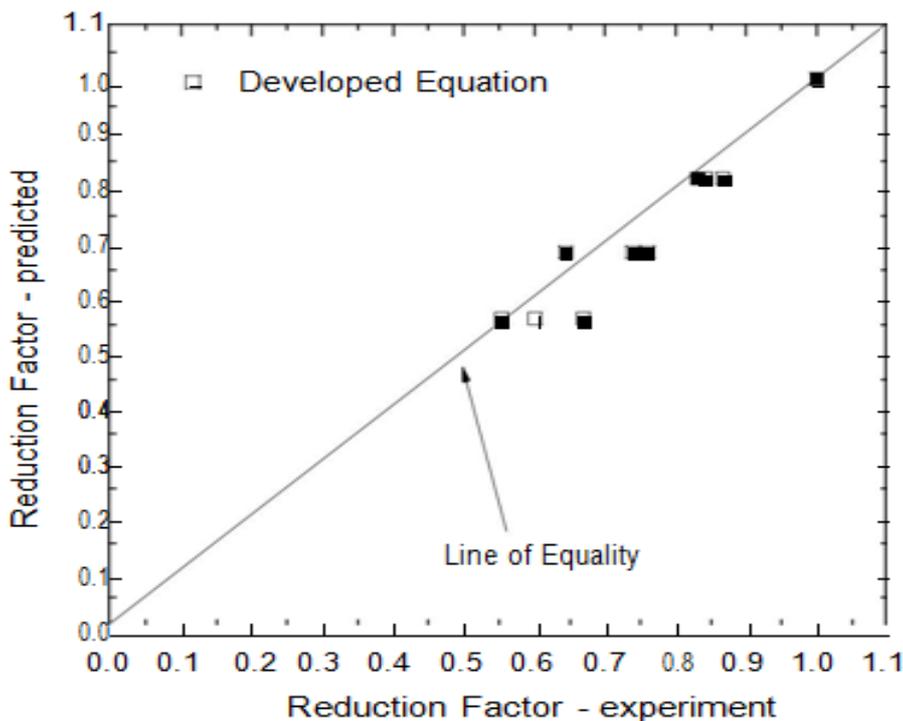


Figure 5.24: Comparison of Reduction Factors obtained from present experimental results



Table 5.12: Reduction Factor Comparison of Meyerhof (1953) with Present results

$D_f/B$	$e/B$	Experimental $qu$ (kN/m <sup>2</sup> )	Experimental $(\frac{qu}{RF})$ RF= $(\frac{qu}{RF})$ (4)	Predicted $RF$ [Eqs.5.4, 5.5,and 5.6]	$RF$ corresponding to Meyerhof	Deviation $\frac{Col.5-col.4}{Col.5}$ (%)
(1)	(2)	(3)		(5)	(6)	(7)
0	0	121	1	1	1	0
	0.05	102	0.84	0.82	0.85	3.54
	0.1	78	0.64	0.68	0.73	6.52
	0.15	67	0.55	0.56	0.62	9.96
0.5	0	238	1	1.00	1.00	0
	0.05	198	0.83	0.82	0.85	3.54
	0.1	176	0.74	0.68	0.73	6.52
	0.15	143	0.60	0.56	0.62	9.96
1	0	339	1.00	1.00	1.00	0
	0.05	294	0.87	0.82	0.85	3.54
	0.1	258	0.76	0.68	0.73	6.52
	0.15	227	0.67	0.56	0.62	9.96

### III. FUTURE RESEARCH WORK

The present thesis pertains to the study on the bearing capacity of eccentrically loaded square footing at different depth of embedment i.e.  $D_f/B=0, 0.5, 1.0$  on sand bed and eccentrically loaded rectangular footing (10cm X 20cm) at surface condition. Due to time constraint all other aspects related to shallow foundations could not be studied. The future research work should address the below mentioned points:



- The present work can be extended to study the behavior of rectangular foundations of different sizes at different depth of embedment ( $D_f/B=0.5, 1.0$ )
- Large scale study should be carried out to validate the present developed equations.
- The present work can be extended to foundations on cohesive soil.
- The present work can be extended to reinforced soil condition for different depth of embedment.

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