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[I-CONCEPTS-18] ISSN 2348 – 8034
Impact Factor- 5.070

GLOBAL JOURNAL OF ENGINEERING SCIENCE AND RESEARCHES

LOAD - DISPLACEMENT AND MOMENT - ROTATION RESPONSE OF SQUARE FOOTING UNDER MOMENT LOADING

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ABSTRACT

Foundations are often subjected to moment loading due to eccentricity of loading. Foundation tilts and the pressure below the footing does not remain uniform. The tilt of footing increases with an increase in the eccentricity and the bearing capacity reduces considerably. The under eccentric loading, the overall load-settlement behavior plays a key role for the design, first in estimating the settlement at a given load and second in interpreting the failure load or bearing capacity. Model tests are conducted on square foundation to study the response of square foundation under moment loading. A laboratory testing program includes 40 tests to analyze displacements and rotations of the foundation due to eccentricity with and without geo-grid in the foundation bed. Tests are performed in which the load eccentricity footing width ratios (e/B) used are 0, 1/48, 1/24 1/12 , 1/8. The test soil consisted of a fine and poorly-graded sand contained in a tank of circular in shape having 111cm diameter in cross section and 55 cm deep. Results shows decrease in ultimate load with the increase in eccentricity footing width ratio (e/B). The foundation settlement at failure is increases with increase in e/B ratio. The reduction in ultimate load is counteracted by the Geogrid reinforcement placed in the foundation soil.

I. INTRODUCTION

Design of foundations requires estimation of bearing capacity and settlements. Many studies are presented for the response of foundations under axial vertical loads. However response of foundations under moment loading is different from that for axially loaded footings. Foundations are often subjected to moment loading due to (1) eccentricity of loading and (2) moments generated from lateral loads like wind, earthquake or any other lateral loads. Hence analysis of shallow and deep foundations subjected to moment loads due to eccentricity or lateral loads is necessary to design with required safety and serviceability. A brief review of literature for both shallow foundations under moment loading is presented.

Ultimate bearing capacity of eccentrically loaded shallow foundations

A semi-empirical method namely effective area method is proposed (Meyerhof, 1953) to estimate the bearing capacity of eccentrically loaded shallow foundations. Linear variation of the contact pressure is assumed from toe to the heel. The eccentrically loaded footing becomes a centrally loaded footing in reduced width. The effective width, B' proposed by Meyerhof (1953) is given by the relation B'=B-2e, where e is eccentricity and is shown in Fig. 1.

ISSN 2348 – 8034
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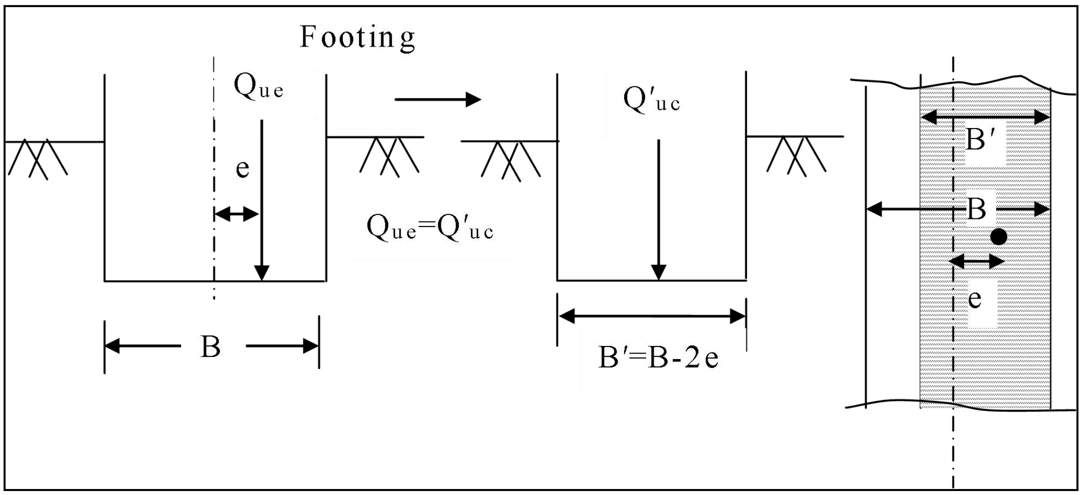

Fig. 1 Effective width concept (Meyerhof, 1953)

The actual contact pressure distribution beneath the footing can be non-linear but is not considered in most analyses. The applicability of effective area method is investigated (Hansen, 1970; Aiban and Zinidarcic, 1995; Loukidis et al. 2008). This method gives conservative results for strip, rectangular, and circular footings (Meyerhof, 1963; Vesic, 1975; Michalowski, 1997; Patra et al. 2006). The bearing capacity of eccentrically loaded footing, $q_{ult(e)}$ is estimated by the reduction factor method (Meyerhof, 1953) as $q_{ult(e)}= R_k\, q_{ult(e=0)}$, where $q_{ult(e=0)}$ is bearing capacity of the footing under concentric vertical load and R_k is reduction factor. R_k is 1-2(e/B) for cohesive soils and $1-(e/B)^2$ for non-cohesive soils for e/B less than 0.3. The effects of footing embedment and soil improvement by reinforcement layers are considered by Purkayastha and Char (1977) and Patra et al. (2006). The bearing capacity of rough strip foundation in c-Φ soil under eccentric loading is estimated by a comprehensive mathematical formulation (Prakash and Saran, 1971). The ultimate bearing capacity for rough continuous foundation by this approach is given by

$$q_u= Q_u/B_e= 0.5\, \gamma\, B\, N_{\gamma(e)}+\gamma\, D_f\, N_{q(e)}+c\, N_{c(e)}, \qquad (2.1)$$

where B_e is the foundation contact width with the soil, $N_{\gamma(e)}$, $N_{q(e)}$ and $N_{c(e)}$ are bearing capacity factors for an eccentrically loaded continuous foundation. Stability analysis for eccentrically loaded continuous foundation on sand (c=0) is carried out by Purkayastha and Char (1977) which is based on method of slices proposed by Janbu (1957). The ultimate bearing capacity of eccentrically loaded continuous foundation is given with a reduction factor, R_k, as

$$q_{u(ecc)}= q_{u(cen)}(1-R_k)= q_{u(cen)}\,(1- a(e/B)^k) \qquad (2.2)$$

where $q_{u(cen)}=qN_qD_q+1/2\, \gamma\, B\, N_\gamma\, D_\gamma$ (2.3)

where $q_{u(ecc)}$ is the ultimate bearing capacity of continuous foundation loaded eccentrically, $q_{u(cen)}$ is ultimate bearing capacity of continuous foundation under central vertical load, e/B is eccentricity ratio, a and k are factors which are function of embedment ratio, D_f/B. Ingra and Baecher (1983) proposed a semi empirical method to predict bearing capacity based on Terzaghi's superposition method. Bearing capacity problem of strip and circular rigid footings on undrained clay under vertical load and moment is carried out using finite element modeling (Taiebat and Carter 2002).

All the research previously discussed here is only for estimation of ultimate bearing capacity of eccentrically loaded foundations but the responses in terms of load-displacement and moment-rotation are not addressed.

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II. METHODOLOGY

Model tests were conducted on a square foundation under compression in a sand bed filled in a circular mild steel tank 111cm in diameter and 55 cm deep. The poorly graded sand was compacted in 5 layers to achieve 73% relative density. The relative density achieved during the test was crosschecked using small bins placed along the circumference of the tank. The complete experimental setup is shown in **Figure 2** below. The test setup consists of the following components.

a) Model tank
b) Model footing (Square Plate)
c) Foundation medium i.e. sand with and without reinforcement
d) Arrangement for application of loads.
e) Measuring devices (dial gauges)

Fig.2 Test tank

Fig. 3 Application of load and Set up of Dial gauges

The model footing was square in plan and it is made up of steel. The dimensions of the footing were 20 cm in length and 20 cm in width. The thickness of plate was 2 cm.

The sand in the tank was placed in five layers of uniform thickness up to 55 cm height, each layer being compacted well. The loading is applied through hydraulic jack which was supported by a rigid steel frame. The load is transferred from hydraulic jack to the plate through a pointed tip as shown in Fig. 2. The grain size distribution curve for the sand is shown in Fig. 4. The uniformity coefficient (C_u) and coefficient of curvature (C_c) for the sand were 3.9 and 1.27, obtained by the formula , D_{60}/D_{10}. As per the I S Soil Classification System the soil is classified as poorly graded sand (SP). Geogrids were used as reinforcement in foundation soil in layers. The properties of Tencate Miragrid used for the study is given in Table1.

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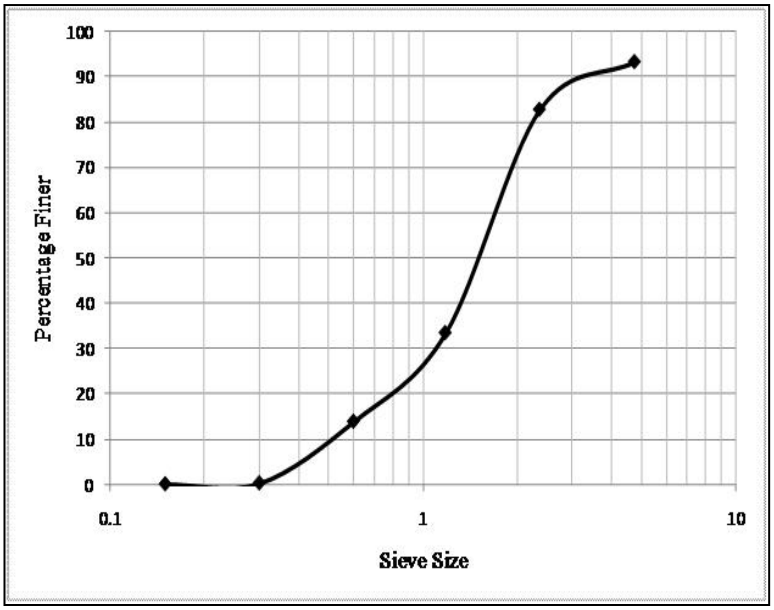

Fig. 4 Grain size distribution of sand used in the study

Table 1 Properties of TenCate Miragrid® GX Geogrids

Property	Unit	GX 60/30
Characteristic short term tensile strength (ISO10319) MD	KN/m	60
Characteristic short term tensile strength (ISO10319) CD	KN/m	30
Strain at short term strength MD	%	11
Nominal roll width	m	5.2
Nominal roll length	m	100
Estimated roll weight (+/- 10%)	kg	129

Experimental Procedure

The experimental testing procedure for the footing is described below.

The sand is filled in 5 layers each of equal thickness and the total weight of the sand is taken for approximate relative densities of 70% and 30%. Geo-grid of three layers are kept within the effective depth(40cm). The sand was filled in layers. Then the footing was placed eccentrically on the tank. The top layer was levelled uniformly. Four dial gauges, all vertical, were placed over the footing top at four edges of the footing as shown in Fig.3 to take the vertical displacement readings. A laboratory testing program was conducted to study the settlement and rotation response of rigid square footings with and without reinforcement under combined axial load and moment. Total of 40 tests were performed in which the load eccentricity footing width ratio was (e/B=1/8,1/12 ,1/24 and 1/48). The test soil consisted of a fine and poorly-graded sand contained in a tank of circular in shape having 111cm diameter in cross section and 55 cm deep. The soil was compacted in 5 layers of each of 74.7% and 34.8%. The Geo-grid used for this test was SG 60/30.The Geo-grid is placed in three layers within the effective depth of 0 to 2B as shown in Fig.5. Each layer of geo-grid is kept above 13.35cm depth after filled with sand, so that required densities is maintained . In each test, the eccentric load and the settlement at the four edges of the footing, were measured. The corresponding moment and rotation of the footing were calculated based on measured values of settlement.

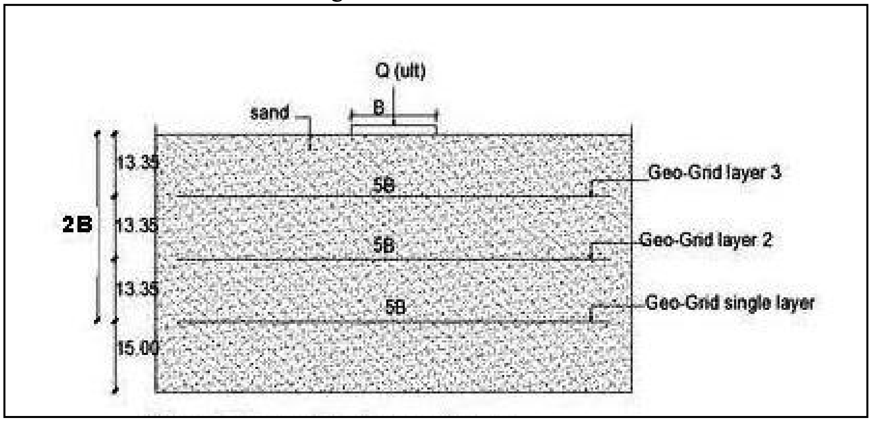

Fig. 5 Square footing resting on reinforced sand bed

III. RESULTS ANALYSIS

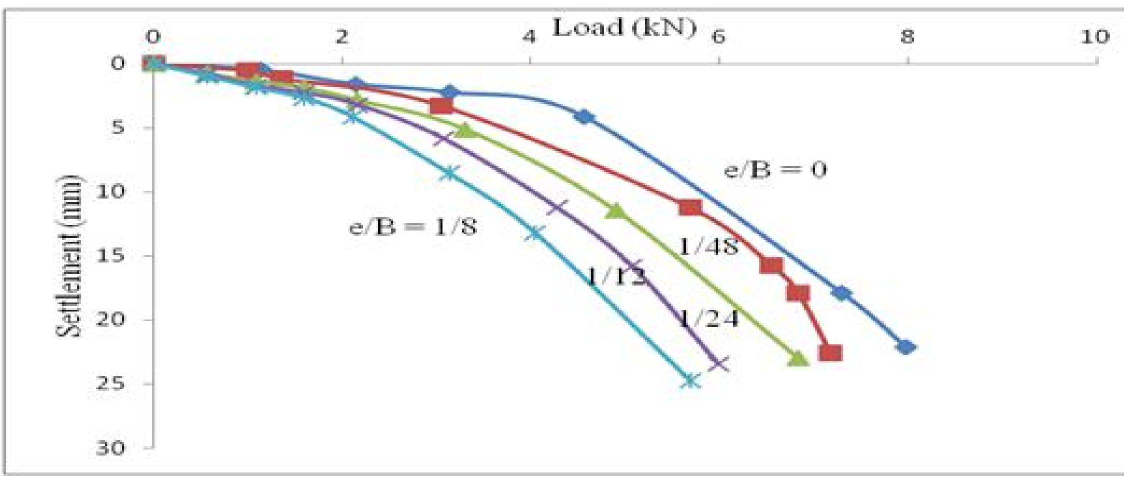

Fig. 6 Load-settlement variation of square foundation on un-reinforced sand with different e/ B (R_D= of 34.8 %)

The load settlement behavior of a square foundation on un-reinforced sand under eccentric loading is shown in Fig. 6. As the e/B increases the ultimate load decreases and the corresponding settlement increases. Ultimate loads are estimated using the double tangent method. For e/B=0, the ultimate load is about 4.53 kN at a displacement of 4.0 mm and as e/B increases to 1/48, the ultimate load decreases to 4.5 kN at a displacement of about 9 mm. And with further increase of e/B to 1/24, the ultimate load attains a value of about 3.97 kN at a corresponding settlement of 7.0 mm. For e/B value of 1/12, the ultimate load is about 3.92 kN at a settlement of 9.8mm. Finally for higher value of applied eccentricity width raio, e/B of 1/8 , the ultimate load further reduces to 2.93 kN at settlement of 8.0 mm. The average rate of reduction in ultimate load and increase in settlement is about 54.6 % and 100 % respectively. The Fig. 6 clearly shows the influence of eccentricity on load –settlement response in terms of reduction in ultimate load and increase in corresponding settlement.

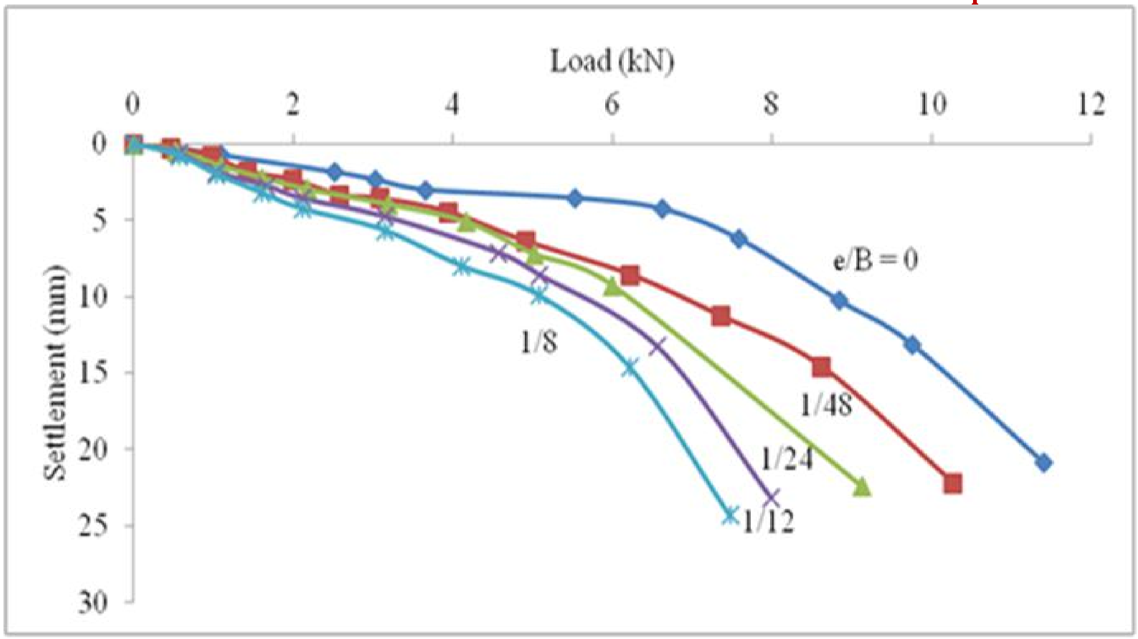

Fig.7 variation of Load with settlement for different eccentricities (e/B) at R_D=34.8% for N = 3

The load settlement behavior of a square foundation on reinforced sand under eccentric loading is shown in Fig. 7. As the e/B increases the ultimate load decreases and the corresponding settlement increases. For e/B = 0. The ultimate load is about 8.22 KN at a displacement of 9.0 mm. The increase in ultimate load with respect to unreinforced case is as high as 81.4 %. Further increase in e/B results in similar trend as discussed in Fig.5.4 but higher values of ultimate loads. This may be due to the effect of increase in number of layers of reinforcement (N=3). For higher value of applied eccentricity width raio, e/B of 1/8 , the ultimate load is 5.39 kN which is 2 times more than the corresponding load for unreinforced case. Hence the influence of e/B is to increase settlement and decrease ultimate besides the Reinforcement counteracts to increase ultimate load.

Comparison of Ultimate Loads with respect to unreinforced soil for different e/B and Rd =34.8%

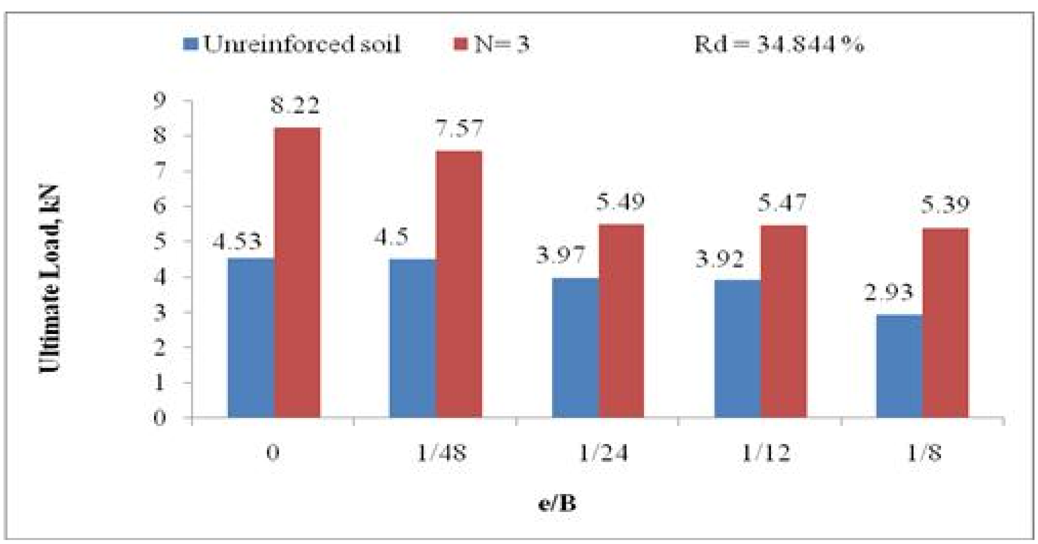

Fig.8 Comparison of ultimate loads with respect to unreinforced soil for different e/B for N=3,R_D =34.8 %

Fig. 8 depicts the increase in ultimate loads for reinforced soil with N=3 with respect to unreinforced one for the Relative density of 34.8%. The increase in ultimate load is about 84 % for e/B of 1/8 which is higher than the corresponding increase for N=1. Hence increase in number of layers counteracts the eccentricity effect.

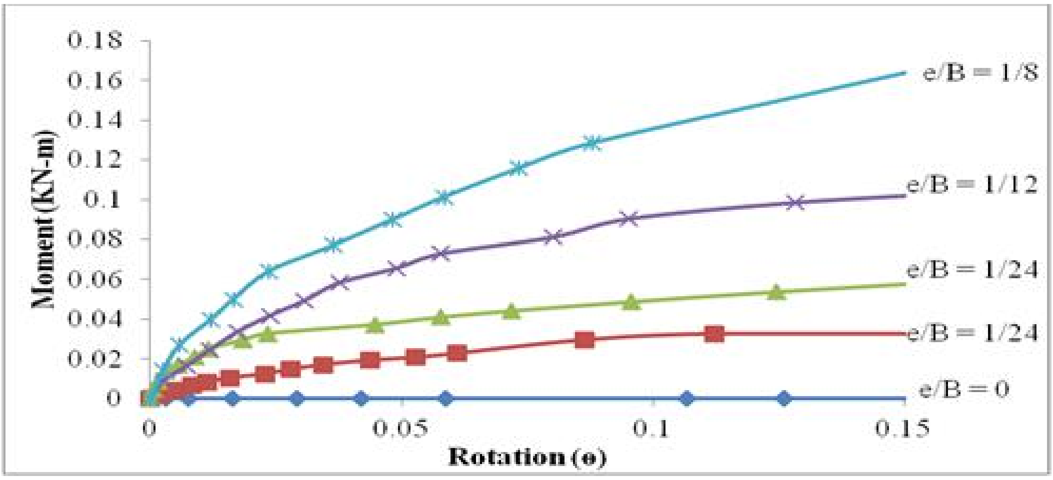

Fig.9 Moment –Rotation response of a square foundation for different e/B on reinforcedsoil for N=1 (R_D =34.8 %)

The moment –Rotation Response of square footing loaded eccentrically with different e/B for a relative density of 34.844% and N =1 is shown in Fig.9. The eccentric load causes moment and results in the footing to tilt/ rotate towards the loading side. The moment on the foundation is increases with increase in applied load for a constant e/B. For the lower value of e/B of 1/48, the footing rotates to an angle of about 0.245 for an applied moment of 0.033 kN-m. And for a medium value of e/B of 1/24, the foundation undergoes a rotation of 0.185 for a moment of 0.057 kN-m., The moment increases with increase in applied eccentricity, as it is proportional to e/B. For a higher value e/B of 1/8 , the rotation is 0.188 at a maximum moment of 0.168 KN-m. And for constant applied moment, rotation increases with increase in e/B.

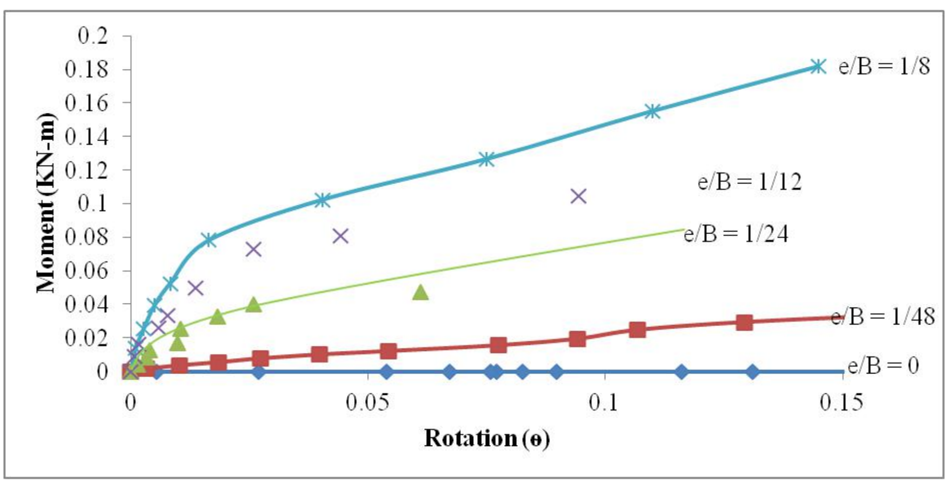

Fig. 10 Moment –Rotation response of a square foundation for different e/B on reinforced soil for N=3 (R_D =34.8 %)

The moment –Rotation Response of square footing loaded eccentrically with different e/B for a relative density of 34.8% and N=3 is shown in Fig.9. The eccentric load causes moment and results in the footing to tilt/ rotate towards the loading side. For a higher value of e/B of 1/8 the footing, rotation is 0.157(rad) at a maximum moment of 0.145

KN-m. Rotation of the footing for ultimate moment reduces with increase in number of layers (N) of geogrid reinforcement in the foundation bed. For example, for e/B=1/8, the rotation of the footing is 0.12 and 0.08 for N=1 and N=3 respectively for a moment of 0.14kN/m.

IV. CONCLUSIONS

A limited number of laboratory test results of eccentrically loaded square footing supported by poorly graded sand with and without geo-grid has been presented. The eccentricity footing width ratio (e/B) was varied from 0 to 1/8andthe relative density used was 34.8%. Based on model test results, the following conclusions are drawn.

- The ultimate loads were decreased with increase in eccentricity footing width ratios e/B from 0 to 1/8 for a given relative density of 34.8%. And for a relative density of 34.8%, the ultimate load reduction is about 35.4% and 30.42% with respect to the concentric load for un-reinforced and reinforced case respectively for N=3. The effect of reinforcement is to counteract the eccentricity effect on ultimate loads.
- The moment on the footing increases the rotation proportionally with increase in eccentricity ratio (e/B).The rotation of the footing is lesser for N=3 with respect to unreinforced case for a constant applied moment. Hence, the increase in reinforcement from N=1 to N=3 improves the response of soil against rotation.

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