UBC of Eccentrically Loaded Strip Foundation Resting on Geogrid Reinforced Sand

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Abstract. Numerical model test results for the ultimate bearing capacity (UBC) of a shallow strip footing resting on geogrid reinforced sand subjected to eccentric vertical loading are presented in the study. The numerical modelling is carried out using finite element tool Plaxis 3D in which the footing of size 5m× 1m×0.1m (L×B×t) is modelled as plate element rests on soil volume of 5.05m× 11m×8m (L×B×H). Deep footing mechanism (i.e. width of reinforcement b is equal to the width of the footing B) is adapted in the present study. Several influencing parameters like relative density of sand (D_r, %), embedment ratio (D_f/B), eccentricity ratio (e/B) and number of reinforced layers (N) have been considered to observe the UBC of the footing. 216 numbers of numerical model have been developed where D_r (%) varies from 25% - 75% @25%, D_f/B varies from 0-1 @0.5, e/B varies from 0-0.15 @0.05 and N varies from 0-5 @1. The Plaxis model is created and analyzed, following HS Small model. The study reveals that irrespective of D_f/B and e/B, among all the simulated conditions, the influence of reinforcement is significant for D_r=25%. It is observed that the failure envelope is shifting from symmetry to one side as the loading is changing from centric vertical to eccentric vertical. The number of reinforced layers (N) for all the cases was found to be in the range of 2 to 3, after which the effect of reinforcement seems to have marginal effect on the UBC of the footing.

Keywords: Numerical model; Strip footing; Geogrid; Sand; Eccentricity ratio; Ultimate bearing capacity.

1 Introduction

Every civil engineering structure mainly consists of two components i.e. Superstructure and Foundation. For designing purpose, there is a need to check the stability of foundations subjected to different loading conditions. The stability of a foundation and supporting soil effects the stability of a structure. Since the publications of Terzaghi's theory on the bearing capacity of shallow foundations in [1], several theoretical and experimental had made by various researchers [2-6]. On basis of plastic theory, Meyerhof [2] extended the surface footing analysis to shallow and deep foundations in a cohesive material with internal friction. He represented the bearing capacity factors in terms of mechanical properties of the material and the physical characteristics of the foundation.

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Most of the studies reveal that the estimation of UBC based on foundation over central and vertical loading conditions. Eccentric loading was possibly observed when bending moments and horizontal thrusts are transmitted from the superstructure to the substructure. The eccentric loading condition is due to the moments acting on the foundation with or without axial forces and their location near property line are some of the reasons. This problem can be analyzed by considering eccentric loading at a distance of e from the centerline of the footing. Due to eccentricity, the overall stability of foundation decreases and it causes a reduction in UBC of the soil. Hence, it is utmost necessary to estimate UBC of foundations under eccentric loading conditions. Empirical procedures developed by Meyerhof [3] estimated the UBC of foundations subjected to eccentric vertical loads. Meyerhof [4] extended the UBC theory by studying the influence of foundation shape and depth, eccentricity and inclination of load, ground water conditions and sloping group. Researchers like Prakash and Saran [5] and Purkayastha and Char [6] studied the behavior of eccentrically loaded footings.

Das et al., [7] analyzed the surface strip foundations when it is resting on geo-grid reinforced sand. They studied the effect on bearing capacity ratio *BCR* by varying foundation width and D_r of sand. An experimental setup with plane strain condition is considered by Sadoglu et al., [8] to carried out tests on shallow strip footings resting on geo-textile reinforced sand. Patra et al., [9] determined the influence of depth of embedment on UBC in case of strip footing resting on geo-grid reinforced sand. Based on experimental and theoretical analysis, the effect of reinforcement on bearing capacity and optimum number of reinforcement layers was given by Sawwaf [10]. Later, it was extended to layered soil by Sawwaf and Nazir [11]. A series of experiments was conducted by Turker et al., [12] by varying eccentricity ratio and embedment ratio of strip footing resting close to geo-textile reinforced sand slope.

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Numerical analysis was done by Sadoglu [13] and Nasr and Azzam [14] on centrally and eccentrically loaded strip footing on geotextile-reinforced sand. Farzam et al., [15] explained the shear behavior of elongated rectangular wall-footing connections under eccentric loads. Reliability analysis of EN 1997 design approaches for eccentrically loaded footings was done by Koker and Day [16]. Dal et al., [17] predicted the footings with geo-grid reinforcement and biaxial eccentricity using multi-linear regression (MLR) and artificial neural network (ANN) methods.

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2 Materials Used

2.1 Soil

Sand with different relative densities (D_r) 25%, 50%, 75% considered in the present study from Kulhawy and Mayne [18]. By substituting relative density values in empirical formulas which are mentioned in Brinkgreve et al., [19], remaining soil properties in Table 1 are calculated. The soils assumed to behave as elastic-perfectly plastic material and hence considered Hardening soil with small stiffness (HS small) model criterion. The basic feature of HS small model is stress dependency of soil stiffness. A cubical soil volume of 5.05 m × 11 m × 8 m *(L* × *B* × *H)* considered for soil geometry. Table 1 lists out the mechanical properties of soil.

Table 1. Mechanical Properties of Soil.

Property	Loose sand	Medium dense	Dense sand
Relative density D_r (%)	25	50	75
Υ_{unsat} (kN/m^3)	16	17	18
Υ_{sat} (kN/m^3)	19.4	19.8	20.2
E_{50}^{ref} (kN/m^2)	15×10^3	30×10^3	45×10^3
E_{oed}^{ref} (kN/m^2)	15×10^3	30×10^3	45×10^3
E_{ur}^{ref} (kN/m^2)	45×10^3	90×10^3	135×10^3
ϕ(°)	31.125	34.25	37.375
ψ(°)	1.125	4.25	7.375
R_f	0.97	0.94	0.91
M	0.62	0.54	0.47
$\gamma_{0.7}$ (kN/m³)	1.75×10^{-4}	1.5×10^{-4}	1.25×10^{-4}
G_o^{ref}	77×10^3	94×10^3	111×10^3

2.2 Footing

An elastic plate with dimensions of 5m × 1m × 0.1m (*L* × *B* × *t*) simulated to represent footing for the numerical analysis. Linear-Elastic-Isotropic nature adopted for the footing used in present numerical analysis. The mechanical properties of footing are tabulated in table 2.

Table 2. Mechanical Properties of Footing and reinforcement.

Property	Footing	Reinforcement
Modelled as	Plate	Geo-grid
Model type	Linear-Elastic-Isotropic	Elastic
Thickness, t (m)	0.1	-
Footing width, B (m)	1	-
γ (kN/m^3)	78	-
Modulus of Elasticity, E (kN/m^2)	200×10^6	-

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Poisson's Ratio, μ	0.3	-
Axial stiffness *EA* (kN/m)	-	60

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2.3 Reinforcement

In Plaxis 3D, reinforcement layers were modelled by using geo-grid option, which represents a structural tensile element with unit thickness and tensile strength. Deep slab mechanism is considered for placing reinforcement in the present study. No slip between the soil and reinforcement was assumed and hence no interface elements were used in the current study. The geo-grid behaves as an elastic material in which can have only tensile resistance but no compressive and flexural resistance. The tensile strength of geo-grid incorporated in terms of axial stiffness per meter length of the geo-grid.

The use of geo-grid as reinforcement in geotechnical applications become unique advantage program especially in foundations resting on weak soils. The soil-reinforcement interface friction is the key factor which derive additional shear strength to the original soil.

It is well established that, the inclusion of reinforcement in soils make them stronger, stiffer and durable and hence the application of reinforcement become quite common in geotechnical engineering applications. The mechanical properties of reinforcement element are tabulated in table 2.

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3 Methodology and Modelling

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3.1 Methodology

In the present study, a finite element program Plaxis 3D is employed to model the footing resisting on sand without reinforcement and with reinforcement. The numerical modelling is carried out using finite element tool Plaxis 3D in which strip footing is modelled as plate element which rests on geo-grid reinforced soil. In present study, the inclusion of reinforcement is done by considering the deep footing mechanism (i.e. the width of reinforcement b is equal to the width of the footing B) explained by Huang and Menq [20].

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3.2 Modelling

In Plaxis 3D, numerical modelling is done by step by step construction. In the first step, soil volume is created and assign the properties to it. In the next step, footing is modelled as plate and assign the footing properties to that plate. After that, loading is placed on the footing. It is assumed that groundwater table not existing below the footing so that it does not affect the UBC of footing. 15 nodded elements are used to generate the mesh for soil volume. Coarse type of mesh is considered for present numerical analysis to make the calculations easy and time effective. The staged construction mode has been adopted to stimulate the procedure of construction practices. In this mode, different phases are considered to define soil, footing, reinforcement and loading. Pre-defined points are taken for stress analysis. In the present study, pre-defined points are considered under loading.

The whole analysis is presented in two cases, unreinforced and reinforced as shown in Figs. 1 and 2. Fig. 1 shows that eccentrically loaded strip footing resting on sand without reinforcement for D_f/B=0, D_r=25% and e/B=0.15. Fig. 2 shows that eccentrically

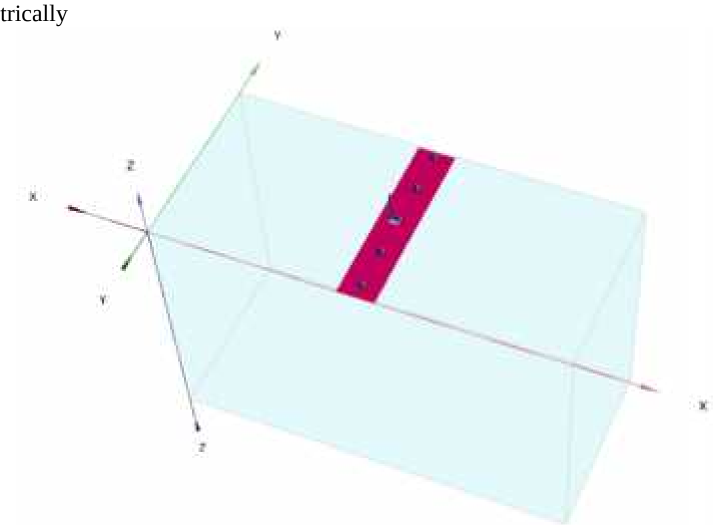

Fig. 1. Eccentrically loaded strip footing resting on sand without reinforcement for D_f /B =0, D_r=25% and e/B =0.15

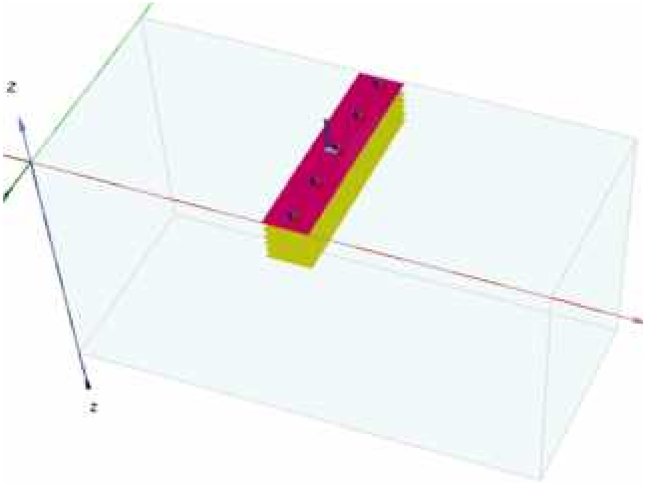

Fig. 2. Eccentrically loaded strip footing resting on sand with reinforcement for D_f /B =0, D_r=75% and e/B =0.15

loaded strip footing resting on sand with reinforcement for D_f /B =0, D_r=75% and e/B =0.15. The first layer of reinforcement is placed at a depth of u/B =0.35.

Several influencing parameters like relative density of sand (D_r, %), embedment ratio (D_f /B), eccentricity ratio (e/B) and number of reinforced layers (N) have been considered to observe the UBC of the footing. 216 number of numerical models had been developed where D_r (%) varies from 25% - 75% @25%, D_f /B varies from 0-1 @0.5, e/B varies from 0-0.15 @0.05 and N varies from 0-5@1. Numerical soil model created and analyzed, following the HS Small model while for footing Linear-Elastic model is used.

4 Results and Discussions

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4.1 Validation of results

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The numerical test results obtained for unreinforced case compared with Meyerhof [4] indicating reasonable accuracy as shown in Fig 3. It is noticed that the present results are in good agreement with those reported by Meyerhof [4].

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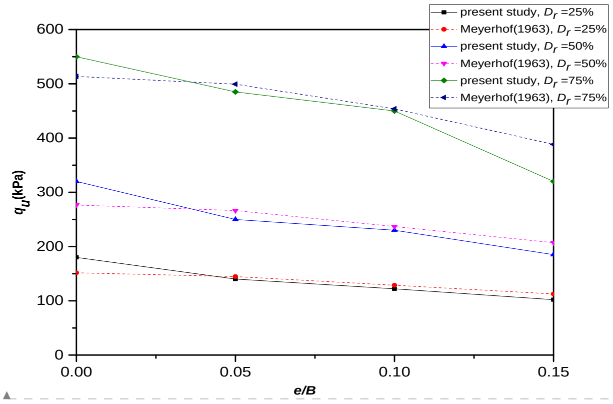

Fig. 3. Comparison of the present results with Meyerhof (1963) for surface footing resting on unreinforced soil

4.2 Effect of Relative Density

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The variation of UBC with relative density of soil is shown in Fig. 4. From Fig. 4 it is found that there is an increment in UBC with increase in D_r of soil for same value of load eccentricity. For a particular value of relative density of soil, reduction in UBC observed with increase in load eccentricity.

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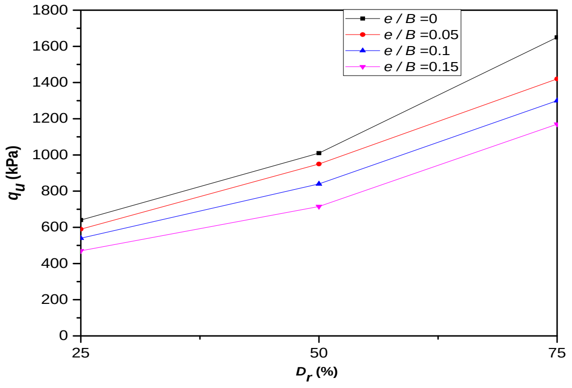

Fig. 4. Effect of Relative density (D_r) for D_f / B =1 and different eccentricity ratios

4.3 Effect of Embedment Depth

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The variation of UBC with embedment depth of footing as shown in Fig. 5. From Fig. 5, it is clear that UBC increases with increase in depth of embedment of footing for same relative density of soil. For a particular depth of embedment of footing, increase in UBC observed with increase in D_r of soil.

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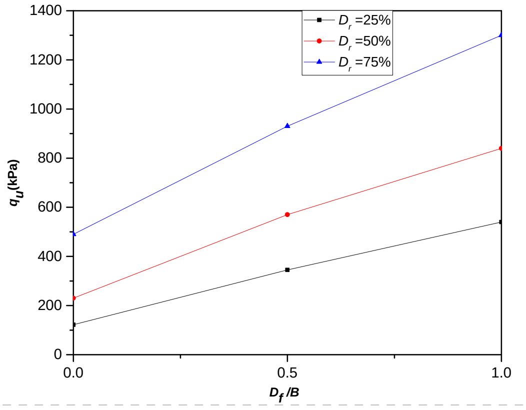

Fig. 5. Effect of Embedment depth (D_f/B) for e / B =0.1 and different relative densities

4.4 Effect of Reinforced layer

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Fig. 6 shows the variation of UBC ratio (*BCR*) vs number of reinforcement layers (*N*) for e/B =0.1 and D_f /B =0. From Fig. 6, it is noticed that reinforcement effect observed more at N=3 for all relative densities considered in the present study. After 3rd layer of reinforcement, there is a marginal effect on the ultimate UBC with increase in reinforced layers.

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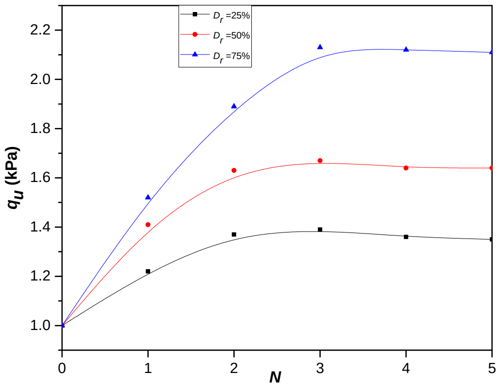

Fig. 6. Effect of Reinforced layers (N) for e / B =0.1 and $D_f /B=0$

4.5 Effect of Eccentricity Ratio

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Fig. 7 shows the effect of eccentricity ratio on UBC of soil. From Fig. 7, it is found that there is a decrement in UBC with increase in eccentricity ratio for same relative density of soil. For a particular value of eccentricity ratio, increase in UBC observed with increase in relative density.

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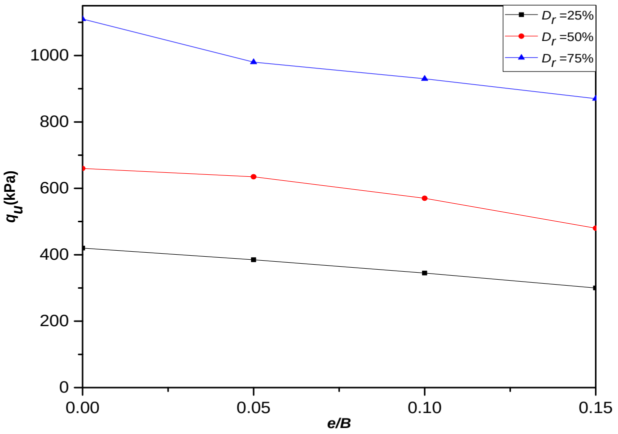

Fig. 7. Effect of Eccentricity ratio (e /B) for D_f / B =0.5 and different relative densities

4.6 Failure Pattern

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Failure pattern for both centric vertical and eccentric vertical loaded strip footing on geo-grid reinforced sand as shown in Figs. 8 and 9. From Fig. 8, it is observed that there is symmetry failure pattern for centric load. From Fig. 9, it is observed that failure pattern shifted to one side as in case of eccentric load.

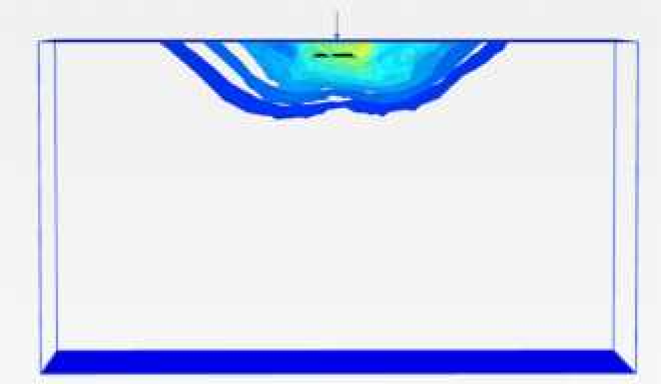

Fig. 8. Failure pattern for centrically loaded strip footing.

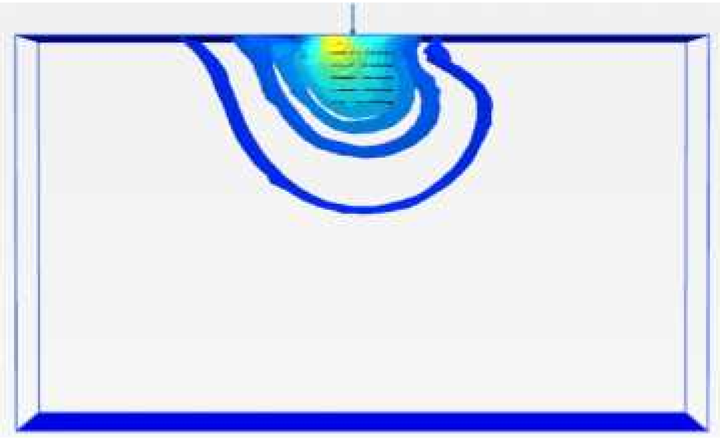

Fig. 9. Failure pattern for eccentrically loaded strip footing.

5 Conclusions

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In the present study, numerical analyses have been done on two hundred and sixteen models using Plaxis 3D to observe the UBC of shallow strip foundation on geogrid reinforced sandy soil subjected to eccentric vertical loading with varying relative density (D_r%), embedment ratio (D_f /B) and number of geogrid layers (N). Based on the results obtained from the study, the following inference may be drawn:

- The optimum number of reinforced layers for centric and eccentric was found to be in range of 2 to 3, after which the effect of reinforcement seems to have marginal effect on the ultimate bearing capacity of footing.
- The reinforcing effect is significant in case of loose sand (D_r=25%).
- When the loading changed from centric vertical to eccentric vertical, the failure pattern shifted from symmetry to eccentrically loaded side.

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