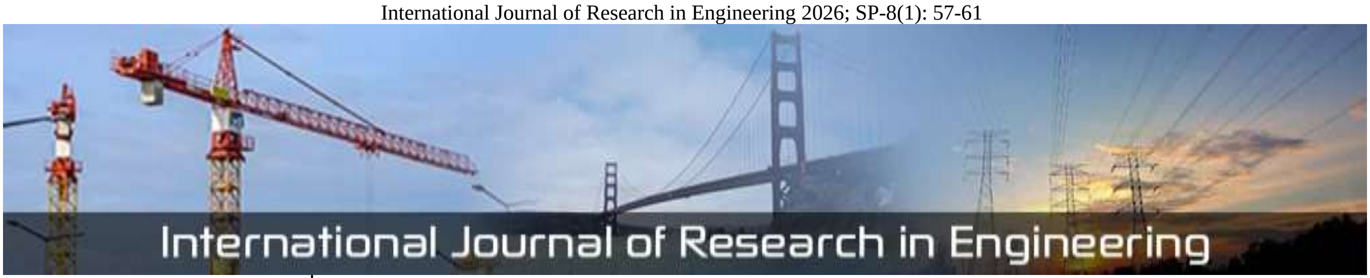

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Bearing capacity of shallow foundation under different loading conditions using Plaxis Software: Review Paper

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Abstract
Civil engineering structures such as buildings, bridges, pavements, and railway tracks rely on foundations to safely transfer loads from the superstructure to the supporting soil or rock. For shallow foundations, the design primarily focuses on two critical criteria: bearing capacity (BC) and settlement (S). BC refers to the maximum pressure the soil can withstand without undergoing shear failure, while settlement deals with the permissible vertical displacement under loading. With advancements in numerical modelling, PLAXIS software has become a widely used tool for accurately analysing soil-structure interaction under various loading conditions. This review paper summarises research studies that employ PLAXIS to evaluate the bearing capacity behaviour of shallow footings subjected to different loading conditions, including vertical, inclined, eccentric, and combined loads. Results from numerical simulations are compared with classical bearing capacity theories proposed by Terzaghi, Meyerhof, Hansen, and Vesic to highlight the accuracy and applicability of PLAXIS in practical design. The review concludes that PLAXIS provides a reliable platform for understanding complex geotechnical behaviour and is highly effective for predicting failure mechanisms and evaluating foundation performance under varied conditions.

Keywords: Eccentric loading, Load inclination, Shallow footing, Ultimate bearing capacity, Plaxis Software

Introduction
Engineering structures such as buildings and bridges have superstructure, which is above ground surface, and substructure including foundation, which is below the ground level. Design loads that include dead load, imposed load, lateral load, seismic load, wind load and earth pressure, play vital role in design and selection of the type of foundation. Besides vertical pressure, foundations may be exposed to moments and shears produced by earth pressure, earthquake, wind, water etc. These loads and moments can be substituted by equivalent eccentric and oblique loads acting on the footing. In general, foundations of earth retaining walls, piers, columns and portal-framed buildings are frequently exposed to eccentric and oblique loads, which can considerably decrease the ultimate bearing capacity (UBC). In designing of foundations, soil characteristics such as, its type, unit weight, shear strength and compressibility, and foundation parameters such as footing shape, width and depth need to be thoroughly examined.
Available literature on shallow foundations resting on unreinforced and reinforced soil under different loading conditions has been reviewed.

Footing resting on reinforced soil
Since 1980s, several laboratory model studies have been conducted to evaluate the UBC of shallow foundation supported on soil reinforced with multiple layers. The schematic view of layout of reinforcement has been shown in Fig. 1.

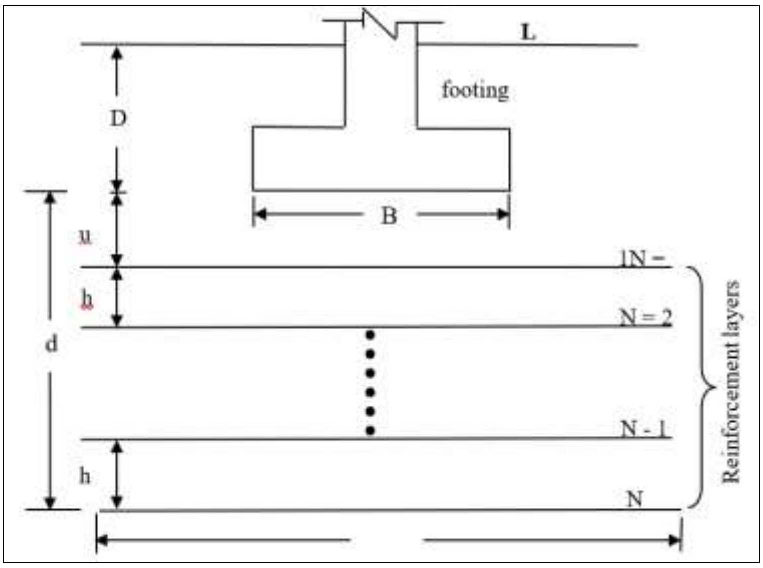

Fig 1: Schematic view of layout of reinforcement

B = width of footing, D = depth of footing, u = depth of first layer of reinforcement below model foundation, h = vertical spacing of subsequent layers of reinforcement, b = width of geogrid layer, N = number of geogrid layers and, d = total depth of reinforcement.

$$d = u + (N - 1)h \quad (1)$$

Several studies have been conducted to investigate the layout and configuration of reinforcement to get optimal performance in a field situation. Some of these studies have been reported in Table 1 below.

Since 1980s, several laboratory model studies have been conducted to evaluate the UBC of shallow foundation supported on soil reinforced with multiple layers. The schematic view of layout of reinforcement has been shown in Fig. 1.

Table 1: Literature on footings resting on reinforced soil

S. No.	Author(s) &Year	Type of investigation	Footing Shape	Type of soil	Reinforcement	Major conclusions related to the improvement of UBC
1	Guido *et al.* (1986) [1]	Experimental	Square	Sand	Geogrid and Geotextile	• u/B = 1, N = 3, b/B = 2.0 (geogrid) and b/B = 3.0 (geotextile). • $h/B \propto \frac{1}{UBC}$. • Geogrid is a superior reinforcing material.
2	Huang and Tatsuoka (1990) [12]	Experimental and Analytical	Strip	Sand	4 types of *phosphor bronze reinforcing strips*	• N = 3, b/B > 2.0, CR= 18%. • The ultimate settlement increases with D/B and d/B = 1.5 for both unreinforced and reinforced sand. • A deep footing effect was observed when L = B. • Two failure models were calculated in analytical analysis (deep footing effect and wide slab effect).
3	Mandal and Sah (1992) [20]	Experimental	Square	Clay	Geogrid	• u/B = 0.175. • u/B = 0.25, then the settlement was reduced up to 45%. • Suggested ranges of u/B are 0 - 0.25.
4	Khing *et al.* (1993) [13]	Experimental	Strip	Sand	Geogrid	• u/B < 1, d/B ≈ 2.25, b/B = 6. • BCR_u and $BCR_s \propto$ N.
5	Omar *et al.* (1993)	Experimental	Strip and Square	Sand	Geogrid	• u/B < 1, b/B = 8 (Strip) and 4.5 (Square), d/B = 2 (Strip) and 1.4 (Square), N = 3.
6	Das *et al.* (1994) [6]	Experimental	Strip	Sand, Clay	Geogrid	• u/B = 0.3 (Sand) and 0.4 (Clay), b/B = 8 (Sand) and 5 (Clay), d/B = 2 (Sand) and 1.75 (Clay). • $BCR_{sand} > BCR_{clay}$.
7	Yetimoglu *et al.* (1994)	Experimental and Analytical (FEM)	Rectangular	Sand	Geogrid	• u/B = 0.25, h/B = 0.2 to 0.4, b/B = 4.5, N = 4. • UBC does not increase beyond a certain limit of reinforcement stiffness.
8	Adams and Collin (1997) [3]	Field tests	Spread	Sand	Geogrid and Geocell	• u/B < 0.5, N = 3. • h/B = 0.25- 0.5 (for one layer and two layers) and 0.5-1.5 (for three layers). • UBC at low stains was found to be maximum when u/B = 0.25.
9	Huang and Menq (1997)	Analytical	Strip	Sand	Reinforcing strips	• Based on the failure mechanisms of deep-footing and wide-slab, the bearing capacity equation may be

	[11]					expressed as • $q_{u(R)} = \gamma D_R N_q S_q d_q + 0.5(B + \Delta B)\gamma N_\gamma S_\gamma$ • $\Delta B = 2D_R \tan\alpha$ • $\tan\alpha = 0.680 - \frac{2.071d}{B} + 0.743CR + \frac{0.030L}{B} + 0.076r$ • Where, d_q = depth factor (=1+0.35D_R/B); B = width of surface footing; ΔB = increase of footing width at the depth D_R due to the wide-slab effect (= 2$D_R \tan\alpha$), α = load-spreading angle.
10	Shin *et al.* (2002) [35]	Experimental and Theoretical	Strip	Sand	Geogrid	• d/B ≈ 2. • BCR $\propto$ D/B. • The magnitude of BCR_s/BCR_u decreases with an increase in D/B for a given d/B. • BCR_s at low levels of the settlement are less than the BCR_u.
11	Kumar and Saran (2003) [15]	Analytical	Rectangular	Reinforced Sand	-	• Extended the previous approach to a rectangular foundation on reinforced sand. • Validation was done with plate-bearing tests conducted by Adam and Collin (1997) [3]. • The design procedure has been made easier by providing charts in a non-dimensional form that can be used in practical situations.
12	Patra *et al.* (2005) [24]	Experimental and Theoretical	Strip	Sand	Geogrid	• UBC $\propto$ d/B. • The experimental results were compared with the theory developed by Hung and Menq (1977).
13	Patra *et al.* (2006) [26]	Experimental and Analytical	Strip	Sand	Geogrid	• Proposed a reduction factor (R_{KR}) • $R_{KR} \approx 4.97\left(\frac{d}{B}\right)^{-0.12}\left(\frac{e}{B}\right)^{1.21}$
14	Kumar *et al.* (2007) [16]	Experimental	Strip	Two-layered sand	Geogrid	• UBC increases 3-4 times when the top weak soil (1B thick) is replaced by well-graded sand and 2- 4 layers of geogrid. • The placing of reinforcement in the subsoil is useful if well-graded soil is placed at the top layer because of better mobilization of interfacial friction between soil and reinforcement.
15	Latha and Somwanshi (2009) [17]	Experimental and Numerical ($FLAC^{3D}$)	Square	Sand	Geogrid and Geonet	• u/B = 0.1- 0.2, h/B = 0.5, b/B = 4, N = 4. • UBC is more dependent on the placement and configuration of reinforcement instead of the tensile strength of the reinforcement material.
16	Lovisa *et al.* (2009) [19]	Experimental and Numerical (PLAXIS 2D)	Circular	Sand	Prestressed geotextile	• Suggested the following modulus of subgrade reaction • $k'_s = k_{s0}\left[1 + 2\left(\frac{D}{B}\right)\right]$ • Where, k'_s = modulus of subgrade reaction at footing embedment depth; k_{s0} = modulus of subgrade reaction for a surface footing. • Numerical results were in good agreement with those obtained from the experimental results.
17	Sadoglu *et al.* (2009) [28]	Experimental	Strip	Sand	Geotextile	• e/B $\propto \frac{1}{UBC}$. • UBC of eccentrically loaded footing is improved by including geotextile.
18	Sharma *et al.* (2009) [34]	Analytical	Square	Sand and Silty clay	Geogrid	• Analytical analysis was done by using previously published results. • Proposed a new bearing capacity formula with the additional term Δ_{qT}, which is added to the effect of tensile force T. • $q_{u(R)} = q_{u(UR)} + \Delta_{qT}$ • Where, $q_{u(UR)}$ is the UBC of unreinforced soil foundation; Δ_{qT} is the increased UBC due to the tensile force of the reinforcement.
19	Sawwaf and Nazir (2012) [33]	Experimental	Ring	Layered Sand	Geogrid	• d/D_o = 1.5, D_i/D_o = 0.39, e/D_o = 0.15, N = 3. • UBC $\propto$ RD.
20	Abu-Farsakh *et al.* (2013) [2]	Experimental	Square and Rectangular	Sand	Geotextile and Geogrid	• u/B = h/B = 0.33, d/B = 1.25, N = 3. • The experimental results were compared with the existing theory (Sharma *et al.*, 2009) [34].

Concluding remarks

The strength of foundation soil can be more effectively improved by the inclusion of geogrid reinforcement as compared to geotextile (Guido *et al*., 1986) [1]. Field studies are the most direct and effective way to examine the load settlement behaviour, but due to the complexity of geological conditions and cost of conducting field tests, very few such studies have been reported. To examine the effect of different layouts and configuration of geogrid reinforcement, laboratory tests have been conducted for various loading conditions, and factors have been suggested for the evaluation of bearing capacity and settlement (Badakhshan and Noorzad, 2015) [5]. Several investigators have proposed reduction factors for bearing capacity analysis (Patra *et al*., 2006, Sahu *et al*., 2016b; Badakhshan *et al*., 2015) [25, 5]. Some analytical studies have been also performed using available experimental data (Huang and Menq, 1997; Kumar and Saran, 2003) [11, 15]. Some numerical studies have been done for the estimation of load-settlement effect of shallow foundations placed on unreinforced and reinforced soil (Keskin and Laman, 2013; Ibrahim, 2014; Naderi and Hataf, 2014; Azzam and Nasr, 2015; Arab *et al*., 2017; Sharma and Kumar, 2019) [7, 23, 4, 34]. The influence of reinforcement layout and configuration on soil improvement, as reported in the literature is summarized below.

Based on literature review, the following gap areas have been identified to define the objectives of present study.

- Many experimental and analytical studies have been done on continuous footing under various loading conditions, but very limited work has been reported on rectangular footing resting on geogrid reinforced sand.
- Various experimental studies have been conducted on shallow foundations under centric loading. Limited attention has been paid to the effect of eccentric (particularly along length) and inclined loading conditions on reinforced soils.
- Lesser studies have been reported in literature on the effect of depth of embedment on load settlement behaviour of geogrid reinforced soils.
- Very few studies have reported on the combined effect of various parameters such as eccentricity ratio (e/L, e/B), load inclination (α), depth of embedment (D/B) and number of reinforcing layers (N) on behaviour of rectangular footing.

Limited literature is available on numerical analysis of geogrid reinforced soils under eccentric and oblique loading using soft computing techniques.

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