Bearing Capacity of Strip Footing on RFB Over Compressible Ground with Granular Trench

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ABSTRACT: The paper presents a method to estimate bearing capacity of a strip footing resting on a reinforced foundation bed (*RFB*) over soft compressible ground stabilized with granular trench. Madhav and Vitkar's solution for bearing capacity of a granular trench-supported strip footing in soft ground together with Meyerhof's punching failure mechanism for dense sand overlying soft clay, extended to include the effect of axial tension in the reinforcement, form the basis of the analysis. The crux of the paper lies in the incorporation of Vesic's cavity expansion theory that considers the stiffness/compressibility of soft ground together with its undrained shear strength, to arrive at the ultimate capacity of the reinforced foundation bed–granular trench system. A parametric study quantifies the contributions of various parameters on the degree of bearing capacity improvement. Predictions compare well with experimental results in literature.

1 INTRODUCTION

Soft ground, encountered commonly along deltaic and coastal regions throughout the world, possess poor geotechnical properties such as high natural moisture content (close to liquid limit), high compressibility, low undrained shear strength and hydraulic conductivity. Most studies for the estimation of bearing capacity of a reinforced dense granular fill over soft ground consider the latter to behave as a rigid-plastic and incompressible material. However, ground/soil being a highly complex entity than metals from which the conventional bearing capacity theories have been developed, requires consideration of stiffness/compressibility of ground together with its shear strength for estimation of ultimate loads.

2 LITERATURE REVIEW

Vesic (1972) proposed a general expression for the ultimate cavity pressure, p_u, based on the expansion of a cylindrical cavity in cohesionless soil under conditions of zero average volumetric strain, by accounting for the compressibility of the ground/soil. Madhav and Vitkar (1978) proposed a solution for the bearing capacity of a strip footing on granular trench-reinforced ground considering a general shear failure mechanism. Hamed *et al.* (1986) presented laboratory model test results for the ultimate bearing capacity of a surface strip foundation installed in soft ground and supported by a granular trench of the same width as the foundation. Unnikrishnan and Rajan (2012) studied the influence of providing a granular trench below strip footings on loose sand deposits. Abhishek *et al.* (2014) presented a method for the estimation of bearing capacity of a strip footing on a geosynthetic-reinforced foundation bed over soft homogeneous ground stabilized with granular trench.

3 PROBLEM DEFINITION & FORMULATION

A strip footing of width, B, is embedded at depth, D_f, below the ground surface in a reinforced granular fill of thickness, H, over compressible ground stabilized with granular trench of width, B_t. (Fig. 1). The cohesion, angle of shearing resistance and unit weight of the trench material are c_1, φ_1 and γ_1 respectively. The shear modulus, undrained shear strength and unit weight of compressible ground are G, s_u and γ_2 respectively. The granular fill is characterized by its angle of shearing resistance, φ, and unit weight, γ. A single layer of geosynthetic reinforcement of length, L_r, is placed just above the granular fill-compressible ground interface, but within the granular fill itself. The interface/bond resistance between the reinforcement and the fill is φ_r and the axial tension mobilized in the reinforcement is T_R.

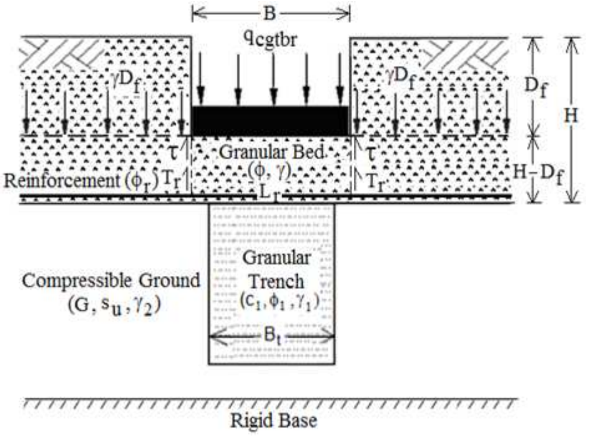


Fig. 1 Definition sketch of strip footing on reinforced granular bed over compressible ground with granular trench

Vesic's (1972) expression for the ultimate cavity pressure, p_u, is given as

$$p_u = s_u N_c^* + q_0 \tag{1}$$

where $N_c^* = \ln(I_r)+1$, $I_r = G/s_u$ – the relative rigidity index and q_0 – the overburden pressure

Madhav and Vitkar (1978) proposed a solution for the ultimate bearing capacity of a strip footing in soft ground stabilized with granular trench considering general shear failure mechanism along with Coulomb's criterion for yielding of soils (Fig. 2). The ultimate bearing capacity, $q_{u,f}$, of the strip footing in soft ground stabilized with granular trench is

$$q_{u,f} = c_2 N_c + \left(\frac{\gamma_2 B}{2}\right) N_\gamma + D_f \gamma_2 N_q \tag{2}$$

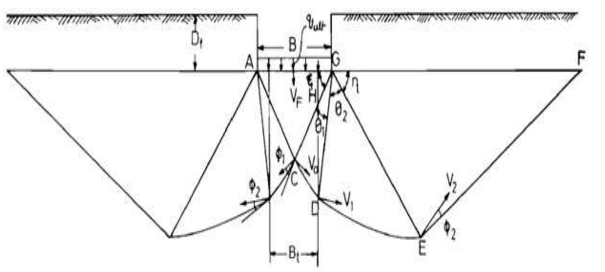
where

$$N_c = \frac{c_1}{c_2} N_{c1} + N_{c2} \tag{3}$$

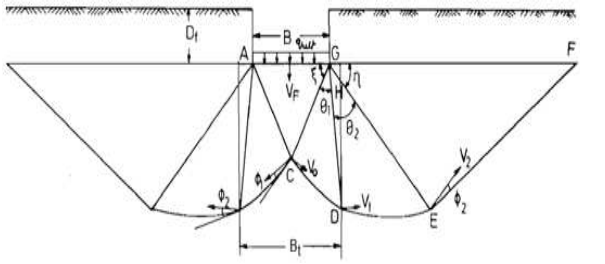
$$N_\gamma = \frac{\gamma_1}{\gamma_2} N_{\gamma 1} + N_{\gamma 2} \tag{4}$$

N_{c1}, N_{c2}, $N_{\gamma 1}$, $N_{\gamma 2}$ and N_q are dimensionless factors that depend on the geotechnical properties of the trench and soft soil materials and the ratio B_t/B. Values of the bearing capacity factors N_c, N_q and N_γ have been given by Madhav and Vitkar (1978) for varying values of B_t/B and φ_1.

Meyerhof (1974) proposed a punching mode of failure for a strip footing of width, B, and depth D, resting on a relatively thin, dense sand stratum of thickness, H with angle of shearing resistance, φ, and unit weight, γ, overlying thick soft clay with undrained cohesion, c, (Fig. 3). A total passive force, P_p, inclined at an angle, δ, acts on a vertical plane through the footing edge. The possible failure modes of the footing, namely punching shear through a relatively thin sand layer (Fig. 3a) and general shear failure within thick sand layer alone



(a)



(b)

Fig. 2 Failure mechanisms for strip footing in soft ground with granular trench (a) $B_t/B \leq 1$ and (b) $B_t/B \geq 1$ (after Madhav and Vitkar 1978)

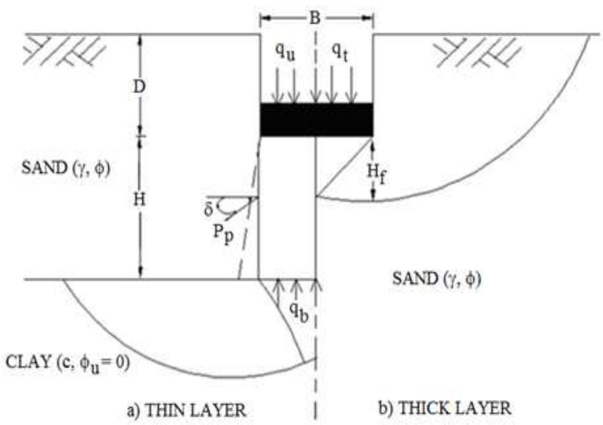


Fig. 3 Failure mechanism for strip footing in dense sand over soft clay (after Meyerhof 1974)

(Fig. 3b) is shown. As the footing punches through the sand layer into soft clay, shear stresses are developed on either sides of the sand column. The ultimate bearing capacity, q_u, of a strip footing in dense sand overlying soft clay is

$$q_u = cN_c + \frac{\gamma H^2}{B}\left(1 + \frac{2D}{H}\right) K_s \tan\varphi + \gamma \mathrm{D} \tag{5}$$

limited by the ultimate bearing capacity of a thick deposit of sand as

$$q_t = \gamma D N_q + 0.5 \gamma B N_\gamma \tag{6}$$

where K_s is coefficient of punching shearing resistance; N_c (equals 5.14 for soft clay with $\varphi_u = 0$), N_q and N_γ are Meyerhof's bearing capacity factors.

3.1 *Bearing capacity of strip footing on granular bed over compressible ground with granular trench*

The ultimate bearing capacity, q_{cgt}, of a strip footing in compressible ground stabilized with granular trench is obtained by incorporating Vesic's expression in Madhav and Vitkar's solution, as

$$q_{cgt} = s_u \left[\ln\left(\frac{G}{s_u}\right) + 1 \right] + 0.5\gamma_2 B N_\gamma + \gamma D_f N_q \quad (7)$$

where N_q and N_γ are Madhav and Vitkar's bearing capacity factors. Normalizing Eq. (7) with the undrained shear strength of compressible ground, s_u, the normalized ultimate bearing capacity, N_{cgt}, of a strip footing in compressible ground stabilized with granular trench is

$$N_{cgt} = \left[\ln\left(\frac{G}{s_u}\right) + 1 \right] + 0.5\left(\frac{\gamma_2 B}{s_u}\right) N_\gamma + \left(\frac{\gamma B}{s_u}\right)\left(\frac{D_f}{B}\right) N_q \quad (8)$$

The ultimate bearing capacity, q_{cgtb}, of a strip footing in a two-layered system of granular fill over compressible ground stabilized with granular trench is obtained by coupling equations (1), (2) and (5), as

$$q_{cgt} = s_u \left[\ln\left(\frac{G}{s_u}\right) + 1 \right] + 0.5\gamma_2 B N_\gamma + \frac{\gamma H^2}{B}\left(1 + \frac{2D_f}{H}\right) K_s \tan\varphi + \gamma D_f N_q \quad (9)$$

where K_s is the coefficient of punching shearing resistance – a function of the angle of shearing resistance of the granular fill, φ, and the ratio q_2/q_1 where q_1 and q_2 are the ultimate bearing capacities of a strip footing on the surface of a thick granular bed and granular trench-reinforced compressible ground respectively. The ratio q_2/q_1 is given by

$$\frac{q_2}{q_1} = \frac{s_u \left[\ln\left(\frac{G}{s_u}\right) + 1 \right] + 0.5\gamma_2 B N_\gamma}{0.5\gamma B N_\gamma} \quad (10)$$

where N_γ in the numerator corresponds to that of Madhav and Vitkar (1978) while N_γ in the denominator is Meyerhof's bearing capacity factor. Considering the total thickness of the granular fill as H (Fig. 1), Eq. 9 gets modified as,

$$q_{cgtb} = s_u \left[\ln\left(\frac{G}{s_u}\right) + 1 \right] + 0.5\gamma_2 B N_\gamma + \frac{\gamma\left(H^2 - D_f^2\right)}{B} K_s \tan\varphi + \gamma D_f N_q \quad (11)$$

Normalizing Eq. (11) with the undrained shear strength of compressible ground, s_u, the normalized ultimate bearing capacity, N_{cgtb}, of a strip footing in a two-layered system of granular fill over compressible ground stabilized with granular trench, is

$$N_{cgtb} = \left[\ln\left(\frac{G}{s_u}\right) + 1 \right] + 0.5\left(\frac{\gamma_2 B}{s_u}\right) N_\gamma + \left(\frac{\gamma B}{s_u}\right)\left\{\left[\left(\frac{H}{B}\right)^2 - \left(\frac{D_f}{B}\right)^2\right] K_s \tan\varphi + \left(\frac{D_f}{B}\right) N_q\right\} \quad (12)$$

3.2 *Bearing capacity of strip footing on reinforced granular bed over compressible ground with granular trench*

The ultimate bearing capacity, q_{cgtbr}, of a strip footing in a two-layered system of reinforced granular fill over compressible ground stabilized with granular trench (Fig. 1), is obtained by adding the contribution of the axial resistance of the geosynthetic reinforcement to pull-out to Eq. 11. The axial tension developed in the reinforcement layer of length, L_r, is due to interface shear resistance mobilized over the top and bottom surfaces of the reinforcement. Figs. 4a & b depict the stresses developed in the reinforced granular column and the geosynthetic reinforcement respectively, due to punching of the footing through the reinforced granular bed into underlying compressible ground.

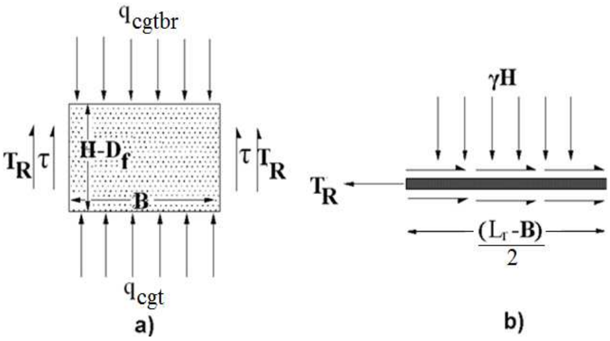


Fig. 4 Stresses on (a) reinforced granular column and (b) geosynthetic reinforcement

The length of the reinforcement beyond the edge of the footing, $(L_r–B)/2$, is considered to be effective in contributing to the resistance to axial pullout and bearing capacity improvement. The axial tension, T_R, developed in the reinforcement on either side of the footing, due to shear stresses developed over the surface of the reinforcement at the granular fill-compressible ground interface is

$$T_R = \gamma H \tan\varphi_r \frac{\left(L_r - B\right)}{2} \quad (13)$$

The ultimate bearing capacity, q_{cgtbr}, of a strip footing in a reinforced two-layered system of granular fill over compressible ground stabilized with granular trench is

$$q_{cgtbr} = s_u\left[\ln\left(\frac{G}{s_u}\right)+1\right]+0.5\gamma_2 BN_\gamma+\frac{\gamma\left(H^2-D_f^2\right)}{B}K_s\tan\varphi$$
$$+\gamma D_f N_q+\frac{\gamma H}{B}\tan\varphi_r\left(L_r-B\right) \quad (14)$$

Normalizing Eq. 14 with the undrained shear strength of compressible ground, s_u, the normalized ultimate bearing capacity, $N_{cgtbr,}$ of a strip footing in a reinforced two-layered system of granular fill over compressible ground stabilized with granular trench is

$$N_{cgtbr} = \left[\ln\left(\frac{G}{s_u}\right)+1\right]+0.5\left(\frac{\gamma_2 B}{s_u}\right)N_\gamma$$
$$+\left(\frac{\gamma B}{s_u}\right)\left\{\left[\left(\frac{H}{B}\right)^2-\left(\frac{D_f}{B}\right)^2\right]K_s\tan\varphi+\left(\frac{D_f}{B}\right)N_q\right\}$$
$$+\left(\frac{\gamma B}{s_u}\right)\left(\frac{H}{B}\right)\tan\varphi_r\left(\frac{L_r}{B}-1\right) \quad (15)$$

Bearing capacities ratios, BCR, are defined to quantify the degrees of improvement as:

$(BCR)_{cgtb} = N_{cgtb}/N_{cgt}$ is the ratio of the normalized ultimate bearing capacity of a strip footing in an unreinforced two-layered system of granular fill over compressible ground stabilized with granular trench to that in granular trench-reinforced ground alone. The ratio $(BCR)_{cgtb}$ quantifies the contribution of the granular fill.

$(BCR)_{cgtbr} = N_{cgtbr}/N_{cgt}$ is the ratio of the normalized ultimate bearing capacity of a strip footing in a reinforced two-layered system of granular fill over compressible ground stabilized with granular trench to that in granular trench-reinforced ground alone. The ratio $(BCR)_{cgtbr}$ quantifies the contribution of both the granular fill as well as the geosynthetic reinforcement.

$(BCR)_{cgtbr}^* = N_{cgtbr}/N_{cgtb}$ is the ratio of the normalized ultimate bearing capacity of a strip footing in a reinforced two-layered system of granular fill over compressible ground stabilized with granular trench to that of an unreinforced two-layered system. The ratio $(BCR)_{cgtbr}^*$ quantifies the contribution of the reinforcement alone.

4 RESULTS AND DISCUSSION

The ultimate bearing capacity of a strip footing in a two-layered system of granular fill over soft compressible ground stabilized with granular trench, depends on the normalized foundation depth, D_f/B, angle of shearing resistance of the granular material, φ, normalized fill thickness, H/B, G/s_u, related to the stiffness of the soft ground and $\gamma B/s_u$ to the unit weight of the granular fill, width of the footing and undrained shear strength of soft ground. If the granular fill is reinforced with a layer of geosynthetic, parameters L_r/B and φ_r/φ also influence the bearing capacity of the footing. The values of the bearing capacity factors as given by Madhav and Vitkar (1978) are adopted for a normalized trench width, B_t/B of 0.5 and c_1/c_2 equal to 0. The granular fill, trench and soft ground are considered to have comparable unit weights while the trench and fill materials possess comparable angles of shearing resistance. A parametric study quantifies the effect of the parameters $\gamma B/s_u$ and G/s_u on the normalized ultimate bearing capacity and bearing capacity ratio of the footing. G/s_u of 63 corresponds to relatively soft ground with N_c of 5.14 while G/s_u of 550 represents stiffer material.

Fig. 5 presents the variations of the normalized bearing capacities, N_{cgtb} and N_{cgtbr}, of a strip footing in a two-layered system of unreinforced and reinforced granular fill over compressible ground with granular trench, respectively, with $\gamma B/s_u$, for φ of 35^0, D_f/B of 0.5, H/B of 1.0, φ_r/φ of 0.75 (reinforced case), L_r/B of 3.0 (reinforced case) and B_t/B equal to 0.5, for G/s_u equal to 63, 250 and 550. Normalized bearing capacities, N_{cgtb} and N_{cgtbr} increase linearly with $\gamma B/s_u$ for different values of G/s_u. Strip footing in a two-layered system of reinforced granular fill over compressible ground with granular trench projects higher normalized bearing capacity when compared to that on unreinforced granular bed. Relatively softer clays and wider footings with higher values of $\gamma B/s_u$ display improved normalized bearing capacity results. The values of N_{cgtb} and N_{cgtbr} for different values of $\gamma B/s_u$ and G/s_u are tabulated in Table 1.

Fig. 6 shows the variations of bearing capacity ratios, $(BCR)_{cgtb}$ and $(BCR)_{cgtbr}$, of strip footing in a two-layered system of unreinforced and reinforced granular fill over compressible ground with granular trench, respectively, with $\gamma B/s_u$, for φ of 35^0, D_f/B of 0.5, H/B of 1.0, φ_r/φ of 0.75 (reinforced case), L_r/B of 3.0 (reinforced case) and B_t/B equal to 0.5, for G/s_u equal to 63, 250 and 550.

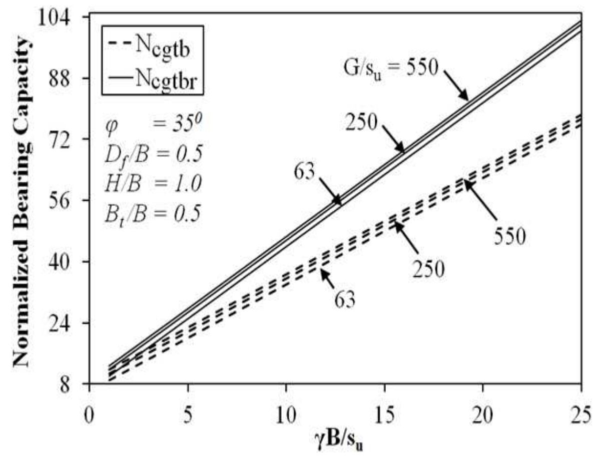


Fig. 5 N_{cgtb} and N_{cgtbr} vs. $\gamma B/s_u$ – effect of G/s_u

Table 1. N_{cgtb} and N_{cgtbr} values for varying G/s_u and $\gamma B/s_u$

	N_{cgtb}			N_{cgtbr}		
G/s_u ⟶	63	250	550	63	250	550
$\gamma B/s_u = 5$ ↓	20.1	21.8	22.8	25.1	26.7	27.7
15	48.0	49.7	50.6	62.8	64.5	65.4
25	75.7	77.4	78.4	100.4	102.1	103.1

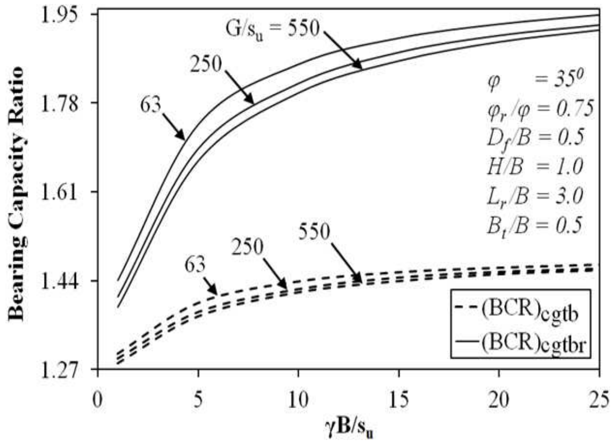


Fig. 6 $(BCR)_{cgtb}$ and $(BCR)_{cgtbr}$ vs. $\gamma B/s_u$ – effect of G/s_u

$(BCR)_{cgtb}$ and $(BCR)_{cgtbr}$ increase non-linearly with $\gamma B/s_u$ for different values of G/s_u. Relatively softer clays and wider footings with higher values of $\gamma B/s_u$ show improved bearing capacity ratios. Further, reinforced granular beds over compressible ground display enhanced *BCR* values when compared to unreinforced ones. The compressibility of the ground decreases with increase in G/s_u, or in other words, its stiffness increases. Consequently, the improvement in bearing capacity of the footing due to provision of a reinforced granular bed decreases, as reflected by the *BCR* values in Fig. 6 and Table 2.

Table 2. $(BCR)_{cgtb}$ and $(BCR)_{cgtbr}$ values for varying G/s_u and $\gamma B/s_u$

	$(BCR)_{cgtb}$			$(BCR)_{cgtbr}$		
G/s_u ⟶	63	250	550	63	250	550
$\gamma B/s_u = 5$ ↓	1.40	1.38	1.37	1.74	1.69	1.67
15	1.46	1.45	1.44	1.90	1.88	1.86
25	1.47	1.46	1.46	1.95	1.93	1.92

The variation of the bearing capacity ratio, $(BCR)_{cgtbr}*$, of strip footing in a two-layered system of reinforced granular fill over compressible ground with granular trench, with $\gamma B/s_u$, for φ of 35^0, D_f/B of 0.5, H/B of 1.0, φ_r/φ of 0.75, L_r/B of 3.0 and B_t/B equal to 0.5, for G/s_u equal to 63, 250 and 550 is shown in Fig. 7. $(BCR)_{cgtbr}*$ increases non-linearly with $\gamma B/s_u$. Similar to Fig. 6, $(BCR)_{cgtbr}*$ decreases with increase in G/s_u due to improved stiffness of ground.

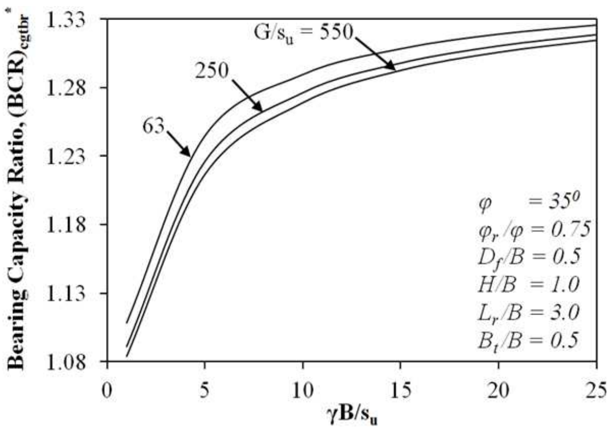


Fig. 7 $(BCR)_{cgtbr}*$ vs. $\gamma B/s_u$ – effect of G/s_u

Figs. 8 and 9 present the variations of the normalized bearing capacities, N_{cgtb} and N_{cgtbr}, and bearing capacity ratios, $(BCR)_{cgtb}$ and $(BCR)_{cgtbr}$, respectively, of a strip footing in a two-layered system of unreinforced and reinforced granular fill over compressible ground with granular trench, with H/B, for φ of 35^0, D_f/B of 0.5, $\gamma B/s_u$ of 15, φ_r/φ of 0.75 (reinforced case), L_r/B of 3.0 (reinforced case) and B_t/B equal to 0.5, for G/s_u equal to 63, 250 and 550. N_{cgtb}, N_{cgtbr}, $(BCR)_{cgtb}$ and $(BCR)_{cgtbr}$ increase non-linearly with the normalized fill thickness, with the reinforced fill yielding relatively higher bearing capacity.

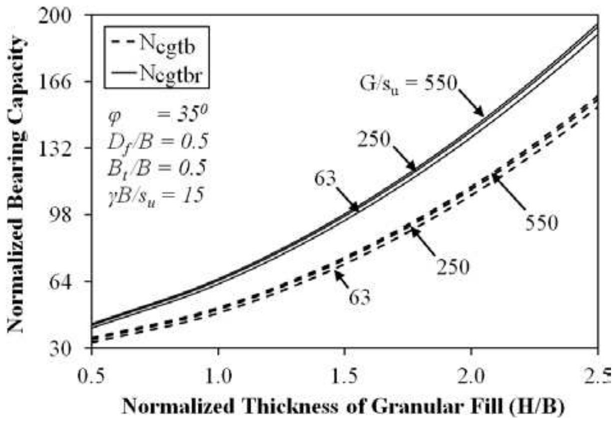


Fig. 8 N_{cgtb} and N_{cgtbr} vs. H/B – effect of G/s_u

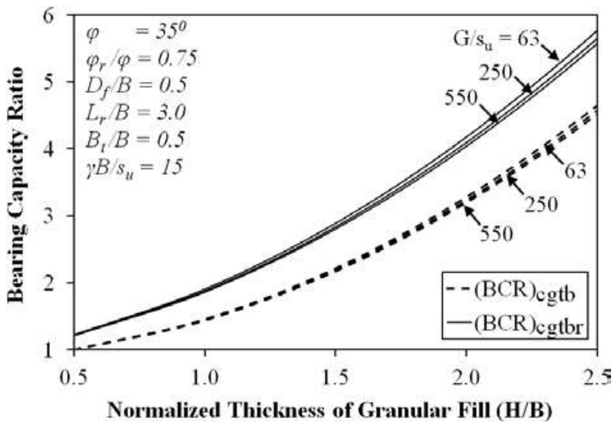


Fig. 9 $(BCR)_{cgtb}$ and $(BCR)_{cgtbr}$ vs. H/B – effect of G/s_u

A relatively thick granular bed distributes the applied load over a wider area per unit depth and reduces the intensity of stresses transmitted to underlying compressible ground. *H/B* equal to 0.5 corresponds to the case of the footing resting directly on compressible ground stabilized with granular trench and hence $(BCR)_{cgtb}$ equals unity. $(BCR)_{cgtbr}$ is however greater than unity due to some contribution from the overlying granular fill in the mobilization of interface shear resistance over the surface of the reinforcement.

Fig. 10 depicts the variation of the bearing capacity ratio, $(BCR)_{cgtbr}$*, of a strip footing in a two-layered system of reinforced granular fill over compressible ground with granular trench, with *H/B*, for φ of 35^0, D_f/B of 0.5, $\gamma B/s_u$ of 15, φ_r/φ of 0.75, L_r/B of 3.0 and B_t/B equal to 0.5, for G/s_u equal to 63, 250 and 550. $(BCR)_{cgtbr}$* increases with *H/B* till a critical value of *H/B*, known as $(H/B)_{cr}$ is reached, and decreases thereafter. Increase in granular fill thickness beyond $(H/B)_{cr}$ restricts the slip surface to within the granular fill, above the reinforcement layer, and consequently decreases the contribution of the reinforcement towards improvement of bearing capacity of footing.

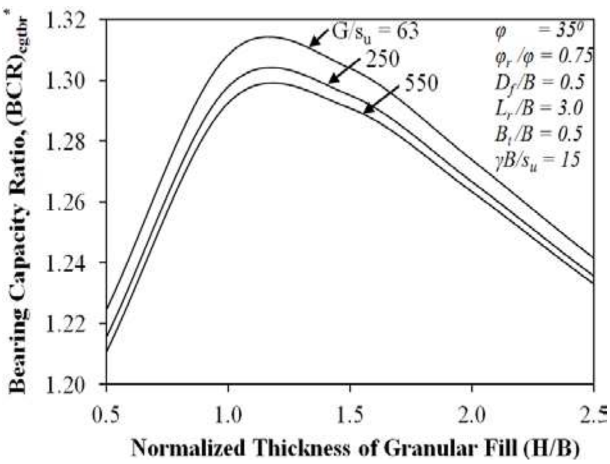


Fig. 10 $(BCR)_{cgtbr}$* vs. *H/B* – effect of G/s_u

Fig. 11 compares the present method for estimation of bearing capacity of a strip footing embedded in a granular bed over compressible ground stabilized with granular trench, with the experimental results of a strip footing in granular trench-reinforced weak clay by Rao *et al*. (1994), for φ of 45^0, D_f/B of 0.5, *H/B* of 0.5, $\gamma B/s_u$ of 1.98, G/s_u of 287.4 and B_t/B of 0.8, 0.9 and 1.0. The bearing capacity ratio plotted along the ordinate is the ratio of the normalized ultimate bearing capacity of a strip footing in soft clay stabilized with granular trench, to that in soft clay alone. Bearing capacity ratios of strip footing estimated from present study compare well with those obtained by Rao *et al*. (1994).

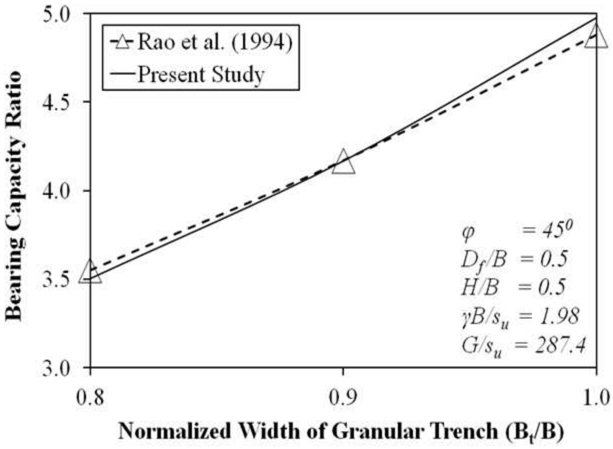


Fig. 11 Comparison with experimental results of Rao *et al*. (1994)

5 CONCLUSIONS

A method for estimating the bearing capacity of a strip footing embedded in a geosynthetic-reinforced granular bed over soft compressible ground stabilized with granular trench is presented. Consideration of compressibility/stiffness of soft ground yields relatively lower bearing capacity of footing but greater improvement upon provision of *RFB*, than otherwise. Relatively wider footings on dense granular fills over soft deposits display enhanced bearing capacity response. *BCR* of the footing in a two-layered system of reinforced granular fill over compressible ground stabilized with granular trench is greater than an unreinforced fill due to additional contribution from interface shear resistance mobilized by the reinforcement.

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