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Bearing Capacity of Geosynthetic Reinforced Foundation Beds on Compressible Clay

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KEYWORDS: Reinforced foundation beds (*RFB*); Bearing capacity ratio (*BCR*); Reinforcement; Axial tension.

ABSTRACT: This paper presents a simple analysis for the estimation of bearing capacity of a strip footing on the surface of a reinforced foundation bed over soft homogeneous clay. Most studies for the estimation of bearing capacity of a dense granular layer over soft clay are based on Meyerhof's approach which is strictly valid for stiff clays and general shear failure. Expressions have been derived by Vesic (1972) for estimating the limit pressure for the expansion of cylindrical cavity in a soil possessing both cohesion and friction. A formulation, to estimate the bearing capacity of a strip footing on a two layered reinforced system (sand over compressible clay with geosynthetic reinforcement in the granular fill) is presented, considering cavity expansion theory of Vesic (1972) which takes into account the compressibility/shear stiffness apart from the undrained strength of the soil, the contribution of the granular fill and axial tension in reinforcement. A parametric study quantifies the effects of various parameters on the bearing capacity of the footing on the reinforced ground. Consideration of compressibility of clay together with shear strength of soil is shown to give results more rational compared to those based on shear strength alone.

1 INTRODUCTION

Reinforced foundation bed (*RFB*) is a two-layered system with reinforcement (geosynthetic) strips, grids or sheets placed at the soil-granular fill interface. In the recent past, the extensive use of *RFB*s has become a salient feature in the course of improving the poor or soft soils with low bearing capacities, which were deemed unfit for construction earlier. The estimation of bearing capacity of the *RFB* has now become a problem of interest and is largely dependent on the behavior of the underlying soft soil, the granular fill and the reinforcement. Most studies for the estimation of bearing capacity of a dense granular layer over soft clay consider the clay layer to behave as a rigid plastic and incompressible material while the current state of understanding of soil behavior clearly establishes the need to include the effect of compressibility of the soil for better simulation of the real conditions. The cavity expansion solutions which consider the strength of the ground together with the relative stiffness of the ground have proved to be a strong alternative to the rigid plasticity analyses. In general, the advantage of the cavity expansion formulation is that it is applicable for compressible to rigid soils and encompasses general, local and punching shear modes of failures implicitly with the consideration of the shear modulus (G) of clay together with its shear strength (c_u).

Gibson and Anderson (1961) establish that the limit pressure is dependent on the shear stiffness apart from the undrained strength of the soil as

$$p_1 = \sigma_h + c_u N_c^* \quad (1)$$

where $N_c^* = 1 + ln(G/c_u)$, G and c_u are respectively the shear modulus and undrained strength of soft soil; σ_h is the total horizontal stress in the ground at a depth to the centre of the expanding cavity. Expressions have been derived by Vesic (1972) for estimating the limit pressure for the expansion of cylindrical cavity in a soil possessing both cohesion and friction.

2 PROBLEM DEFINITION AND FORMULATION

A strip footing of width, B, rests on the surface of a sand stratum of thickness, H, overlying a compressible clay deposit with geosynthetic reinforcement laid in the granular layer close to the interface (Figs. 1a &b). The unit weight and the angle of shearing resistance of the granular stratum are γ_s and φ respectively while G is the shear modulus and s_u is the undrained shear strength of soft compressible ground. φ_r is the interface/bond resistance between geosynthetic layer and the granular fill.

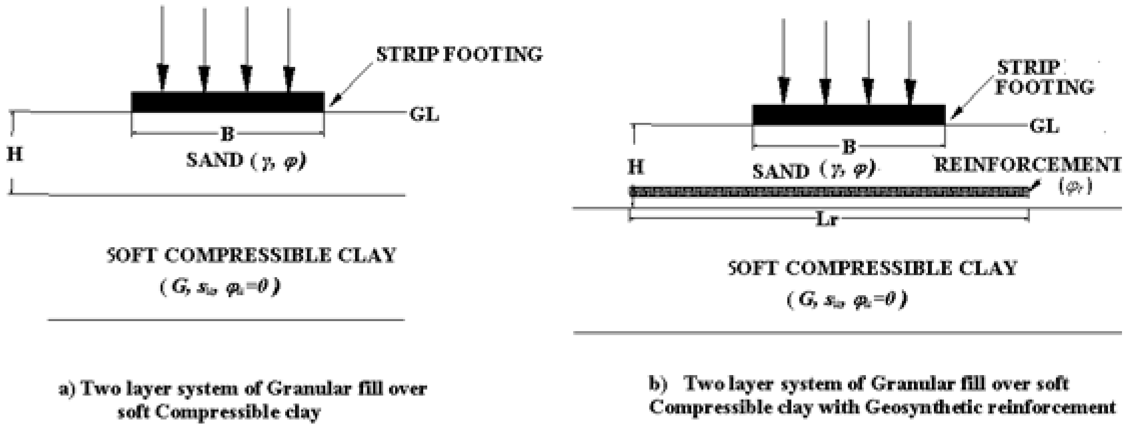

Figure1

3 METHOD OF ANALYSIS

Bearing capacity of compressible clays

Vesic (1973) proposed a more general expression for bearing capacity, q_b, of a footing based on expansion of cylindrical cavity in undrained clay under the conditions of zero average volumetric strain by accounting for compressibility of the ground/soil as

$$q_b = N_c{}^* s_{u+} q_0{}' \quad (2)$$

where $\boldsymbol{q_0{}'}$ is the overburden pressure. For footings on the surface of the ground, $q'_0 = 0$, and Eq. 2 reduces to

$$q_b = N_c{}^* s_u \quad (3)$$

where $N_c^* = (\ln I_r + 1)$ and $I_r = G/s_u$ - the relative rigidity index. Madhav & Padmavathi (2008) establish and emphasize that ground/soil, a heterogeneous/complex material, requires the consideration of stiffness as well as the strength parameters for the estimation of ultimate loads as a more appropriate alternative to the theories developed based on those for metals.

Bearing capacity of layered soils

Meyerhof (1974) proposed a punching mode of failure for a two layered system of granular fill overlying soft clay. It consists of a block of granular material with width equal to that of the footing and thickness equal to that of the granular layer (Fig. 2). In a reinforced two layer system of granular fill over soft ground with reinforcement at the soil-granular fill interface, a downward movement of the footing causes the geosynthetic to be dragged down transversely.

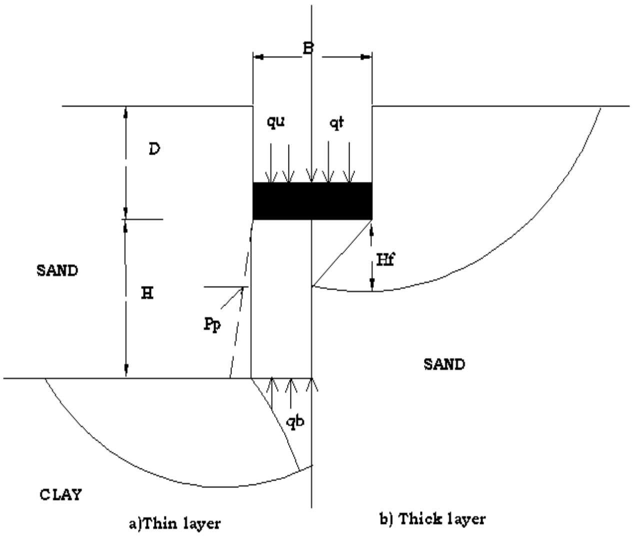

Figure 2 Bearing capacity analysis for sand overlying clay (Meyerhof, 1974)

The bearing capacity, $q_{ug,}$ of a footing at the surface of the granular bed of finite thickness, H, overlying soft soil (Meyerhof 1974) is

$$q_{ug=}s_uN_c + \frac{\gamma H^2}{B}\left(1+\frac{2D}{H}\right)K_s tan\varphi' + \gamma \mathrm{D} \quad (3)$$

where s_u is the undrained shear strength of the soft soil; H - thickness of the granular layer; D- depth of the footing; B - width of the footing; γ - unit weight of the sand, and K_s - coefficient of punching shear. For a surface footing, D equals zero.

Substituting Vesic's solution for the expansion of cylindrical expansion for undrained clay under the conditions of zero average volumetric strain (assuming $q_0' = 0$) in the Meyerhof's equation for bearing capacity of a two layer soil, the bearing capacity, $q_{ug,}$ of a footing at the surface of the granular bed overlying soft compressible soil is

$$q_{ug=}s_u(\ln\frac{G}{su}+1) + \frac{\gamma H^2}{B}K_s tan\varphi' \quad (4)$$

where G is the shear modulus of the soft compressible ground/clay.

The bearing capacity, q_{ug}, of a footing on the above two-layered soil is limited by the ultimate bearing capacity of the granular layer of infinite extent (Meyerhof, 1974) as

$$q_{ug} = \gamma D N_q + 0.5\gamma B N_\gamma \quad (5)$$

where N_q and N_γ are the bearing capacity factors. Eq. (4) is normalised by undrained shear strength, 's_u' to get the equivalent bearing capacity factor, N_{cg}, for a two-layered soil as

$$N_{cg} = N_c{}^* + \frac{\gamma B}{s_u}\left(\frac{H}{B}\right)^2 K_s tan\varphi \tag{6}$$

where $N_{cg} = q_{ug}/s_u$.
N_{cg} combines the contributions of the two layers, the soft compressible clay and the overlying granular fill to the bearing capacity of the footing.

Bearing Capacity of Reinforced Granular Bed on Soft Compressible Soil

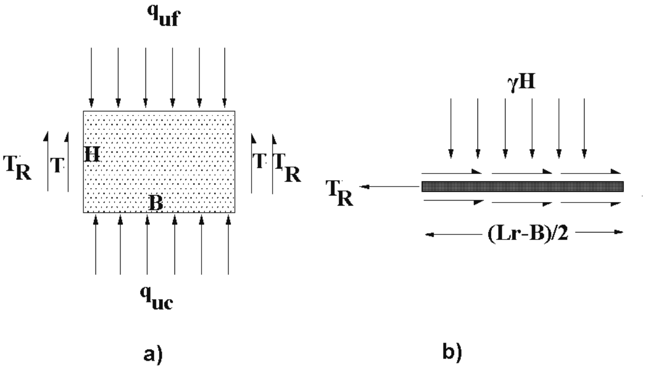

Figure 3 Stresses on (a) Sand Column & (b) Reinforcement

The stresses on the block of sand due to punching shear failure of the footing are shown in Fig. 3a. The reinforcement is assumed to be placed in the granular fill and therefore, the axial tensile force gets developed in the reinforcement layer of effective length (L_r - B) beyond the footing of width B, due to interface shear resistance (Fig. 3b). The tension mobilized in the reinforcement layer by considering the shearing resistance on both sides is

$$T_R = \frac{\gamma H}{B} \tan \varphi_r \left(\frac{L_r - B}{2} \right) \tag{7}$$

where L_r = length of the reinforcement layer. The bearing capacity, $q_{ur}*$, of the reinforced granular bed on soft compressible soil can be obtained by summing the bearing capacity of an unreinforced granular bed overlying soft compressible ground and the contribution of the tensile force mobilized in the reinforcement layer considering that only the lengths of reinforcement beyond the edge of the footing contribute, as

$$q_{ur} *= s_u N_c{}^* + \frac{\gamma H^2}{B} K_s tan\varphi + \frac{\gamma H}{B} tan\varphi_r (L_r - B) \tag{8}$$

The axial pullout force mobilized is considered by Shivashankar et al. (1993) and Rethaliya and Verma (2009). Normalising Eq. (8) by the undrained shear strength, 's_u' one gets

$$\boldsymbol{N_{cr}} * = \boldsymbol{N_c}{}^* + \boldsymbol{\frac{\gamma B}{s_u}\left(\frac{H}{B}\right)^2 K_s tan\varphi + \frac{\gamma B}{s_u}\frac{H}{B} tan\varphi_r \left(\frac{L_r}{B} - 1\right)} \tag{9}$$

where $N_{cr}{}^* = q_{ur}{}^*/s_u$.

The bearing capacity ratios, *BCR*, are defined as
$(BCR)_{ug} = N_{c,g}/N_c$ is the ratio of bearing capacity of the unreinforced two layered system to that of footing on clay alone. This ratio quantifies the contribution of the granular layer to the bearing capacity of the footing.
$(BCR)_{ax} = N_{cr}{}^*/N_c$ is the ratio of bearing capacity of the reinforced two layered system (considering the effect of axial tension only) to that of footing on clay alone. This ratio quantifies the

contributions of the granular layer and the axial tension mobilized in the reinforcement to the overall bearing capacity of the footing.

$(BCR)_{ax}^* = N_{cr}^*/N_{c,g}$ is the ratio of bearing capacity of the reinforced two layered system (considering the effect of axial tension only in the reinforcement) to that of an unreinforced two-layered system.

The bearing capacity of a footing resting on reinforced granular bed overlying a homogeneous clay layer, depends on H/B related to the granular layer, $\gamma B/s_u$, to the ratio of the unit weight of granular fill times the width of the footing to the undrained strength of the clay layer and G/s_u, the ratio of shear modulus to the undrained strength of the clay layer. The crux of this paper lies in the consideration of the stiffness of the soft compressible ground in the estimation of the ultimate bearing capacity of the reinforced two layer system of granular fill over soft compressible ground. Parametric study is carried out to study the effect of compressibility on the bearing strength of an unreinforced and reinforced two layer systems, for the following ranges of parameters: H/B: 0 to 4.25 and G/s_u: 30 to 1000 (an incompressible soil).

4 RESULTS AND DISCUSSION

Figs. 4 and 5 present the variation of normalized bearing capacity of a two layer system of granular fill over soft soil, $N_{c,g}$ for a granular fill with φ of 35^0 and $\gamma B/s_u$ of 15.0 and that of the normalized bearing capacity of a reinforced two layer system of granular fill over soft soil, N_{cr}^*, for a granular fill with φ of 35^0, $\gamma B/s_u$ 15.0, φ_r/φ of 0.75 and L_r/B of 3.0 with H/B, for G/s_u value equal to 30, 63, 150, 350 and 1000. A G/s_u value of 63 corresponds to the Meyerhof's approach where N_c value equals 5.14 (considering shear strength alone). $N_{c,g}$ and N_{cr}^* values increase rapidly with increase in normalised granular layer thickness, H/B, for different values of G/s_u, upto a critical value of H/B denoted by $(H/B)_{cr}$. For $H/B > (H/B)_{cr}$, the values remains constant as it is limited by the ultimate bearing capacity of the granular layer. The bearing strength of a clay layer increases with increase in stiffness (i.e, with increase in G/s_u), as per the Cavity expansion theory, while, it remains constant as per the Meyerhof's approach. Table 1 shows the values of N_{cg} & N_{cr}^* for different G/s_u and H/B. The maximum bearing strength is obtained with a relatively lesser granular layer thickness in a reinforced two layer system than in an unreinforced two layer system. The increase in strength due to increase in stiffness of soft clay is significant for values of H/B between 0 and 2 in the case of an unreinforced two layer system with the increase in strength being 80% at H/B = 0 (clay alone) and decreasing to 10 % at H/B = 2, while, for a reinforced two layer system, the strength gain equals 12% at H/B =1.0, for G/su increasing from 30 to 1000.

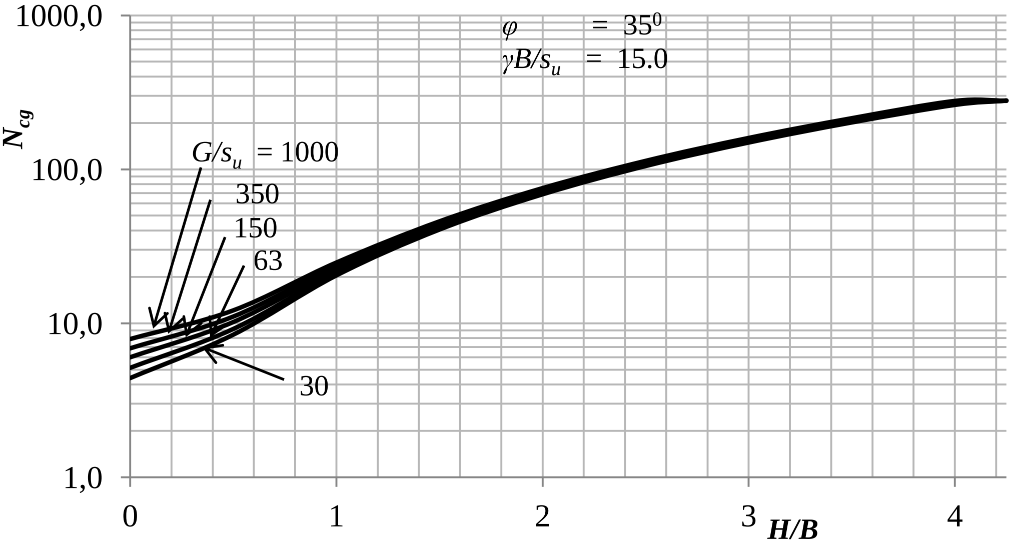

Figure 4 N_{cg} versus H/B – Effect of G/s_u

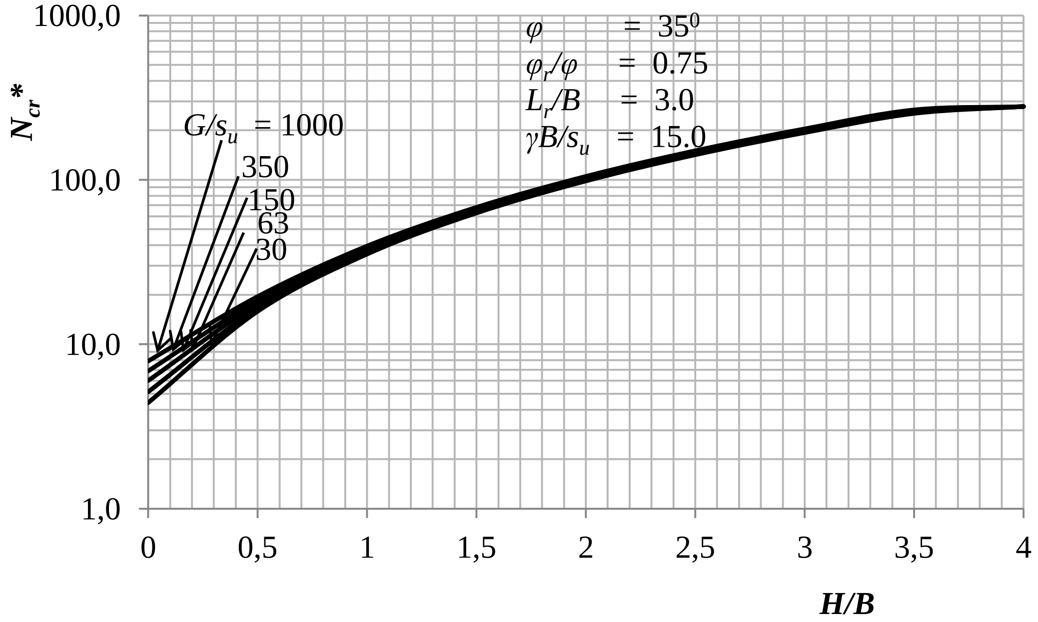

Figure 5 N_{cr}*versus *H/B* – Effect of G/s_u

Table 1 Values of N_{cg} & N_{cr}* for G/s_u and *H/B*

G/s_u	***Value of N_{cg} at H/B=***						***Value of N_{cr}* at H/B=***				
	0	**0.5**	**1.0**	**1.5**	**2.0**	**2.5**	**0.5**	**1.0**	**1.5**	**2.0**	**2.5**
30	4.4	8.4	20.4	40.6	68.7	104.8	15.8	35.3	62.8	98.3	141.8
63	5.14	9.2	21.3	41.5	69.8	106.2	16.6	36.1	63.7	99.4	143.2
150	6.01	10.2	22.4	42.9	71.6	108.4	17.5	37.2	65.1	101.1	145.4
350	6.86	11.0	23.6	44.4	73.7	111.2	18.4	38.4	66.6	103.3	148.2
1000	7.91	12.1	24.8	46.0	75.6	113.6	19.5	39.6	68.1	105.1	150.6

The effect of G/s_u on the variation of the ratio of bearing capacity of the unreinforced two layered system to that of footing on clay alone, $(BCR)_{ug}$ with *H/B*, for φ of 35^0 and $\gamma B/s_u$ of 15.0 and that on the variation of the ratio of bearing capacity of the reinforced two layered system (considering the effect of axial tension only) to that of footing on clay alone, $(BCR)_{ax}$ with *H/B*, for φ of 35^0, φ_r/φ of 0.75, $\gamma B/s_u$ of 15.0 and L_r/B of 3.0 are shown in Figs. 6 & 7 respectively, for and G/s_u equal to 30, 60, 150 350 & 1000. The values of $(BCR)_{ug}$ and $(BCR)_{ax}$ increase with *H/B*. The values decrease with G/s_u increasing from 30 to 1000 (Table 2), due to increase in strength with stiffness (G/s_u).

Table 2 Values of $(BCR)_{ug}$ & $(BCR)_{ax}$ for G/s_u and *H/B*

G/s_u	***Value of $(BCR)_{ug}$ at H/B=***						***Value of $(BCR)_{ax}$ at H/B=***			
	0	**1.0**	**2.0**	**3.0**	**4.0**	**4.25 (max. value)**	**1.0**	**2.0**	**3.0**	**4.0 (max. value)**
30	1.0	4.7	15.6	33.9	59.4	63.4	8.0	22.3	44.0	63.4
63	1.0	4.1	13.6	29.3	51.3	54.2	7.0	19.3	37.9	54.2
150	1.0	3.7	11.9	25.5	46.4	46.4	6.2	16.8	32.9	46.4
350	1.0	3.4	10.7	22.9	40.0	40.7	5.6	15.1	29.4	40.7
1000	1.0	3.1	9.6	20.3	35.2	35.3	5.0	13.3	25.9	35.3

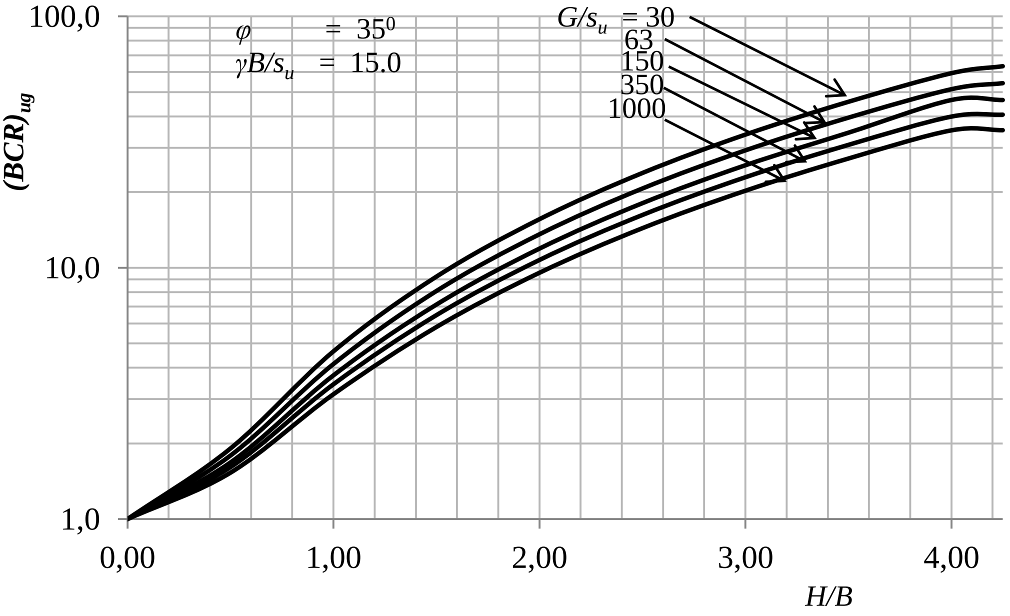

Figure 6 $(BCR)_{ug}$ versus H/B – Effect of G/s_u

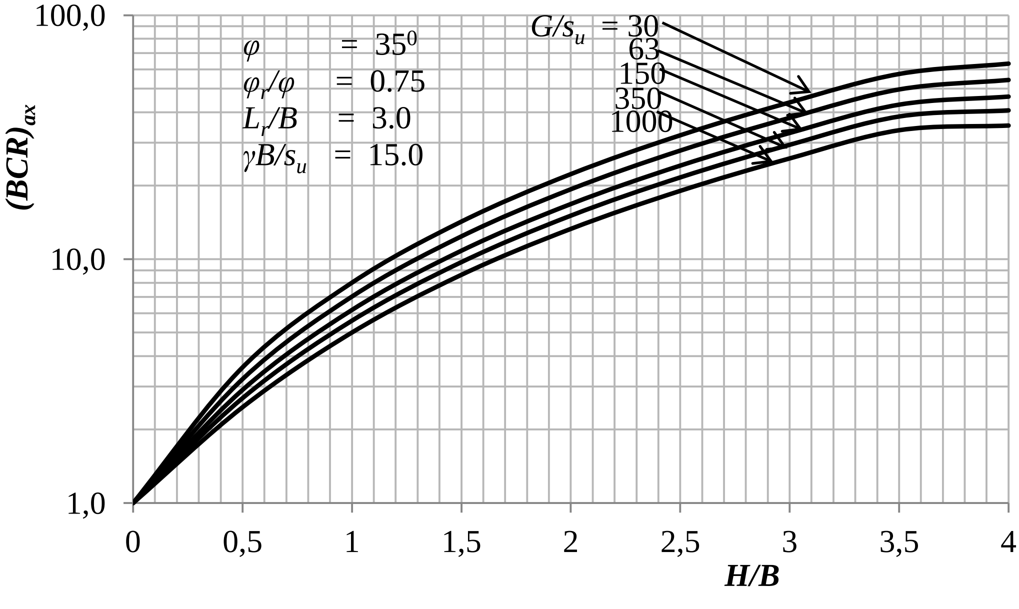

Figure 7 $(BCR)_{ax}$versus H/B – Effect of G/s_u

The effect of G/s_u on the variation of the *BCR* response in terms of the ratio of bearing capacity of the reinforced two layered system (considering the effect of axial tension only in the reinforcement) to that of an unreinforced two-layered system, $(BCR)_{ax}*$ with H/B, for φ of 35^0, φ_r/φ of 0.75, L_r/B of 3.0 and $\gamma B/s_u = 15.0$, for G/s_u equal to 30, 60, 150 350 & 1000 is presented in Fig. 7. $(BCR)_{ax}^*$ decreases with G/s_u, due to increase in strength of an unreinforced system, as a result of increase in N_c with increase in G/s_u. The maximum value of $(BCR)_{ax}*$ decreases from 1.92 to 1.66, with negligible increase in $(H/B)_{cr}$, for values of G/s_u increasing from 30 to 1000 (Fig. 8). Beyond $(H/B)_{cr}$, the effect of reinforcement gradually becomes zero and as a result, $(BCR)_{ax}*$ reduces to zero.

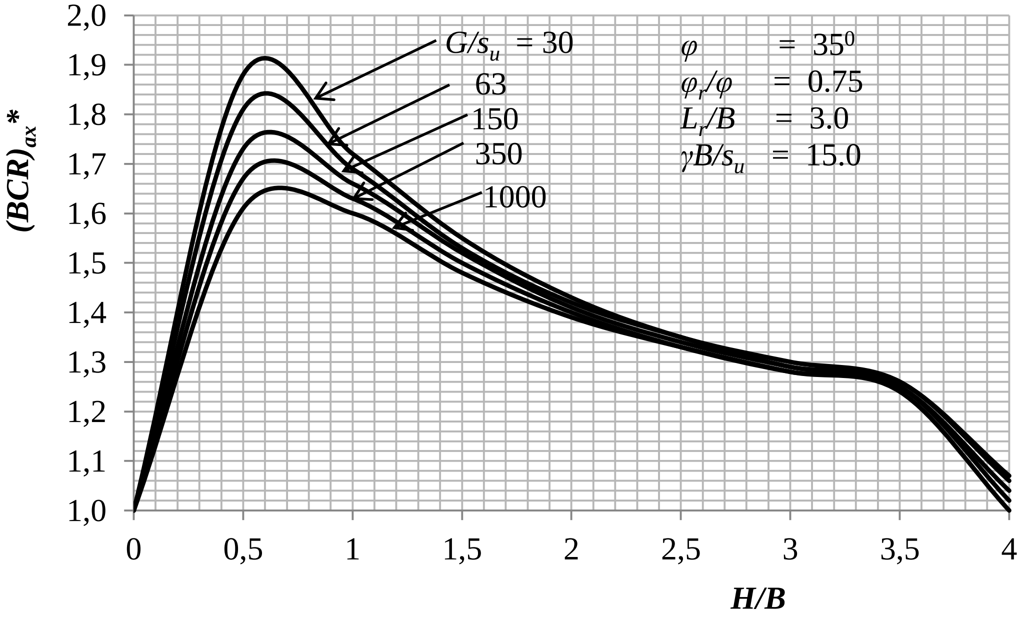

Figure 8 *(BCR)$_{ax}$** versus *H/B* – Effect of *G/s$_u$*

5 SUMMARY AND CONCLUSIONS

A formulation, to estimate the bearing capacity of a strip footing on a two layered reinforced system (sand over compressible clay with geosynthetic reinforcement in the granular fill) is presented, considering cavity expansion theory in clay of Vesic (1972) which takes into account, the compressibility/shear stiffness apart from the undrained strength of the soil, the contribution of the granular fill and the axial tension in reinforcement. A parametric study quantifies the effects of various parameters on the bearing capacity of the footing on the reinforced ground. Consideration of compressibility of clay together with shear strength indicates enhanced results when compared to those based on shear strength alone. $(BCR)_{ug}$ and $(BCR)_{ax}$ values increase with *H/B*, for different values of G/s_u until a maximum value is attained at $(H/B)_{cr}$. $(BCR)_{ax}$* values increase with *H/B*, for different values of G/s_u upto a maximum value at $(H/B)_{cr}$. Beyond the maximum value, a gradual decrease followed by a sharp decrease is indicated for *BCR*, beyond which *BCR* becomes unity, indicating that the effect of reinforcement is zero. $(BCR)_{ug}$, $(BCR)_{ax}$ and $(BCR)_{ax}$* values decrease with increase in G/s_u.

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