Bearing capacity of circular footing on reinforced foundation bed over soft non-homogeneous ground with granular pile

Capacité de support circulaire sur un fond de béton armé sur un sol non homogène doux avec pile granulaire

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ABSTRACT: The paper presents a simple method to estimate the ultimate bearing capacity of a circular footing resting on a reinforced foundation bed (RFB) over soft non-homogeneous ground improved by a granular pile. The reinforced bed consists of a single layer of geosynthetic reinforcement embedded within granular fill. Meyerhof's theory for bearing capacity of footings on layered soils along with Madhav *et al.*'s solution for bearing capacity of granular pile-engineered ground form the basis of the analysis. The non-homogeneity of soft ground is represented by a linear increase of undrained shear strength with depth. The contribution from the frictional resistance mobilized along the planar surfaces of the reinforcement is incorporated in the formulation. Bearing capacity ratios are proposed to quantify the relative contributions of pile, fill and reinforcement towards the ultimate bearing capacity of the footing. Predictions compare fairly well with experimental results in literature.

RÉSUMÉ: Le papier présente une méthode simple pour estimer la capacité d'appui ultime d'une semelle circulaire reposant sur un lit de fondation renforcé (RFB) sur un sol mou non homogène amélioré par un tas granulaire. Le lit renforcé se compose d'une seule couche de renforcement géosynthétique encastrée dans le remplissage granulaire. La base de l'analyse est la théorie de Meyerhof sur la capacité d'appui des semelles sur des sols stratifiés avec la solution de Madhav et al. Pour la capacité d'appui d'un sol granulaire à pieux. La non homogénéité du sol mou est représentée par une augmentation linéaire de la résistance au cisaillement non drainé avec la profondeur. La contribution de la résistance de friction mobilisée le long des surfaces planes du renfort est incorporée dans la formulation. Des rapports de capacité portante sont proposés pour quantifier les contributions relatives de la pile, du remplissage et de l'armature vers la capacité de support finale de la semelle. Les prédictions se comparent assez bien aux résultats expérimentaux de la littérature.

KEYWORDS: Bearing capacity, circular footing, geosynthetic-reinforced foundation bed, granular pile, non-homogeneous ground.

1 INTRODUCTION

Over the past couple of decades, rapid urbanization and land reclamation have led to inevitable construction over soft and weak soils. Such soils possess low undrained shear strength, are highly compressible under loads, and therefore pose problems of stability and serviceability to structures founded on them. Several ground improvement techniques have been developed to improve the load–settlement response of soft ground, one of them being granular piles, also known as stone columns. Granular piles are stronger as well as stiffer than soft ground and thus carry a large portion of the applied load by themselves and transfer relatively little to surrounding soft/weak ground.

Several studies have been carried out to investigate the behaviour of granular pile-reinforced ground (Madhav and Vitkar 1978, Alamgir *et al.* 1996, Ambily and Gandhi 2007, Sivakumar *et al.* 2011, Indraratna *et al.* 2015). In the field, a layer of compacted granular material is often placed on top of granular piles in order to facilitate continuity of drainage and provide a stable working platform for construction machinery to operate. A geosynthetic (geotextile, geogrid or geocell)-reinforced granular fill enhances the load-carrying capacity and reduces the settlement of granular pile-improved soft ground. However, the combined effect of granular pile, granular fill, geosynthetic reinforcement and soft ground non-homogeneity on the ultimate bearing capacity of a circular footing has not been investigated. This paper presents an approach to predict the ultimate bearing capacity of a circular footing in geosynthetic-reinforced granular fill over soft non-homogeneous ground improved by granular pile.

2 PROBLEM DEFINITION AND FORMULATION

A circular footing of diameter B is embedded at depth D below the ground surface in a reinforced granular fill of thickness H over a thick deposit of soft ground improved by a granular pile of diameter d_p and length L_p (Figure 1). The granular pile is relatively long with length to diameter ratio L_p/d_p being greater than four. A single layer of geosynthetic sheet reinforcement of diameter L_r is placed just above the granular fill–soft ground interface, but within the granular fill. The footing is loaded vertically without any eccentricity or inclination of the load.

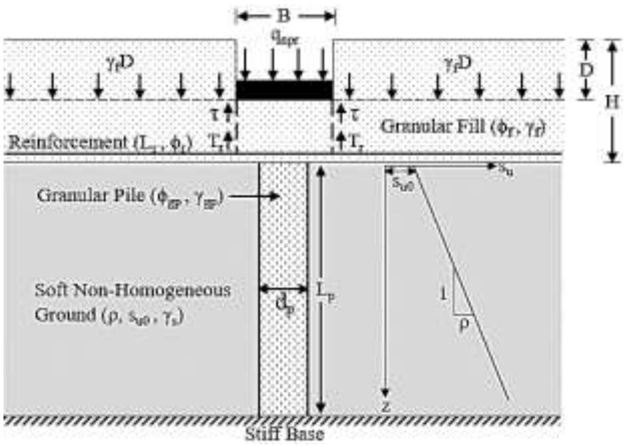

Figure 1. Schematic of circular footing on RFB over soft non-homogeneous ground improved by granular pile.

The angle of shearing resistance and moist unit weight of granular fill are φ_f and γ_f, respectively, while those of granular pile are φ_{gp} and γ_{gp}, respectively. Soft non-homogeneous ground is characterized by its moist unit weight γ_s and undrained shear strength s_u, which increases from a value of s_{u0} (at granular fill-soft ground interface) linearly with depth z at a rate ρ (= ds_u/dz). The interface/bond resistance between the reinforcement and the fill is φ_r and the axial tension in the reinforcement is T_r.

The ultimate capacity of granular pile-reinforced ground depends on the mode of failure of granular pile. Three modes of failure are possible, namely, (i) bulging (ii) side shear/end bearing and (iii) general shear failure, out of which bulging is most common. Hughes and Withers (1974) and Hughes *et al.* (1975) estimate the bulging capacity of a granular pile as

$$q_u = \left(\frac{1+\sin\phi_{gp}}{1-\sin\phi_{gp}}\right)\left(4s_u + \sigma_{r0}\right) \tag{1}$$

where σ_{r0} is the initial total radial stress at a depth equal to half the diameter of the pile. Eq. (1) is valid only when the ratio of the pile diameter to the diameter of the loaded area d_p/B is unity. Madhav *et al.* (1979) extended the theory of Hughes and Withers (1974) for pile to loaded area diameter ratios of less than unity and proposed the following general equation for ultimate bearing capacity of granular pile-reinforced ground as

$$q_{gp} = N_\phi\left(4s_u + \sigma_{r0} + K_0 q_s\right)\frac{d_p^2}{B^2} + \left(1 - \frac{d_p^2}{B^2}\right)q_s \tag{2}$$

where N_ϕ is the flow number of the pile material [= $(1+\sin\varphi_{gp})/(1-\sin\varphi_{gp})$], K_0 is the coefficient of lateral earth pressure at-rest of soft ground and q_s is the vertical annular stress acting over an area of $(\pi/4)\times(B^2 - d_p^2)$ on soft ground.

Meyerhof (1974) proposed a punching mode of failure for a circular footing of diameter 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 (Figure 2). 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 (Figure 2a) and general shear failure within a thick sand layer alone (Figure 2b) are shown. As the footing punches through the sand layer into soft clay, shear stresses τ are developed along the cylindrical surface of the sand column. The ultimate bearing capacity of a circular footing in dense sand over soft clay is given by (Meyerhof 1974)

$$q_u = 1.2cN_c + \frac{2\gamma H^2}{B}\left(1+\frac{2D}{H}\right)sK_s\tan\phi + \gamma D \tag{3}$$

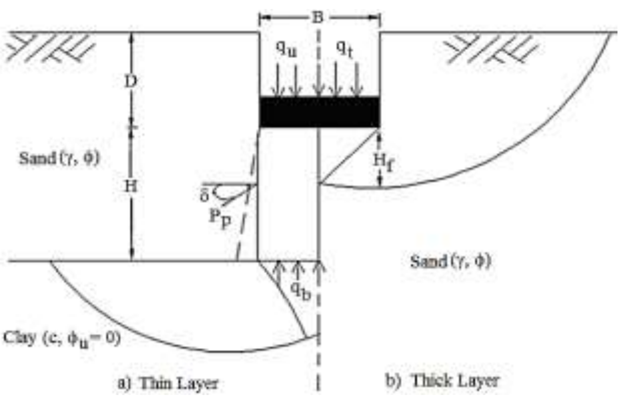

Figure 2. Failure mechanism for footing in dense sand over soft clay (Meyerhof 1974).

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

$$q_t = \gamma DN_q + 0.3\gamma BN_\gamma \tag{4}$$

where s is a shape factor governing the passive earth pressure on a cylindrical wall (which according to Meyerhof (1974) may be conservatively taken as unity for relatively small H/B ratios); K_s is a coefficient of punching shear resistance; N_c (equal to $2+\pi$), N_q and N_γ are Meyerhof's bearing capacity factors.

2.1 Non-homogeneity of soft ground

The variation of the undrained shear strength of soft ground s_u with depth z, normalized by the length of granular pile L_p, can be expressed as

$$s_u(z) = s_{u0}\left(1+\rho\frac{z}{L_p}\right) = s_{u0}\left(1+\frac{0.5\rho}{L_p/d_p}\right) \tag{5}$$

In Eq. (5), $z = d_p/2$ since bulging of granular pile typically occurs at a depth of half the pile diameter measured from the top of the pile. Eq. (5) expresses the non-homogeneity of soft ground as a function of pile geometry.

Davis and Booker (1973), using the method of characteristics, obtained plasticity solutions for the ultimate bearing capacity of smooth and rough strip footings resting on the surface of a non-homogeneous clay deposit. The ultimate bearing capacity of a strip footing on the surface of a deposit whose undrained shear strength increases linearly with depth is given by (Davis and Booker 1973)

$$q_u = F\left[s_{u0}N_c + \frac{1}{4}\rho B\right] \tag{6}$$

where F is a correction factor, which is a function of $\rho B/s_{u0}$ and the roughness of the footing base (Davis and Booker 1973).

For a circular footing, Eq. (6) can be modified as (Salgado 2008)

$$q_u = s_\rho F\left[s_{u0}N_c + \frac{1}{4}\rho B\right] \tag{7}$$

where s_ρ is a shape factor, which is not a constant but also depends on $\rho B/s_{u0}$ as (Salgado 2008)

$$s_\rho = 1 + C_1\frac{B}{L}\left\{\frac{2.3}{\exp\left[0.353\left(\frac{\rho B}{s_{u0}}\right)^{0.509}\right]} - 1.3\right\} \tag{8}$$

where C_1 = 0.163 (for a circle with B/L = 1) and L is the length of the footing.

2.2 Bearing capacity of circular footing on unreinforced granular bed over soft non-homogeneous ground with granular pile

The ultimate bearing capacity of a circular footing in unreinforced granular fill over soft non-homogeneous ground with granular pile is obtained by incorporating Madhav *et al.*'s granular pile solution in Meyerhof's two-layered theory together with the non-homogeneity formulation as

$$q_{npb} = q_{gp} + \frac{2\gamma_f H^2}{B}\left(1+\frac{2D}{H}\right)sK_s\tan\phi_f + \gamma_f D \tag{9}$$

where s_u in the equation for q_{gp} is now not a constant but is a function of ρ (Eq. 5), q_s in the equation for q_{gp} is equal to q_u from Eq. (7), K_s is the coefficient of punching shear resistance which is a function of the angle of shearing resistance of granular fill φ_f and the ratio q_2/q_1, where q_1 and q_2 are the ultimate bearing capacities of a circular footing on the surface (D/B = 0) of thick granular bed and granular pile-reinforced ground, respectively, defined as

$$\frac{q_2}{q_1} = \frac{q_{gp}}{0.3\gamma_f B N_\gamma} \tag{10}$$

Meyerhof (1974) considered the thickness of granular bed below the footing to be H (Figure 2). However, considering the total thickness of granular fill as H (Figure 1), Eq. (9) becomes

$$q_{npb} = q_{gp} + \frac{2\gamma_f\left(H^2 - D^2\right)}{B} sK_s \tan\phi_f + \gamma_f D \tag{11}$$

where σ_{r0} in the equation for q_{gp} is equal to $K_0(\gamma_f H + 0.5\gamma'_s d_p) + 0.5\gamma_w d_p$, where γ'_s is the submerged unit weight of soft ground and γ_w is the unit weight of water.

Normalizing Eq. (11) with the undrained shear strength of soft ground s_{u0}, the normalized ultimate bearing capacity of a circular footing in unreinforced granular fill over soft non-homogeneous ground with granular pile is

$$N_{npb} = N_{gp} + \left(\frac{\gamma_f B}{s_{u0}}\right)\left\{2\left[\left(\frac{H}{B}\right)^2 - \left(\frac{D}{B}\right)^2\right] sK_s \tan\phi_f + \frac{D}{B}\right\} \tag{12}$$

where

$$N_{gp} = N_\phi\left(c_1 + c_2 + c_3\right)\left(\frac{d_p}{B}\right)^2 + c_4\left[1 - \left(\frac{d_p}{B}\right)^2\right] \tag{13}$$

$$c_1 = K_0\left(\frac{\gamma_f B}{s_{u0}}\right)\left(\frac{H}{B}\right) \tag{14}$$

$$c_2 = 0.5\left(\frac{\gamma_w B}{s_{u0}}\right)\left(\frac{d_p}{B}\right)\left(1 + \frac{K_0\gamma'_s}{\gamma_w}\right) \tag{15}$$

$$c_3 = K_0 c_4 + 4\left(1 + \frac{0.5\rho}{L_p/d_p}\right) \tag{16}$$

$$c_4 = s_\rho F\left[N_c + \frac{1}{4}\left(\frac{\rho B}{s_{u0}}\right)\right] \tag{17}$$

2.3 Bond resistance of geosynthetic reinforcement

Figure 3 shows a geosynthetic reinforcement of diameter L_r below a circular footing of diameter B.

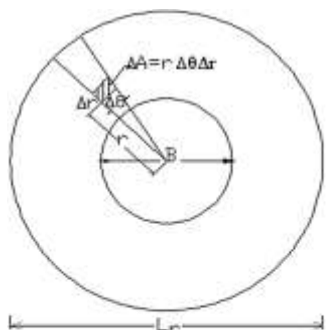

Figure 3. Circular footing over geosynthetic reinforcement (in plan).

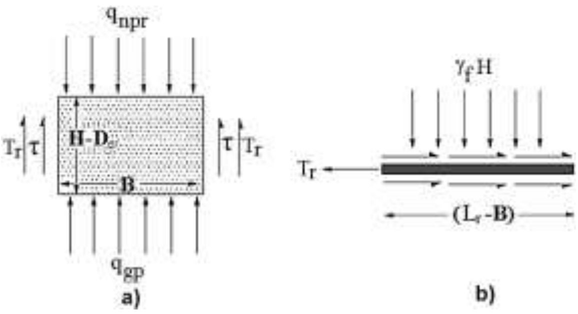

Figure 4. Stresses on a) granular column and b) reinforcement.

Figures 4a and b depict the stresses developed in the reinforced granular column and geosynthetic reinforcement, respectively, due to the punching of the footing through the granular fill. The axial tension in the reinforcement T_r is due to interface shear stresses developed over the top and bottom surfaces of the reinforcement. Integrating an elemental area of the reinforcement ΔA (= $r\Delta\theta\Delta r$) under the footing, the axial tension developed in the reinforcement due to shear stresses mobilized over the top and bottom interfaces of reinforcement and granular fill is

$$T_r = \frac{\pi B^2}{4}\left\{2\gamma_f H \tan\phi_r\left[\left(\frac{L_r}{B}\right)^2 - 1\right]\right\} \tag{18}$$

The contribution from the bond resistance of the reinforcement towards the ultimate bearing capacity of the footing thus becomes

$$q_r = 2\gamma_f H \tan\phi_r\left[\left(\frac{L_r}{B}\right)^2 - 1\right] \tag{19}$$

2.4 Bearing capacity of circular footing on geosynthetic-reinforced granular bed over soft non-homogeneous ground with granular pile

The ultimate bearing capacity of a circular footing on *RFB* over soft non-homogeneous ground with granular pile (Figure 1) is obtained by adding the contribution of the bond resistance of the reinforcement (Eq. 19) to Eq. 11 as $q_{npr} = q_{npb} + q_r$. Normalizing with the undrained shear strength of soft ground s_{u0}, the normalized ultimate bearing capacity of a circular footing on *RFB* over soft non-homogeneous ground with granular pile is $N_{npr} = N_{npb} + N_r$ where

$$N_r = 2\left(\frac{\gamma_f B}{s_{u0}}\right)\left(\frac{H}{B}\right)\tan\phi_r\left[\left(\frac{L_r}{B}\right)^2 - 1\right] \tag{20}$$

3 RESULTS AND DISCUSSION

Figure 5 shows the variation of the normalized ultimate bearing capacity of the footing N_{npr} with the normalized diameter of granular pile d_p/B for $\rho B/s_{u0}$ = 0–5 with φ_f of 35^0, φ_{gp} of 40^0, φ_r/φ_f of 0.75, K_0 of 0.75, D/B of 0.5, H/B of 1, L_p/d_p of 10, L_r/B of 3, $\gamma_f B/s_{u0}$ of 8.5 and $\gamma_w B/s_{u0}$ of 4.9. N_{npr} increases with d_p/B due to improvement of soft ground with granular pile of increasing size. For a given $\rho B/s_{u0}$, N_{npr} increases by 27–34% and 77–83% as d_p/B increases from 0–0.5 and 0.5–1, respectively. N_{npr} for homogeneous ground ($\rho B/s_{u0}$ = 0) is lower than that for non-homogeneous ground ($\rho B/s_{u0} > 0$), which implies the bearing capacity of footing is underestimated if soft ground non-homogeneity (ds_u/dz) is not taken into account. N_{npr} increases by 6% (for d_p/B = 0; no granular pile) and 16% (for d_p/B = 1) as $\rho B/s_{u0}$ increases from 0 to 5.

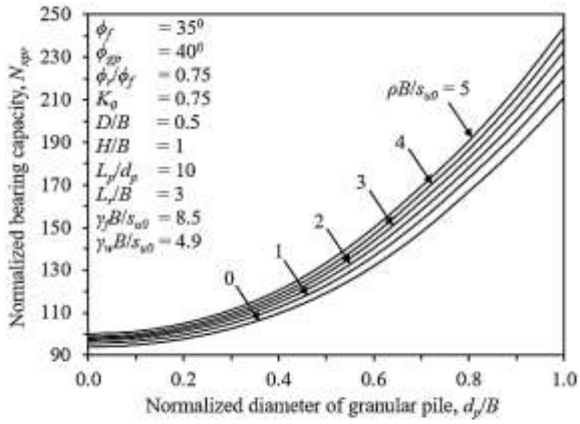

Figure 5. N_{npr} vs. d_p/B – effect of $\rho B/s_{u0}$.

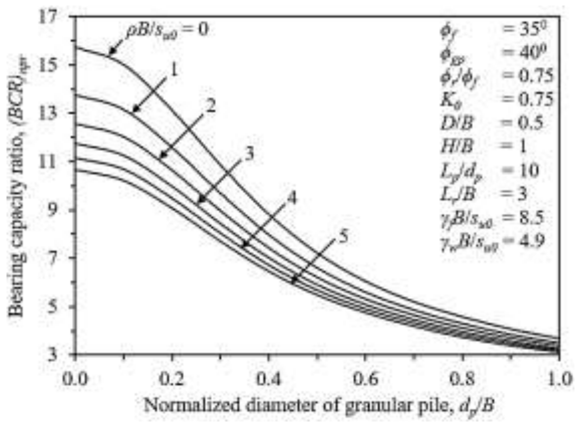

Figure 6. $(BCR)_{npr}$ vs. d_p/B – effect of $\rho B/s_{u0}$.

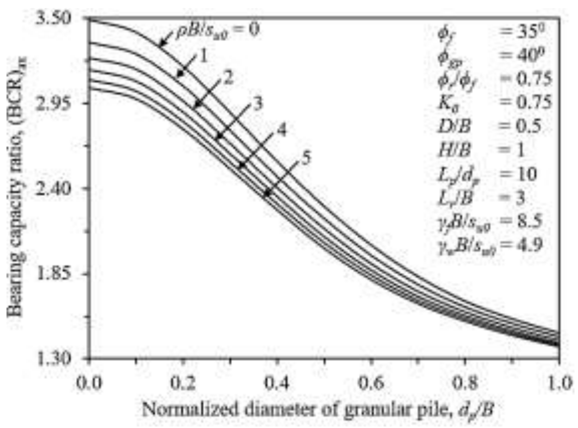

Figure 7. $(BCR)_{ax}$ vs. d_p/B – effect of $\rho B/s_{u0}$.

Figures 6 and 7 present the variations of bearing capacity ratios $(BCR)_{npr} = N_{npr}/N_{gp}$ and $(BCR)_{ax} = N_{npr}/N_{npb}$, respectively, with d_p/B for $\rho B/s_{u0}$ = 0–5. $(BCR)_{npr}$ and $(BCR)_{ax}$ quantify the contributions of RFB and geosynthetic reinforcement, respectively, towards improvement of bearing capacity of footing. $(BCR)_{npr}$ and $(BCR)_{ax}$ decrease with both d_p/B and $\rho B/s_{u0}$ due to higher contributions from granular pile and soft ground non-homogeneity. The effect of $\rho B/s_{u0}$ on $(BCR)_{npr}$ and $(BCR)_{ax}$ is more pronounced for relatively lower values of d_p/B. Referring to Figure 7, $(BCR)_{ax}$ decreases by 0.44 (for $d_p/B = 0$) and 0.09 (for $d_p/B = 1$) as $\rho B/s_{u0}$ increases from 0 to 5.

Figure 8 compares predictions from this study with measured bearing pressures from laboratory model tests of Deb *et al.* (2011) for φ_f of 42^0, φ_{gp} of 45^0, K_0 of 0.8 (assumed), d_p/B of 0.5, L_p/d_p of 6, $\gamma_f B/s_{u0}$ of 0.2 and $\gamma_w B/s_{u0}$ of 0.1. It should be noted that the values measured by Deb *et al.* (2011) correspond to a relative footing settlement w/B of 20% (with B = 100 mm).

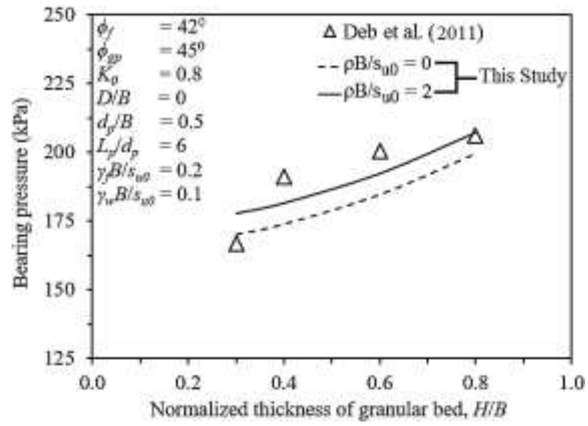

Figure 8. Comparison with experimental results of Deb *et al.* (2011).

Predictions for $\rho B/s_{u0}$ values of 0 and 2 compare fairly well with the measured capacities of the footing (Figure 8).

4 CONCLUSIONS

The paper presents an approach to estimate the ultimate bearing capacity of a circular footing on RFB over soft non-homogeneous ground with granular pile. Madhav *et al.'s* solution for bulging capacity of a granular pile is extended to include Meyerhof's punching failure mechanism for two-layered soils along with the bond resistance of geosynthetic reinforcement. Results indicate that idealization of soft ground as homogeneous (with constant s_u) underestimates the normalized bearing capacity of footing and overestimates the BCR.

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