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# Bearing Capacity of Thin Ring Footing on Reinforced Foundation Bed over Soft Ground

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**Abstract.** A reinforced foundation bed (*RFB*), a composite of granular material and geosynthetic reinforcement, enhances the bearing capacity of shallow foundation in soft ground due to the shear resistance mobilized along the granular fill–geosynthetic interface. This paper presents a simple approach to estimate the ultimate bearing capacity of a ring footing on *RFB* over soft ground, based on Meyerhof's analysis of ultimate bearing capacity of footings on two-layered soils. The values provided by Keshavarz and Kumar (2017) for the bearing capacity factor $N_c$ for rough ring footings on a $c$-$\phi$ soil are incorporated in the formulation. The proposed model considers the effect of axial resistance mobilized by a single circular sheet of geosynthetic reinforcement due to interfacial shear stresses developed over its top and bottom surfaces together with shear resistances of the granular fill along the outer and inner edges of the ring and that of the soft ground to arrive at the total ultimate bearing capacity of the reinforced two layer system. A parametric study quantifies the effects of various parameters (considering the shear resistance on the outer face of the footing alone and the resistance on the inner face together with that on the outer face) on the degree of bearing capacity improvement. Predictions compare well with experimental results of Shalaby (2017) for relatively smaller thickness of granular layer.

**Keywords:** ring footing, reinforced foundation bed, geosynthetic reinforcement, bearing capacity ratio.

## 1 Introduction

Ring footings supporting chimneys, silos, storage tanks and bridge piers, etc., on soft grounds having high water content, low undrained shear strength and high compressibility pose very interesting stability and deformation problems, for geotechnical engineers. Boushehrian and Hataf (2003) performed a study to investigate the bearing capacity of ring footings on reinforced sand by conducting laboratory model tests along with numerical analysis. Sawwaf and Nazar (2012) presented an experimental study of the behaviour of an eccentrically loaded model ring footing resting on a compacted dense layer of sand that overlies an extended layer of loose sand with emphasis on the potential benefits of reinforcing the replaced sand layer with geogrid reinforcement. Shalaby (2017) investigated the use of a combination of stone piles and sand trench instead of using complete sand replacement cushion above weak soft clay soil, experimentally using a model ring footing.

## 2 Problem Definition

A ring footing of outer diameter $d_o$ and inner diameter $d_i$, embedded at a shallow depth $D$ below the ground surface in a relatively thin, dense granular fill of thickness $H$, unit weight $\gamma$ and angle of shearing resistance $\phi$ over thick, homogeneous, saturated soft ground with undrained shear strength $s_u$ is shown in the figure 1(b). The plan view of a circular geosynthetic sheet reinforcement of diameter $d_r$ placed below a ring footing of outer diameter $d_o$ and inner diameter $d_i$ is shown in figure 1(a). The reinforcement–fill interface angle of shearing resistance is $\phi_r$. The ultimate bearing capacity of the ring footing in reinforced granular fill over soft ground is $q_{ur}$*. The additional shear stresses $\tau_f$, $\tau_{f1}$ and $\tau_r$ are those that develop along a vertical cylindrical surface passing through the outer, inner edges of the footing due to the shear layer effect of granular fill (Shivshankar et al.1993) and axial tension (Rethaliya and Verma 2009; Rajyalakshmi et al. 2012) respectively.

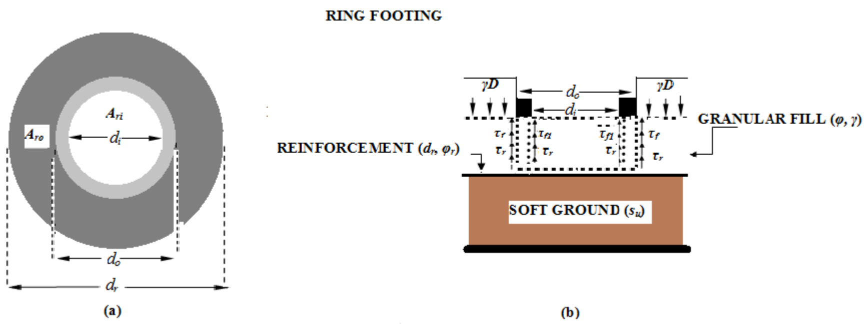


**Fig. 1.** (a) Plan view of Ring footing over circular geosynthetic sheet reinforcement
b) Schematic of Ring footing

Meyerhof (1974) proposed a punching mode of failure for a circular footing ($d_i$= 0) of diameter $d_o$ = $B$ embedded at depth $D$ in a relatively thin, dense sand layer of thickness $H$ with angle of shearing resistance $\phi$ and unit weight $\gamma$, overlying thick soft clay with undrained cohesion $s_u$, by considering the failure as an inverted uplift problem.

### 2.1 Formulation

According to Meyerhof (1974), the ultimate bearing capacity $q_u$ of a circular footing in a thin, dense sand layer over soft clay is

$$q_u = 1.2cN_c + \frac{2\gamma H^2}{B}\left[1 + \frac{2D}{H}\right] sK_s tan\varphi + \gamma D \quad (1)$$

which is limited by the ultimate bearing capacity $q_t$ of the footing in a thick deposit of sand ($c$ = 0) as

$$q_t = \gamma DN_q + 0.3\gamma BN_\gamma \quad (2)$$

where $s$ is a shape factor governing the passive earth pressure on a cylindrical wall (taken as unity for relatively small $H/B$ ratios); $K_s$ is a coefficient of punching shear resistance; $N_c$ (= $2+\pi$), $N_q$ and $N_\gamma$ are Meyerhof's bearing capacity factors.
Substituting $B = (d_o\text{-}d_i)$ for a ring/annular footing and normalizing by $s_u$, Equation 2 becomes

$$N_{limiting} = \left[\frac{\gamma d_0}{s_u}\right]\left[\frac{D}{d_0}\right]N_q + 0.3\left[\frac{\gamma d_0}{s_u}\right]\left[1-\frac{d_i}{d_0}\right]N_\gamma \quad (3)$$

Keshavarz and Kumar (2017) used the method of characteristics and the finite difference technique to estimate the ultimate bearing capacity of smooth and rough ring footings in $c$–$\phi$ soil considering stress singularities at the inner as well as outer edges of the footing as

$$q_u = cN_c + qN_q + 0.5\gamma(d_0 - d_i)\left[1-0.5\frac{d_i}{d_0}\right]N_\gamma \quad (4)$$

where $q = \gamma D$, the overburden pressure at the base of the footing, $N_c$, $N_q$ and $N_\gamma$ are bearing capacity factors, which depend on the angle of shearing resistance $\phi$ of soil and the ratio $r_i/r_o$ of the ring footing, where $r_i$ and $r_o$ are the internal and external radii of the footing, respectively.

## 3 Bearing Capacity of Ring Footing in an Unreinforced Granular Fill over Soft Ground

### 3.1 Ring footing in an unreinforced granular fill over soft ground considering only shear stresses along the outer periphery

The ultimate bearing capacity $q_u$ of a ring footing, in an unreinforced granular fill over soft ground is obtained by extending Meyerhof's two-layered theory for a solid circular footing given in Eq.(1), by substituting $B = d_o$ for the shear stresses acting along only the outer periphery, of the ring footing, as

$$q_{u/outer} = s_u N_c + \left\{\frac{2\gamma H^2}{(do)}\left[1+\frac{2D}{H}\right]sK_s tan\varphi\right\} + \gamma D \quad (5)$$

where $N_c$ is the bearing capacity factor obtained by Keshavarz and Kumar (2017). No shape factor is required for the first term because the bearing capacity factor $N_c$ corresponds directly for a ring footing itself and not for a footing of any other shape. $K_s$ is the coefficient of punching shear resistance, which is a function of the angle of shearing resistance $\phi$ of granular fill and the ratio $q_2/q_1$ (Meyerhof and Hanna 1978), where $q_1$ and $q_2$ are the ultimate bearing capacities of a ring footing on the surfaces ($D$ = 0) of homogeneous thick beds of granular fill ($c$ = 0) and soft ground, respectively, defined as

$$\frac{q_2}{q_1} = \frac{s_u N_c}{0.5\gamma(d_0-d_i)\left[1-0.5\frac{d_i}{d_0}\right]N_\gamma} \quad (6)$$

where $N_\gamma$ can be obtained from values given by Keshavarz and Kumar (2017) for different radii ratios, $r_i/r_o$. Since the shear strength of granular fill is greater than that of soft ground, the ratio $q_2/q_1$ ranges between 0 and 1.

Meyerhof (1974) represented the thickness of the granular bed below the footing as $H$. However, since the entire thickness of the granular fill is considered as $H$ (Fig. 1), the thickness of the granular bed below the footing is now equal to $H - D$ and Eq. (5) gets reduced as below

$$q_{u/outer} = s_u N_c + \left\{\frac{2\gamma(H-D)^2}{(do)}\left[1+\frac{2D}{(H-D)}\right] sK_s tan\varphi\right\} + \gamma D \quad (6)$$

$$q_{u/outer} = s_u N_c + \left\{2\gamma(H-D)^2 \frac{1}{(do)} K_s tan\varphi\right\} + \gamma D \quad (7)$$

Normalizing Eq. (7) with the undrained shear strength $s_u$ of soft ground, the normalized ultimate bearing capacity $N_u$ of a ring footing in an unreinforced two layered system of granular fill over soft ground, considering the shearing resistances acting along vertical cylindrical surfaces passing through the outer edge of the footing is

$$N_{u,o} = N_c + \left\{2\left(\frac{\gamma d_0}{s_u}\right)\left[\left(\frac{H}{d_0}\right)^2 - \left(\frac{D}{d_0}\right)^2\right] K_s tan\emptyset\right\} + \left\{\left(\frac{\gamma d_0}{s_u}\right)\left(\frac{D}{d_0}\right)\right\} \quad (8)$$

### 3.2 Ring footing in/an unreinforced granular fill over soft ground considering shear stresses along both outer and inner peripheries

The ultimate bearing capacity $q_u$ of a ring footing, on unreinforced granular fill over soft ground is obtained by extending Meyerhof's two-layered theory for a solid circular footing given in Eq.(1), by substituting $B = d_o$ and $B = d_i$ for the shear stresses acting along both outer and inner peripheries, respectively, of the ring footing, as

$$q_{u/outer+inner} = s_u N_c + \left\{\frac{2\gamma H^2}{(do)}\left[1+\frac{2D}{H}\right] sK_s tan\varphi\right\} + \left\{\frac{2\gamma H^2}{(d_i)}\left[1+\frac{2D}{H}\right] sK_s tan\varphi\right\} + \gamma D \quad (9)$$

$$q_{u/outer+inner} = s_u N_c + \left\{2\gamma H^2\left[1+\frac{2D}{H}\right] sK_s tan\varphi\left(\frac{1}{d_0}\right)\left[1+\left(\frac{d_i}{d_o}\right)^{-1}\right]\right\} + \gamma D \quad (10)$$

Meyerhof (1974) represented the thickness of the granular bed below the footing as $H$. However, since the entire thickness of the granular fill is considered as $H$ (Fig. 1), the thickness of the granular bed below the footing is now equal to $H - D$ and Eq. (10) gets reduced as below

$$q_{u/outer+inner} = s_u N_c + \left\{2\gamma(H-D)^2\left[1+\frac{2D}{(H-D)}\right] K_s tan\varphi\left(\frac{1}{d_0}\right)\left[1+\left(\frac{d_i}{d_o}\right)^{-1}\right]\right\} + \gamma D \quad (11)$$

or $$q_u/_{outer+inner} = s_u N_c + \left\{2\gamma(H^2-D^2)\left(\frac{1}{d_0}\right)\left[1+\left(\frac{d_i}{d_o}\right)^{-1}\right] K_s tan\varphi\right\} + \gamma D \quad (12)$$

Normalizing Eq. (12) with the undrained shear strength $s_u$ of soft ground, the normalized ultimate bearing capacity $N_u$ of a ring footing in an unreinforced two layered system of granular fill over soft ground, considering the shearing resistances acting along vertical cylindrical surfaces passing through the outer and inner edges of the footing is

$$N_{u,oi} = N_c + \left\{2\left(\frac{\gamma d_0}{s_u}\right)\left[1+\left(\frac{d_i}{d_o}\right)^{-1}\right]\left[\left(\frac{H}{d_0}\right)^2 - \left(\frac{D}{d_0}\right)^2\right] K_s tan\emptyset\right\} + \left\{\left(\frac{\gamma d_0}{s_u}\right)\left(\frac{D}{d_0}\right)\right\} \quad (13)$$

## 4 Bond Resistance of Geosynthetic Reinforcement

As the ring footing moves down into the granular fill, it tries to displace the fill particles radially over the effective outer area $A_{ro}$ (dark shaded area) and $A_{ri}$ (inner area of the ring footing) in Fig. 1(a) of the reinforcement. However, the radial motion of the fill particles is restrained by frictional or shear stresses $\gamma H\tan\phi_r$ mobilized along the interface between the reinforcement and the fill (Fig. 1b).

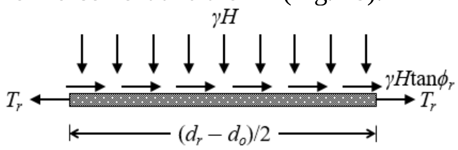


**Fig. 2.** Free body diagram of reinforcement segment beyond outer edge of ring footing

Subsequently axial tensile stresses and strains are induced in the reinforcement (Fig. 2). Thus, the reinforcement provides additional lateral confinement to the fill, which leads to additional shearing resistance along the vertical cylindrical surface passing through the outer and inner edges of the ring footing – this in turn enhances the ultimate bearing capacity of the footing.

The axial tension $T_r$ that develops in the reinforcement due to radial shear stresses mobilized along the interface between the reinforcement and the fill for a Circular footing is

$$T_r = \int_0^{2\pi}\int_{B/2}^{L_r/2} 2\,\sigma_z\, tan\varphi_r\, rdrd\theta \tag{14}$$

$$= \int_{B/2}^{L_r/2} 2\pi\; 2\,\sigma_z\, tan\varphi_r\, rdr$$

$$= 2\pi\; 2\,\sigma_z\, tan\varphi_r \frac{\left(\frac{L_r}{2}\right)^2 - \left(\frac{B}{2}\right)^2}{2}$$

$$= 2\pi\;\; \sigma_z\, tan\varphi_r \left[\frac{{L_r}^2 - B^2}{4}\right]$$

$$= \frac{1}{4}\pi B^2\;\left(2\,\sigma_z\, tan\varphi_r\left[\left(\frac{L_r}{B}\right)^2 - 1\right]\right)$$

$$T_r = \frac{1}{4}\pi B^2\;\left(2\,\gamma H\, tan\varphi_r\left[\left(\frac{L_r}{B}\right)^2 - 1\right]\right) \tag{15}$$

### 4.1 Bond resistance of Geosynthetic reinforcement considering the outer area

For a ring footing of outer diameter $d_o$, inner diameter $d_i$ and reinforcement diameter $d_r$, the axial resistance mobilised in the reinforcement, considering the outer area of the geosynthetic, is obtained by substituting $L_r = d_r$ and $B = d_o$, in Equation 15, as

$$T_{r,outer} = \frac{1}{4}\pi {d_o}^2\left(2\,\gamma H\, tan\varphi_r\left[\left(\frac{d_r}{d_o}\right)^2 - 1\right]\right) \tag{16}$$

where $\sigma'_v$ (at $z = H$) is the vertical effective stress/ normal stress acting on the reinforcement, $\mu = \tan\phi_r$ is the coefficient of friction between the reinforcement and the fill, $\phi_r$ is the reinforcement-fill interface angle of shearing resistance.

The contribution from the interface/bond resistance $q_r$ of the reinforcement towards the ultimate bearing capacity of the footing considering the outer area, $A_{eo}$ of the reinforcement is

$$q_{r,ax/outer} = \frac{T_{r,outer}}{\frac{\pi}{4}({d_0}^2 - {d_i}^2)} = \frac{\left[\left(\frac{1}{4}\pi {d_o}^2\ \left(2\,\gamma H\ tan\varphi_r\left[\left(\frac{d_r}{d_o}\right)^2 - 1\right]\right)\right)\right]}{\frac{\pi}{4}({d_0}^2 - {d_i}^2)} \tag{17}$$

$$q_{r,ax/outer} = 2\gamma H tan\varphi_r\left[\frac{\left(\frac{d_r}{d_0}\right)^2 - 1}{1 - \left(\frac{d_i}{d_0}\right)^2}\right] \tag{18}$$

Normalizing $q_{r,ax/outer}$ with the undrained shear strength $s_u$ of soft ground, $N_{r,ax/outer}$ is obtained as

$$N_{r,ax/outer} = 2\left[\frac{\gamma d_0}{s_u}\right]\left[\frac{H}{d_0}\right] tan\varphi_r\left[\frac{\left(\frac{d_r}{d_0}\right)^2 - 1}{1 - \left(\frac{d_i}{d_0}\right)^2}\right] \tag{19}$$

## 4.2 Bond resistance of Geosynthetic reinforcement considering both the outer and inner areas

The resistance mobilised in the reinforcement, considering the effective inner circular area of diameter $d_i$ of the geosynthetic, is obtained as

$$T_{r,inner} = \frac{1}{4}\pi {d_i}^2\ \ (2\,\gamma H\ tan\varphi_r) \tag{20}$$

The total axial resistance mobilised in the reinforcement, considering the outer and inner areas of the reinforcement is obtained by adding Equations 16 and 20 as

$$T_r = T_{r,outer} + T_{r,inner} =$$

$$= \left(\frac{1}{4}\pi {d_o}^2\left(2\,\gamma H\ tan\varphi_r\ \left[\left(\frac{d_r}{d_o}\right)^2 - 1\right]\right)\right) + \left(\frac{1}{4}\pi {d_i}^2\ \ (2\,\gamma H\ tan\varphi_r)\right) \tag{21}$$

The contribution from the interface/bond resistance $q_r$ of the reinforcement towards the ultimate bearing capacity of the footing is

$$q_{r,ax(outer+inner)} = \frac{T_r}{\frac{\pi}{4}\left({d_0}^2 - {d_i}^2\right)}$$

$$= \frac{\left[\left(\frac{1}{4}\pi {d_o}^2\ \left(2\,\gamma H\ tan\varphi_r\left[\left(\frac{d_r}{d_o}\right)^2 - 1\right]\right)\right) + \left(\frac{1}{4}\pi {d_i}^2\ \ (2\,\gamma H\ tan\varphi_r)\right)\right]}{\frac{\pi}{4}({d_0}^2 - {d_i}^2)} \tag{22}$$

$$q_{r,ax(outer+inner)} = 2\gamma H tan\varphi_r\left[\frac{\left(\frac{d_r}{d_0}\right)^2 - 1 + \left(\frac{d_i}{d_O}\right)^2}{1 - \left(\frac{d_i}{d_0}\right)^2}\right] \tag{23}$$

Normalizing $q_{r,ax(outer+inner)}$ with the undrained shear strength $s_u$ of soft ground, $N_{r,ax(outer+inner)}$ is obtained as

$$N_{r,ax(outer+inner)} = 2\left[\frac{\gamma d_0}{s_u}\right]\left[\frac{H}{d_0}\right] tan\varphi_r\left[\frac{\left(\frac{d_r}{d_0}\right)^2 - 1 + \left(\frac{d_i}{d_O}\right)^2}{1 - \left(\frac{d_i}{d_0}\right)^2}\right] \tag{24}$$

## 5 Bearing Capacity of Ring Footing in Reinforced Granular Fill over Soft Ground

### 5.1 Ring Footing in reinforced granular fill over Soft Ground considering response of reinforcement over outer area

The ultimate bearing capacity $q_{ur(outer)}^{*}$ of a ring footing in reinforced granular fill over soft ground (Fig. 1) is obtained by adding the contribution of the bond resistance $q_{r,ax/outer}$ of the reinforcement (considering axial response of the outer area of reinforcement to pullout) in Eq. 18 to the ultimate bearing capacity $q_{u/outer}$ of a ring footing, on unreinforced granular fill over soft ground (considering the shear stresses on the outer periphery of the footing) in Eq.7 as

$$q_{ur(outer)}^{*} = q_{u/outer} + q_{r,ax/outer}$$

$$q_{ur(outer)}^{*} = s_u N_c + \left\{2\gamma(H^2 - D^2)\left(\frac{1}{d_0}\right)K_s tan\varphi\right\} + \gamma D + \left\{2\gamma H tan\varphi_r\left[\frac{\left(\left(\frac{d_r}{d_0}\right)^2 - 1\right)}{\left(1 - \left(\frac{d_i}{d_0}\right)^2\right)}\right]\right\} \quad (25)$$

The normalized ultimate bearing capacity of a ring footing in reinforced granular fill over soft ground considering axial resistance of reinforcement in the outer area to pullout, is obtained by adding Eq. 8 and Eq.19 as

$$N_{ur,o}^{*} = N_{u/outer} + N_{r,ax/outer}$$

$$N_{ur,o}^{*} = N_c + \left\{2\left(\frac{\gamma d_0}{s_u}\right)\left[\left(\frac{H}{d_0}\right)^2 - \left(\frac{D}{d_0}\right)^2\right]K_s tan\emptyset\right\} + \left\{\left(\frac{\gamma d_0}{s_u}\right)\left(\frac{D}{d_0}\right)\right\} + \left\{2\left[\frac{\gamma d_0}{s_u}\right]\left[\frac{H}{d_0}\right]tan\varphi_r\left[\frac{\left(\frac{d_r}{d_0}\right)^2 - 1}{1 - \left(\frac{d_i}{d_0}\right)^2}\right]\right\} \quad (26)$$

### 5.2 Ring footing in reinforced granular fill over soft ground considering response of reinforcement over both outer and inner areas

The ultimate bearing capacity $q_{ur(outer+inner)}^{*}$ of a ring footing in reinforced granular fill over soft ground (Fig. 1) is obtained by adding the contribution of the bond resistance $q_{r,ax(outer+inner)}$ of the reinforcement (considering axial response of reinforcement to pullout along the outer and inner areas of reinforcement to pullout) to the ultimate bearing capacity $q_{u(outer+inner)}$ of a ring footing, on unreinforced granular fill over soft ground by adding Eq 12 and Eq.23, as

$$q_{ur(outer+inner)}^{*} = q_{u(outer+inner)} + q_{r,ax(outer+inner)}$$

$$q_{ur(outer+inner)}^{*} = s_u N_c + \left\{2\gamma(H^2 - D^2)\left(\frac{1}{d_0}\right)\left[1 + \left(\frac{d_i}{d_o}\right)^{-1}\right]K_s tan\varphi\right\} + \gamma D + \left\{2\gamma H tan\varphi_r\left[\frac{\left(\frac{d_r}{d_0}\right)^2 - 1 + \left(\frac{d_i}{d_o}\right)^2}{1 - \left(\frac{d_i}{d_0}\right)^2}\right]\right\} \quad (27)$$

The normalized ultimate bearing capacity of a ring footing in reinforced granular fill over soft ground considering axial resistance of reinforcement to pullout, is obtained by adding Eq. 13 and Eq. 24, as

$N_{ur,oi}{}^{*} = N_{u(outer+inner)} + N_{r,ax(outer+inner)}$

$$N_{ur,oi}{}^{*} = N_c + \left\{2\left(\frac{\gamma d_0}{s_u}\right)\left[1+\left(\frac{d_i}{d_o}\right)^{-1}\right]\left[\left(\frac{H}{d_0}\right)^2-\left(\frac{D}{d_0}\right)^2\right]K_s tan\emptyset\right\} + \left\{\left(\frac{\gamma d_0}{s_u}\right)\left(\frac{D}{d_0}\right)\right\} + \left\{2\left[\frac{\gamma d_0}{s_u}\right]\left[\frac{H}{d_0}\right] tan\varphi_r \left[\frac{\left(\frac{d_r}{d_0}\right)^2-1+\left(\frac{d_i}{d_o}\right)^2}{1-\left(\frac{d_i}{d_0}\right)^2}\right]\right\} \quad (28)$$

Bearing capacity ratios *BCR* are defined to quantify the degrees of improvement of the bearing capacity of ring footing as

$(BCR)_{f,o} = N_{u,o}/N_c$; $(BCR)_{f,oi} = N_{u,oi}/N_c$; $(BCR)_{fr,o}{}^{*} = N_{ur,o}{}^{*}/N_c$; $(BCR)_{fr,oi}{}^{*} = N_{ur,oi}{}^{*}/N_c$;

The ratios $(BCR)_{f,o}$ and $(BCR)_{fr,o}{}^{*}$ quantify the contribution of granular fill and that of the reinforced granular fill (considering the shear resistance along the outer periphery of the ring footing and the outer area of reinforcement), while $(BCR)_{f,oi}$ $(BCR)_{fr,oi}{}^{*}$ quantify the contribution of granular fill and that of the reinforced granular fill (considering shear resistances on both the outer and inner peripheries of the ring footing and the response of reinforcement on the outer and inner areas of reinforcement).

## 6 Results and Discussion

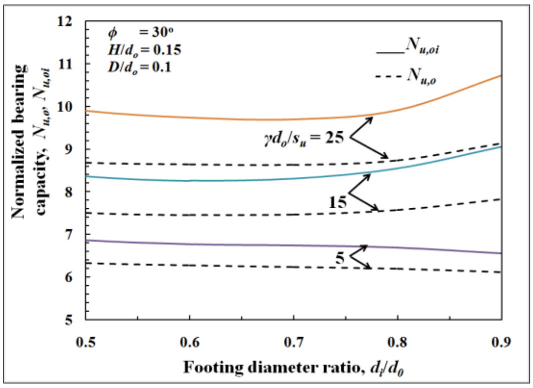


**Fig. 3.** Variation of Normalized bearing capacities $N_{u,o}$ and $N_{u,oi}$ with footing diameter ratio ($d_i/d_o$) - Effect of $\gamma d_0/s_u$

Figure 3 presents the variations of the normalized ultimate bearing capacity of a ring footing in an unreinforced two layered system of granular fill over soft ground, $N_{u,o}$ (considering the shearing resistances acting along vertical cylindrical surfaces passing through the outer edge of the ring footing) , and $N_{u,oi}$ (considering the shearing resistances acting along vertical cylindrical surfaces passing through the outer and inner edges of the footing) while figure 4 presents the variations of the normalized ultimate bearing capacity of a ring footing in a reinforced two layered system of granular fill over soft ground, $N_{ur,o}{}^{*}$ (considering the shearing resistances acting along vertical cylindrical surfaces passing through the outer edge of the footing) , and $N_{ur,oi}{}^{*}$ (considering the shearing resistances acting along vertical cylindrical surfaces passing through the outer and inner edges of the footing) with the footing diameter ratio, $d_i/d_0$,, for $\gamma B/s_u$ equal to 5, 15 and 25, for $\varphi$ of $30^0$, $H/d_0$ of 0.15, $D/d_0$ of 0.1, $\varphi_r/\varphi$ of 0.75 and $d_r/d_0$ of 3. The values of $N_{u,o}$, $N_{u,oi}$, $N_{ur,o}$ and $N_{ur,oi}$, of thin ring footings (for $d_i/d_o$ varying from 0.5 to 0.9) for different values of $\gamma d_0/s_u$ are tabulated in Table 1.

**Table 1.** Variation of Normalized bearing capacities, $N_{u,o}$, $N_{u,oi}$, $N_{ur,o}$* and $N_{ur,oi}$* with footing diameter ratio ($d_i/d_o$), for varying $\gamma d_0/s_u$

| $\frac{d_i}{d_0}$ ⟹ | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 |
|---|---|---|---|---|---|---|---|---|---|---|
| $\frac{\gamma d_0}{s_u}$ ⇓ | | | $N_{u,o}$ | | | | | $N_{u,oi}$ | | |
| 5 | 6.33 | 6.27 | 6.24 | 6.20 | 6.12 | 6.86 | 6.77 | 6.74 | 6.69 | 6.56 |
| 15 | 7.50 | 7.46 | 7.47 | 7.58 | 7.83 | 8.36 | 8.26 | 8.31 | 8.55 | 9.06 |
| 25 | 8.68 | 8.64 | 8.63 | 8.74 | 9.14 | 9.90 | 9.74 | 9.70 | 9.91 | 10.72 |
| | | | $N_{ur,o}$* | | | | | $N_{ur,oi}$* | | |
| 5 | 8.82 | 9.19 | 9.89 | 11.37 | 12.39 | 9.55 | 10.03 | 11.00 | 12.98 | 12.39 |
| 15 | 14.96 | 16.20 | 18.44 | 23.11 | 37.17 | 16.44 | 18.05 | 21.06 | 27.40 | 37.17 |
| 25 | 21.11 | 23.20 | 26.91 | 34.63 | 58.19 | 23.37 | 26.05 | 30.96 | 41.32 | 61.94 |

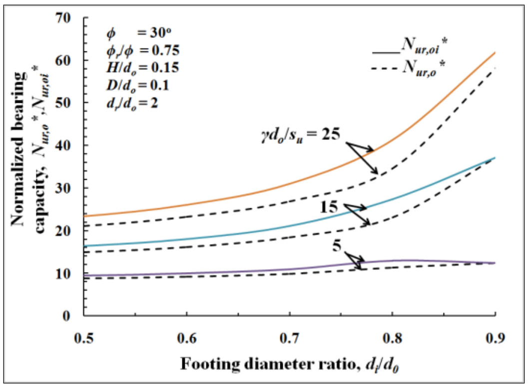


**Fig. 4.** Variation of Normalized bearing capacities $N_{ur,o}$* and $N_{ur,oi}$* with footing diameter ratio ($d_i/d_o$) - Effect of $\gamma d_0/s_u$

Improved normalized bearing capacity values are obtained by considering shear resistance along both the outer and inner peripheries of ring footings in a two-layered system of unreinforced and reinforced granular fill over soft ground, when compared to those obtained by considering the shear resistance along the outer periphery alone, due to the increased length of vertical cylindrical surface considered and thereby increased contribution of shear resistance. Enhanced normalized bearing capacity values are obtained for a Ring footing in a two-layered system of reinforced granular fill over soft ground, when compared to those in an unreinforced two-layered system. Thinner Ring footings in/on a two-layered system of reinforced granular fill over soft ground show improved normalized bearing capacity values, due to the increased contribution from the granular fill and reinforcement. Softer clays or relatively wider footings with higher values of $\gamma d_0/s_u$, show improved bearing responses, due to inclusion of granular fill and reinforcement.

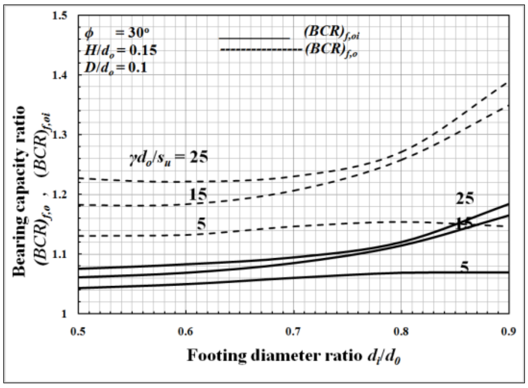


**Fig. 5.** Variation of Bearing Capacity Ratios, *(BCR)f,o* and *(BCR)f,oi* with footing diameter ratio ($d_i/d_o$) - Effect of $\gamma d_0/s_u$

Figure 5 presents the variations of the Bearing Capacity Ratios of a ring footing in an unreinforced two layered system of granular fill over soft ground, $(BCR)_{f,o}$ (considering the shearing resistances acting along vertical cylindrical surfaces passing through the outer edge of the footing) , and $(BCR)_{f,oi}$ (considering the shearing resistances acting along vertical cylindrical surfaces passing through the outer edge and inner edge of the footing) with the footing diameter ratio, $d_i/d_0$, , for $\gamma B/s_u$ equal to 5, 15 and 25, for $\varphi$ of $30^0$, $H/d_0$ of 0.15 and $D/d_0$ of 0.1.

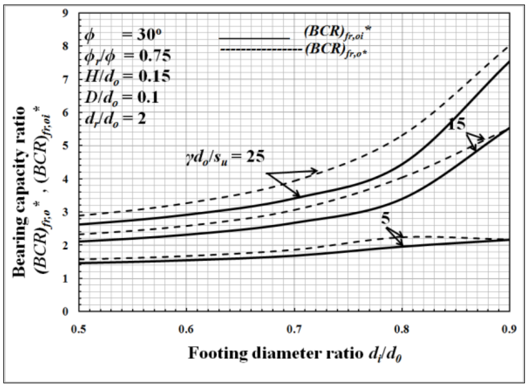


**Fig. 6.** Variation of Normalized bearing capacities $(BCR)_{fr,o}$* and $(BCR)_{fr,oi}$*with footing diameter ratio ($d_i/d_o$) - Effect of $\gamma d_0/s_u$

Figure 6 presents the variations of the Bearing Capacity Ratios of a ring footing in a reinforced two layered system of granular fill over soft ground, $(BCR)_{fr,o}$* (considering shear resistance on the outer periphery of the ring footing and the response of reinforcement on the outer area of reinforcement) , and $(BCR)_{fr,oi}$* (considering shear resistances on both the outer and inner peripheries of the ring footing and the response of reinforcement on the outer and inner areas of reinforcement) with the footing diameter ratio, $d_i/d_0$, , for $\gamma B/s_u$ equal to 5, 15 and 25, for $\varphi$ of $30^0$, $H/d_0$ of 0.15, $D/d_0$ of 0.1, $\varphi_r/\varphi$ of 0.75 and $d_r/d_0$ of 3.

Improved normalized Bearing Capacity Ratio values are obtained by considering shear resistance along both the outer and inner peripheries of Ring footings in a two-layered system of unreinforced and reinforced granular fill over soft ground, when compared to those obtained by considering the shear resistance along the outer periphery alone, due to the increased contribution of shear resistance. Enhanced normalized Bearing Capacity Ratio values are obtained for a Ring footing in/on a two-layered system of reinforced granular fill over soft ground, when compared to those in an unreinforced two-layered system. Thinner Ring footings in a two-layered system of reinforced granular fill over soft ground show improved normalized Bearing Capacity Ratio values, due to the increased contribution from the granular fill and reinforcement. Softer clays or relatively wider footings with higher values of $\gamma d_0/s_u$ show improved bearing responses. The Bearing Capacity Ratios, $(BCR)_{f,o}$, $(BCR)_{f,oi}$, $(BCR)_{fr,o}$* and $(BCR)_{fr,oi}$* of thin ring footings ($d_i/d_o$ varying from 0.5 to 0.9) for different values of $\gamma d_0/s_u$ and $d_i/d_o$ are tabulated in Table 2.

**Table 2** Variation of Normalized Bearing Capacity Ratios, $(BCR)_{f,o}$, $(BCR)_{f,oi}$, $(BCR)_{fr,o}$* and $(BCR)_{fr,oi}$* with footing diameter ratio ($d_i/d_o$), for varying $\gamma d_0/s_u$

| $\frac{d_i}{d_0}$ → | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 |
|---|---|---|---|---|---|---|---|---|---|---|
| $\frac{\gamma d_0}{s_u}$ ↓ | | | $(BCR)_{f,o}$ | | | | | $(BCR)_{f,oi}$ | | |
| 5 | 1.04 | 1.05 | 1.06 | 1.07 | 1.07 | 1.13 | 1.13 | 1.15 | 1.15 | 1.15 |
| 15 | 1.06 | 1.07 | 1.09 | 1.11 | 1.17 | 1.18 | 1.18 | 1.21 | 1.26 | 1.35 |
| 25 | 1.08 | 1.08 | 1.09 | 1.12 | 1.18 | 1.23 | 1.22 | 1.23 | 1.27 | 1.39 |
| | | | $(BCR)_{fr,o}$* | | | | | $(BCR)_{fr,oi}$* | | |
| 5 | 1.45 | 1.54 | 1.68 | 1.96 | 2.17 | 1.57 | 1.68 | 1.87 | 2.24 | 2.17 |
| 15 | 2.12 | 2.32 | 2.68 | 3.40 | 5.53 | 2.33 | 2.59 | 3.06 | 4.03 | 5.53 |
| 25 | 2.62 | 2.91 | 3.41 | 4.44 | 7.54 | 2.90 | 3.27 | 3.93 | 5.30 | 8.02 |

Figure 7 shows the analytical results from the present study, obtained for ultimate bearing capacity of a ring footing on the surface ($z$=0) of an unreinforced and reinforced (considering axial response of reinforcement to pull out) granular fill over soft ground, $(BCR)_{f,o}$, $(BCR)_{f,oi}$, $(BCR)_{fr,o}$* and $(BCR)_{fr,oi}$*, in comparison with the experimental results of Shalaby (2017) for soft clay partly replaced with sand and without stone piles for ($B/b$) = 2 and the results are tabulated in Table 3. Figure 7 shows that results from the present study compare well for relatively smaller thicknesses ($H/d_0$ = 0 to 1.0) of granular layer, but for relatively thick granular fill (with $H/d_0$ > 1.0), "conservative" values of *BCR* are obtained, when compared to those obtained by Shalaby (2017). Possible reasons for the conservative values obtained for relatively thicker granular fills, could be the surcharge effect which has been neglected in this study and/or the application of Meyerhof's limiting criterion.

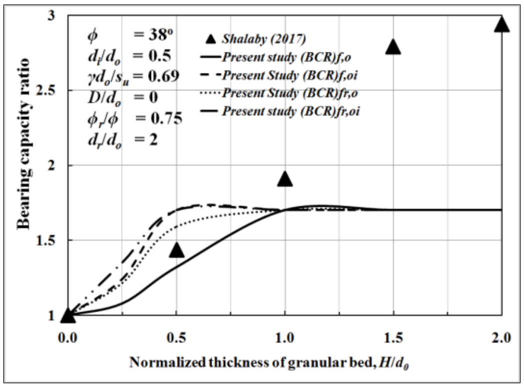


**Fig. 7.** Variation of Bearing Capacity Ratio *(BCR)* with Normalised thickness of granular bed $(\boldsymbol{H/d_0})$

**Table 3.** Variation of *(BCR)* with ($H/d_o$)

| $\frac{H}{d_0}$ | Reinforced/ Unreinforced | 0.0 | 0.5 | 1.0 | 1.5 | 2.0 |
|---|---|---|---|---|---|---|
| | | | | *(BCR)* values from | | |
| Shalaby (2017)$(BCR)_f$ | Unreinforced | 1.0 | 1.43 | 1.91 | 2.79 | 2.94 |
| Present Study $(BCR)_{f,o}$ | Unreinforced | 1.0 | 1.32 | 1.70 | 1.70 | 1.70 |
| Present Study $(BCR)_{f,oi}$ | Unreinforced | 1.0 | 1.70 | 1.70 | 1.70 | 1.70 |
| Present Study$(BCR)_{fr,o}$* | Reinforced | 1.0 | 1.59 | 1.70 | 1.70 | 1.70 |
| Present Study$(BCR)_{fr,oi}$* | Reinforced | 1.0 | 1.70 | 1.70 | 1.70 | 1.70 |

## 7 Conclusions

The proposed model considers the effect of axial resistance mobilized by a single circular sheet of geosynthetic reinforcement due to interfacial shear stresses developed over its top and bottom surfaces, shear resistances of the granular fill along the outer and inner edges of the ring and that of the soft ground to arrive at the total ultimate bearing capacity of the reinforced two layer system. The values provided by Keshavarz and Kumar (2017) for the bearing capacity factor $N_c$ for rough ring footings on a cohesive–frictional soil are incorporated in the formulation. Predictions compare well with experimental results of Shalaby (2017) in literature for relatively smaller thicknesses of granular layer.

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