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BEARING CAPACITY OF STRIP, CIRCULAR AND RING FOOTINGS ON LIMITED DEPTH OF SOIL

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ABSTRACT

The vertical bearing capacity factors N'_c, N'_q and N'_γ are evaluated using the finite element (FE) method for rough base strip, circular and ring footings resting on c-ϕ soil of limited depth varying from $H = 1B$ to $5B$ underlain by a rigid rough base. The N'_c, N'_q and N'_γ are also evaluated for rough base ring footing resting on c-ϕ soil of limited depth varying from $H = 0.25B$ to $1B$. The Mohr-Coulomb material model is used in the FE analysis and the effect of dilatancy is considered for higher friction angles ($\phi > 30°$). Plane strain formulation is used to model strip footing and axisymmetric formulation is used to model circular and ring footings. Appropriate boundary conditions and the size of FE mesh domain are chosen to restrict the development of plastic failure of soil with the FE domain. The present study FE results are observed to compare well with the theoretical and numerical results available in the literature. Based on the outcome of present study, a few suggestions are drawn in regard to the determination of the bearing capacity of footings resting on a limited depth of soil.

Key words: Bearing capacity factors, strip footing, circular footing, ring footing, finite element method, limited depth of soil.

1. INTRODUCTION

Strip footing, also called as continuous footing, a shallow foundation, is used to support lengthy structures having load bearing walls. Circular footing, a shallow foundation, is used to support the structures with circular geometry like wind turbines, silos, water tanks, *etc.* Ring footing is a shallow foundation, also termed as annular footing, used to support isolated structures with annular geometry like silos, chimneys, light houses, *etc.* (Chouhan *et al.* 2023a). To ensure the safety and stability of a structure, a detailed evaluation of ultimate bearing capacity of footings and the corresponding failure mechanism is necessary. The classical theory on the ultimate bearing capacity of shallow foundation assumes that the soil strata extend to a semi-infinite depth (Terzaghi 1943; Meyerhof 1963). Whereas, in the field the depth of bedrock is very uncertain and sometimes it may be encountered at shallow depth which will have a significant influence on the ultimate bearing capacity of footings and the corresponding failure mechanism. This leads to the condition in which the failure mechanism in soil is restricted to evolve within limited depth of soil. Various past studies report the bearing capacity of strip, circular and ring footings considering a minimum boundary of ~5 times the width of footing so as the full failure zones are formed. For example bearing capacity of footing is evaluated by limit equilibrium method (Terzaghi 1943; Hansen 1961; Meyerhof 1963), method of characteristics (Bolton and Lau 1993; Chandrashekhara *et al.* 1998; Kumar and Ghosh 2005; Gholami and Hosseininia 2017), upper and lower bound plastic limit analyses (Drucker *et al.* 1951; Sloan 1988; Michalowski 1997; Soubra 1999; Ukritchon *et al.* 2003; Kumar and Khatri 2008; Kumar and Chakraborty 2015; Chakraborty 2016), finite element method (FEM) (Zienkiewicz *et al.* 1975; Griffiths 1982; Griffiths 1989; Hijaj *et al.* 2005; Choobbasti *et al.* 2010; Tang and Phoon 2018; Chavda and Dodagoudar 2019; Chavda and Dodagoudar 2021), finite difference method (FDM) (Yin *et al.* 2001; Maheshwari and Madhav 2006; Zhao and Wang 2008; Benmebarek *et al.* 2012; Hosseininia 2016; Remadna *et al.* 2016; Benmebarek *et al.* 2017; Sargazi and Hosseininia 2017), experimental method (Saha 1978; Ismael 1996; Ohri *et al.* 1997; Clark 1998; Zhu 1998; Boushehrian and Hataf 2003; Hataf and Razavi 2003; Laman and Yildiz 2003; Saran *et al.* 2003; Sawwaf and Nazir 2012), and finite element limit analysis (FELA) (Chouhan *et al.* 2023b). However, the above methodology is applicable to cases where fully developed failure zones are formed. Moreover, the above-mentioned solutions need to be modified to account the restricted failure mechanism in limited depth of soil.

The ultimate load applied to a foundation in a homogeneous soil extending to a great depth result in shear failure with failure surface developing up to a certain depth D depending on internal friction angle of the soil and the roughness of the foundation (Lundgren and Mortensen 1953). But in the case of a rigid boundary (rock layer) located at a depth of $H < D$ the developed failure surface will be modified in contrast to that in the case of infinite depth and the modified ultimate bearing capacity of a surface foundation resting on a cohesionless soil of limited depth may be given by

$$q_u = \frac{1}{2}\gamma B N'_\gamma \tag{1}$$

where N'_γ is the modified bearing capacity factor which accounts the failure mechanism in limited depth of soil, H is the limited depth of soil, D is the depth of fully developed failure zone, B is the width of footing, γ is the unit weight of soil, q_u is the ultimate bearing capacity.

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Mandel and Salencon (1972) attempted to determine the solution for the bearing capacity of strip footing on a soft ground with a rigid base by limit equilibrium method and found that bearing capacity factor (N_γ) is a function of friction angle of soil (ϕ) and B/H, where B is the width of footing and H is limited depth of soil. Meyerhof (1974) proposed that the shape factor (s_γ) of the footing is also affected by rigid layer and suggested a relation for the shape factor for circular footing for $H/B \leq 1$. Cerato and Lutenegger (2006) performed laboratory model tests on square and circular footings and proposed that the modified bearing capacity factor is directly proportional to the friction angle and relative density of sand layer, they are directly proportional to H/B ratio and width of the footing, and the modification of bearing capacity factor is not required in the case of $H/B \geq 3$. Yang *et al.* (2016) evaluated the ultimate bearing capacity of strip footings resting on cohesionless soil layer with rigid basement by upper-bound finite element method with rigid translatory moving elements (UBFEM - RTME) using nonlinear programming for the solutions to bearing capacity factor (N_γ) and correction factor (K_γ) and obtained the associated failure mechanisms.

From the above review, it is observed that bearing capacity factors for strip and circular footings resting on cohesionless soil of limited depth were evaluated for $H < 3B$. But in practice, if any rigid rough base is encountered at depths $H \leq 1B$ (like $H = 0.1B$, $0.3B$, $0.5B$, and $1B$) then, if possible, the foundation can be laid directly on the rigid base itself by removing the top layer which is of limited depth (H). This is because, in the case of shallow foundations, the minimum depth of excavation for concrete structures should be 0.5 m as per IS 1904-1986 (sec. 7.2) and 0.3 m as per IBC (2012) (sec. 1805.2) and normally laid at a depth of 3 m as per IS 1904-1986 (sec. 3.1). For example, if the width of footing is of 1 m (minimum recommended as per standard codes) and shallow depth of soil is at 1 m, then, in such case, authors recommend to remove 1 m layer of soil and place the footing directly on firm strata, *i.e.,* rock layer. It is to be noted that the solution to the bearing capacity factors for ring footing resting on limited depth of soil is not available. Keeping in view of the practical implication for shallow foundations, the present study is attempted to evaluate the bearing capacity factors for rough base strip, circular and ring footings resting on c-ϕ soil with limited depth ($H = 1B$, $2B$, $3B$, $4B$ and $5B$) by using finite element method. However, there are situations where the foundations are rested on soil with limited depth even $H \leq 1B$ such as offshore foundations. Therefore, in this study, the bearing capacity factors are also evaluated for rough base ring footing resting on c-ϕ soil with limited depth $H \leq 1B$. The results corresponding to $H = 5B$ can be directly applied to classical theory of foundation on soil.

The present study attempts to the evaluate the bearing capacity factors for rough base strip, circular and ring footings with respect to cohesion, surcharge and unit weight components of soil and resting on soil with limited depth varying from $H = 1B$ to $5B$ by using finite element based PLAXIS program. The bearing capacity factors are also evaluated for rough base ring footing resting on c-ϕ soil with limited depth $H \leq 1B$. In case of ring footing, the radius ratio r_i/r_o is varied from 0.25 to 0.75 (*i.e.*, r_i/r_o = 0.25, 0.50, and 0.75) where r_i is the internal radius and r_o is the external radius of the ring footing. Mesh convergence study is carried out and the optimum mesh size is used in the analysis. The present study also describes the method of defining the geometry of soil domain in layers and assigning the corresponding material properties as required to account for a limited depth concept to avoid the errors due to no control over meshing in PLAXIS and also to save time by avoiding the changes in geometry of soil domain for every limited depth case. The Mohr-Coulomb material model is used in the FE analysis and the effect of dilatancy is considered for higher friction angles ($\phi > 30°$). The present study results are depicted in the form of design charts and are compared with the experimental, theoretical and numerical results available in the literature. The failure planes are also presented for a few typical cases of ring footing. Finally, a few suggestions are given based on the comparisons made.

2. METHODOLOGY

2.1 Problem Formulation

The classical equation commonly used for the determination of the bearing capacity of strip (continuous) footing for shallow foundation given by Terzaghi (1943) may be expressed as:

$$q_u = c\,N_c + q\,N_q + \frac{1}{2}\gamma\,B\,N_\gamma \tag{2}$$

where q_u is the ultimate bearing capacity of soil, c is the cohesion of soil, q is the applied surcharge, γ is the unit weight of soil, B is the width of footing and N_c, N_q, N_γ are the bearing capacity factors with respect to cohesion, surcharge and unit weight components of soil, respectively. The above bearing capacity equation has been more generalized to account for the shapes of other footings like circular footings and may be expressed as (Erickson and Drescher 2002):

$$q_u = c\,N_c' + q\,N_q' + \frac{1}{2}\gamma\,D\,N_\gamma' \tag{3}$$

where $N_c' = s_c N_c$, $N_q' = s_q N_q$, $N_\gamma' = s_\gamma N_\gamma$, s_c, s_q, s_γ are shape factors, N_c', N_q', N_γ' are modified bearing capacity factors and D is the diameter of the circular footing. Though a few other equations are available, the equation for the evaluation of bearing capacity factors of ring footing used by Chavda and Dodagoudar (2018) is adopted in the present study as it represents a more realistic and practical way of calculating the N_γ' which accounts the width ($r_o - r_i$) of the ring footing (Chavda and Dodagoudar 2021) and is expressed as:

$$q_u = c\,N_c' + q\,N_q' + (r_o - r_i)\gamma\,N_\gamma' \tag{4}$$

where r_i is the internal radius and r_o is the external radius of the ring footing.

The Griffiths (1982) approach is used for the evaluation of bearing capacity factors of strip, circular, and ring footings with respect to cohesion, surcharge, and unit weight components of soil. In this approach, the N_c or N_c' term is evaluated by assuming the soil has negligible unit weight ($\gamma = 0.01$ kN/m^3) and the footing is modeled as surface footing (*i.e.,* surcharge, $q = 0$). The N_q or N_q' term is evaluated by assuming the soil with a negligible cohesion ($c = 0.1$ kPa) and unit weight ($\gamma = 0.01$ kN/m^3) and a uniform surcharge acting above the footing base. Similarly, the N_γ or N_γ' term is carried out by assuming the soil with negligible cohesion ($c = 0.1$ kPa) with no surcharge ($q = 0$) acting above the base of footing. Chavda and Dodagoudar (2019) can be referred to get more insight into the Griffiths (1982) approach to evaluate the bearing capacity factors of footing using FEM.

2.2 FE Modeling of Strip, Circular and Ring Footings

The finite element based PLAXIS program is used for the evaluation of bearing capacity factors of strip (B = 2 m), circular (D = 2 m) and ring footings of radius ratio r_i/r_o = 0.25, 0.50, 0.75 with width of ring ($r_o - r_i$ = 2 m) resting on c-ϕ soil of limited depth varying from H = 1B to 5B. The FE model with mesh and element details of the strip, circular and ring footings are depicted in Figs. 1(a)-1(c), respectively. The size of the FE domain considered in the study are chosen such that the plastic regions developed at the failure load are well within the boundaries of soil domain. In the case of strip/circular footings, the minimum size of soil domain is considered as 5 times the width/diameter of the footing in horizontal or radial direction as well as in vertical direction. Whereas, in the case of ring footing, the minimum size of soil domain is considered as 5 times the width of ring footing ($r_o - r_i$) in vertical direction and sum of r_o plus 5 times the width of ring footing ($r_o - r_i$) in horizontal direction (Chavda and Dodagoudar 2019). The vertical boundary of the FE domain is assigned with roller support (*i.e.,* roller support; U_x = 0) and bottom horizontal boundary is constrained (*i.e.,* fixed support; $U_x = U_y = 0$).

The strip footing is modeled as half strip by utilizing the advantage of symmetry. The 15-noded triangular elements with 12 Gaussian quadrature points and fine mesh is considered for the FE analyses. The linear-elastic perfectly-plastic Mohr-Coulomb soil model is considered with the deformation parameters (E = 200 MPa and v = 0.35) assigned to the soil. The dilatancy effect for higher friction angles (ϕ > 30°) is also considered in the study based on the relationship, $\psi = \phi - 30°$; $\phi > 30°$ (Bolton 1986). The material properties assigned to the soil are: c = 25 kPa, γ = 20 kN/m^3, E = 200 MPa, v = 0.35 and ϕ = 0 to 35°. For the case ϕ = 35°, a dilation angle of ψ = 5° is assigned. The non-associated flow rule is used in the analyses. Following Griffiths (1982), the c = 25 kPa when evaluating N_c ($\gamma = q = 0$), the q = 25 kPa for evaluating N_q ($c = \gamma = 0$), and γ = 20 kN/m^3 when evaluating N_γ ($c = q = 0$). The material properties used in the study are also depicted in the Figs. 1(a)-1(c). The rock layer is modeled as linear elastic having γ = 20 kN/m^3, E = 20 GPa and v = 0.1. Since, the rock is modelled as linear elastic, the failure is attributed within the soil mass only, and hence the assigned properties of rock mass will not affect the FE outcome of bearing capacity factors of the strip, circular and ring footings resting on limited depth of soil. In the case of ring footing, c = 20 kPa, γ = 20 kN/m^3, q = 50 kPa, E = 200 MPa, v = 0.35 and ϕ = 0 to 35°. The K_0-procedure is used in the present study to generate the initial stresses which account for the loading history of the soil. Note that, in general, the K_0-procedure is especially used when the surface is horizontal and K_0 values can be specified as $K_{0,x} = \sigma'_{xx}/\sigma'_{zz}$ in the x-direction and $K_{0,y} = \sigma'_{yy}/\sigma'_{zz}$ in the y-direction (Alam *et al.* 2021). The analysis is performed for dry condition without considering the effect of groundwater. In the study, the bearing capacity factors of the strip, circular and ring footings are evaluated for varying depth of soil deposits H = 1B to 5B to account the limited depth of soil. Where, B is the width of footing, and H is limited depth of soil deposit.

The limited depth of soil (from H = 1B to 5B) underlain by a rigid base is accounted by considering the entire geometry of soil domain defined by five layers, with each layer defined by a

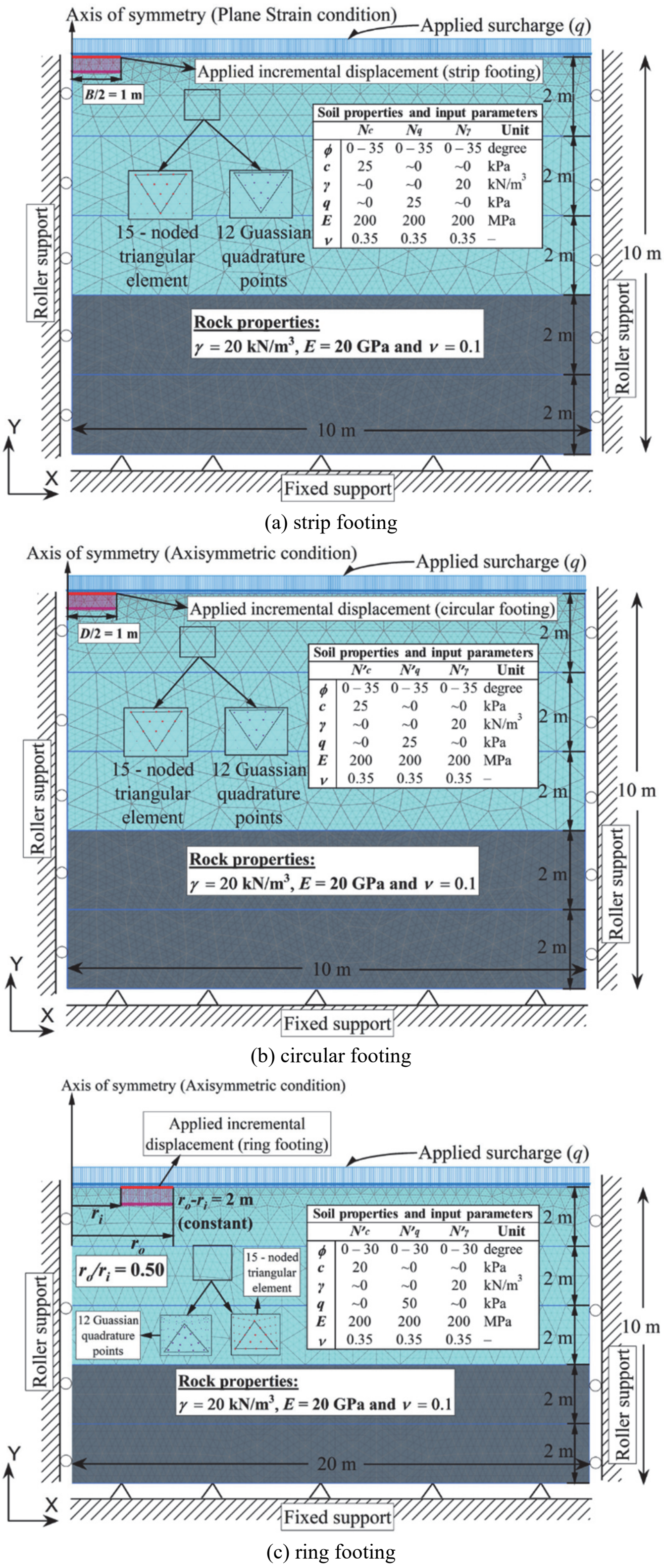


Fig. 1 FE model, mesh and element details

thickness of 1B (B = 2 m) and the meshing of each layer of entire soil domain is fine mesh size. As the meshing of a domain does not depend upon material property but depends only on the domain of the geometry, which is layered in the present study, the meshing is same for every case of H = 1B to 5B. For the case of H = 5B shown in Fig. 2, the soil domain consists of 5 layers of soil with no rock layer and for the case of H = 4B, the soil domain consists

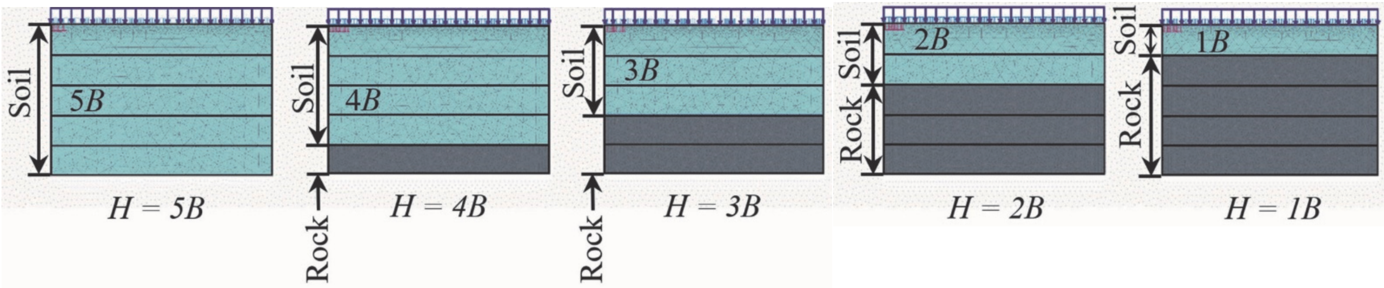


Fig. 2 Schematic representation of variation of depth of soil layer by addition of rock layer

of 4 layers of soil with 1 layer of rock in the bottom. Similarly, for the case of $H = 3B$, $2B$, and $1B$ shown in figure the domain is defined by decreasing one layer of soil and increasing one layer of rock in each case. Therefore, in each case of $H = 1B$ to $5B$ only material properties are varied without varying the FE domain in vertical direction which results in unaltered meshing. This method of assigning rock layer eliminates the error associated with revision in the mesh size. Also, utilizing the advantage of symmetry in the present study reduces the computational time. Therefore, the present study is more towards the elimination of error by utilizing the advantages of layered geometry and symmetry. The interface between soil and rock is assumed to be rigid and rough due to which the full development of failure surface is restricted and constrained within limited depth of soil resulting in increase in bearing capacity of foundation which ultimately results in higher values of bearing capacity factors. It is noted that the rock layer is modelled using linear elastic model, this allows the failure to occur only within soil domain.

2.3 Mesh Convergence Study

The mesh convergence study is carried out by evaluating the ultimate bearing capacity of circular footing by axisymmetric modeling corresponding to the different mesh size options available in PLAXIS program. The PLAXIS program consists of five different mesh sizes ranging from very coarse to very fine mesh size. The results of mesh convergence study for circular footing of diameter of 1 m resting on soil having $\gamma = 20$ kN/m^3, $c = 25$ kPa, $\phi = 20°$, $E = 200$ MPa, $\nu = 0.35$ and surcharge of 25 kPa (*i.e.*, $q = 25$ kPa) are depicted in Fig. 3. The bearing capacity (q_u) versus average mesh element size is plotted in the figure. It is observed that the variation in q_u is 27.22% between very coarse and very fine mesh size and the q_u corresponding to fine mesh is almost same as very fine mesh and hence it can be considered as optimum mesh. Similarly, for strip and ring footing, the optimum mesh was determined and fine mesh was obtained as optimum mesh. Based on the mesh convergence study, fine mesh is selected as the optimum mesh size for the present study to determine the bearing capacity factors of strip, circular and ring footings resting on c-ϕ soil of limited depth varying from $H = 1B$ to $5B$ underlain by a rigid rough base.

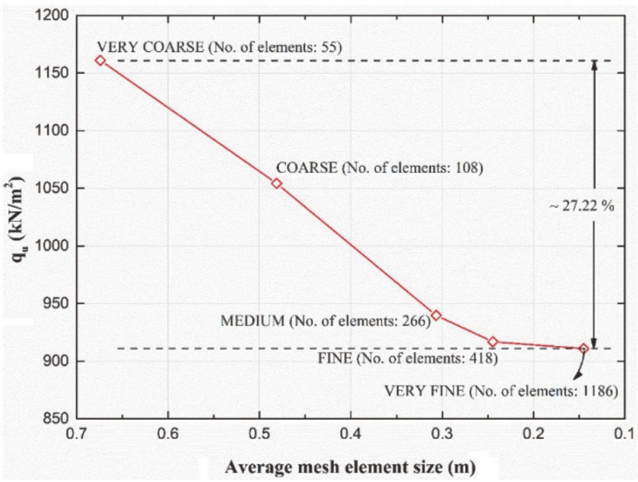


Fig. 3 Typical mesh convergence study shown for circular footing

3. RESULTS AND DISCUSSION

Finite element analysis of strip footing of width $B = 2$ m is carried out for the case of $H = 5B$ to evaluate the bearing capacity factors N_c, N_q, N_γ and the obtained results are compared with the published literature. Then in the same validated model, the depth is varied from $5B$ to $1B$ to account the effect of limited depth of soil. Similarly, the bearing capacity factors N_c', N_q', N_γ' of circular footing of diameter $D = 2$ m and ring footings with radius ratio, $r_i/r_o = 0.25$, 0.50, 0.75 keeping the width of ring ($r_o - r_i = 2$ m) as constant are evaluated for the case of $H = 5B$ and validated by comparing with the values available in the published literature. Then in the same validated model, the depth is varied from $5B$ to $1B$ to account the effect of limited depth of soil.

3.1 Strip Footing

3.1.1 Validation of Strip Footing

The finite element analysis of strip footing is carried out for the case of $H = 5B$ to determine the bearing capacity factors N_c, N_q, N_γ by Griffiths (1982) approach with a surcharge (q) of 25 kPa applied above the footing base with the material properties shown in Fig. 1(a). The bearing capacity factors N_c, N_q, N_γ of strip footing for $H = 5B$ are depicted in Figs. 4(a)-4(c). In the same figures, the theoretical and numerical results available in the literature are also presented. The present study results are found to be lesser than theoretical results reported by Terzaghi (1943) and Meyerhof (1963) and limit equilibrium solution by Mandel and Salencon (1972). However, the present study FEM results are good in comparison with the lower bound finite element limit analysis (FELA) results of Kumar and Khatri (2008) and Chakraborty and Kumar (2013) and FEM results of Chavda and Dodagoudar (2018).

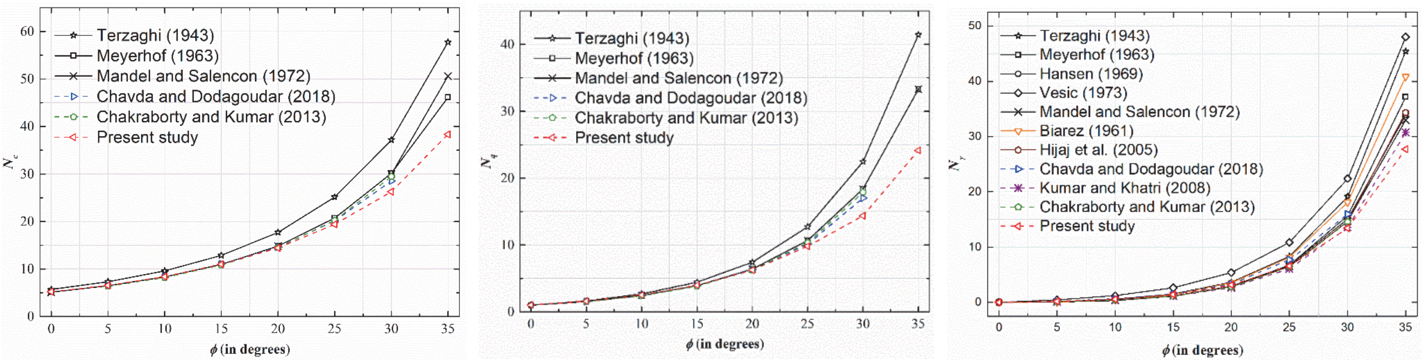
3.1.2 Strip Footing on Limited Depth of Soil

The FE analysis of strip footing on limited depth of soil is carried out by varying the depth of soil from $H = 1B$ to $5B$ and the obtained results are depicted as charts representing the variation of bearing capacity factors with H/B for given range of friction angles (ϕ = 5°-35°). The FE results are presented in the form of reduction in bearing capacity factors with increase in the H/B ratio (Fig. 5). Figures 5(a)-5(c) show the bearing capacity factors N_c, N_q, N_γ increase with increase in friction angle and increase with decrease in H/B ratio. Figures 5(a)-5(c) show that the effect of limited depth is observed to be more significant for N_q than N_c and N_γ and also the limited depth has significant effect for higher friction angles (ϕ > 30°).

3.2 Circular Footing

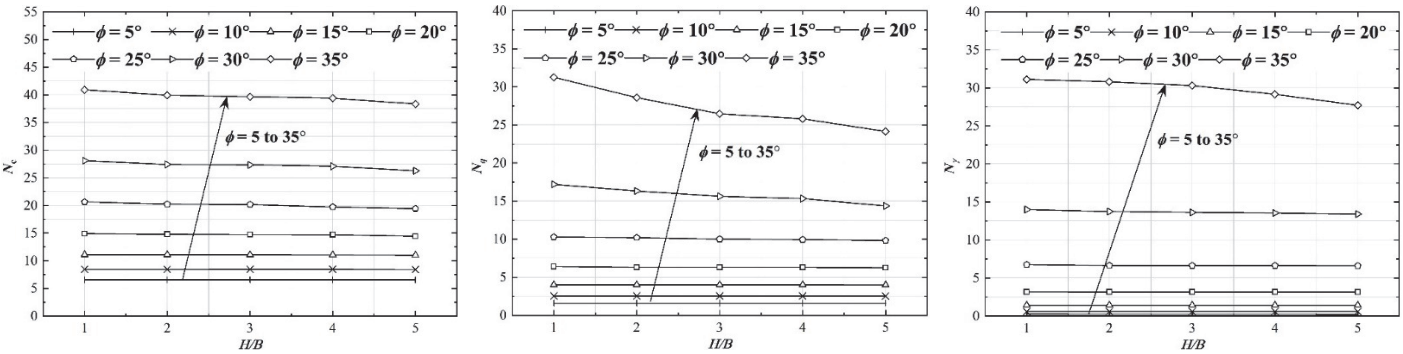
3.2.1 Validation of Circular Footing

The finite element analysis of circular footing is carried out for the case of $H = 5B$ to determine the bearing capacity factors N'_c, N'_q, N'_γ by Griffiths (1982) approach with a surcharge (q) of 25 kPa applied above the footing base with the material properties shown in Fig. 1(b). Figures 6(a)-6(c) show the comparison of FE results with theoretical and numerical results available in the literature and it is observed that in case of N'_c, the obtained results are lower than theoretical results of Terzaghi (1943) and Meyerhof (1963) and match well with the FDM results of Remadna *et al.* (2016) and



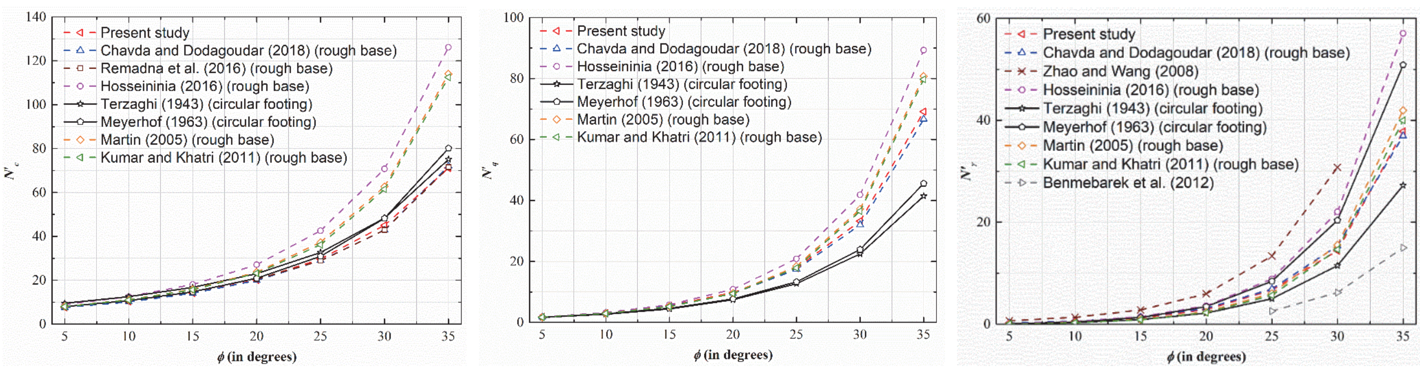
(a) N_c (b) N_q (c) N_γ

Fig. 4 Comparison of bearing capacity factors of strip footing for $H = 5B$



(a) N_c (b) N_q (c) N_γ

Fig. 5 Variation of bearing capacity factors of strip footing with increasing H/B



(a) N_c (b) N_q (c) N_γ

Fig. 6 Comparison of bearing capacity factors of circular footing for $H = 5B$

FEM results of Chavda and Dodagoudar (2018). In the case of N'_q and N'_γ the obtained results match well with the method of characteristics results of Martin (2005), lower bound FELA results of Kumar and Khatri (2011) and FEM results of Chavda and Dodagoudar (2018).

3.2.2 Circular Footing on Limited Depth of Soil

The FE analysis of circular footing on limited depth of soil is carried out by varying the depth of soil from $H = 1B$ to $5B$ and the obtained results are depicted as charts representing the variation of bearing capacity factors with H/B for given range of friction angles ($\phi = 5°$-$35°$). The FE results are presented in the form of reduction in bearing capacity factors with increase in the H/B ratio (Fig. 7). Figures 7(a)-7(c) show the bearing capacity factors N'_c, N'_q, N'_γ increase with increase in friction angle and increase with decrease in H/B ratio. Figures 7(a)-7(c) show that the effect of limited depth is observed to be more significant for N'_c than N'_q and N'_γ and also the limited depth has significant effect for higher friction angles ($\phi > 30°$) which is similar in the case of strip footing. Also, it is observed that the effect of limited depth is more predominant for strip footing than circular footing of same size/width.

3.3 Ring Footing

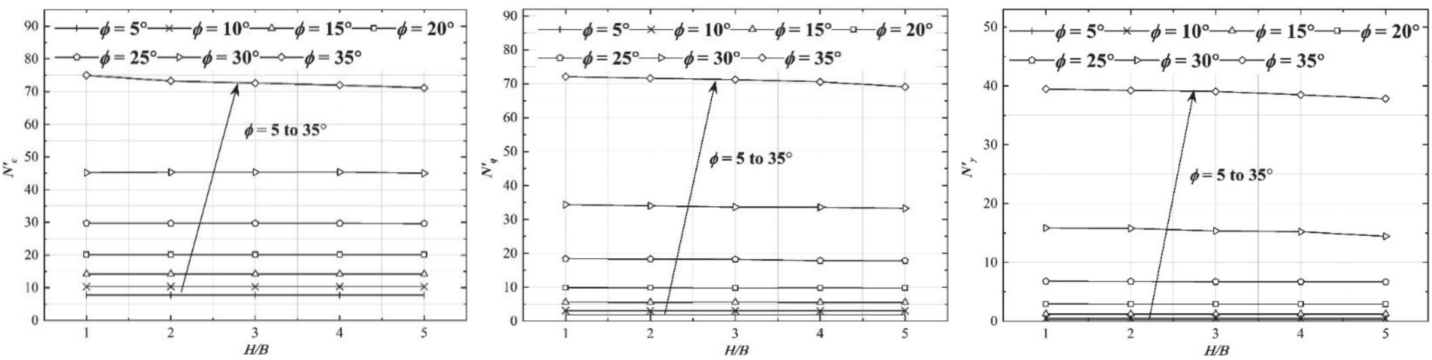
3.3.1 Validation of Ring Footing

The finite element analysis of ring footing is carried out for the case of $H = 5B$, to determine the bearing capacity factors N'_c, N'_q, N'_γ by redefining the Griffiths (1982) approach with a surcharge (q) of 50 kPa applied above the footing base with the material properties shown in Fig. 1(c). The validation of obtained FE results of ring footing (for $\phi = 20°$) is carried out by comparing the bearing capacity factors of ring footing with varying radius ratio with others result available in the literature. The comparison of present study results and results from the published literature are depicted Figs. 8(a)-8(c) for $r_i/r_o = 0.25$, 0.5, and 0.75. It is observed from the figure that the obtained results are comparable with the results of others and are almost similar to the FEM results-reported by Chavda and Dodagoudar (2018). It is also observed from the present study results that the values of N'_c and N'_q are higher for the case of $r_i/r_o = 0.25$ (for $\phi = 20°$) and the general trend shows the increase in bearing capacity factors with decrease in radius ratio. Similar observations were reported by Chavda and Dodagoudar (2021).

3.3.2 Ring Footing on Limited Depth of Soil, $H/B \geq 1$

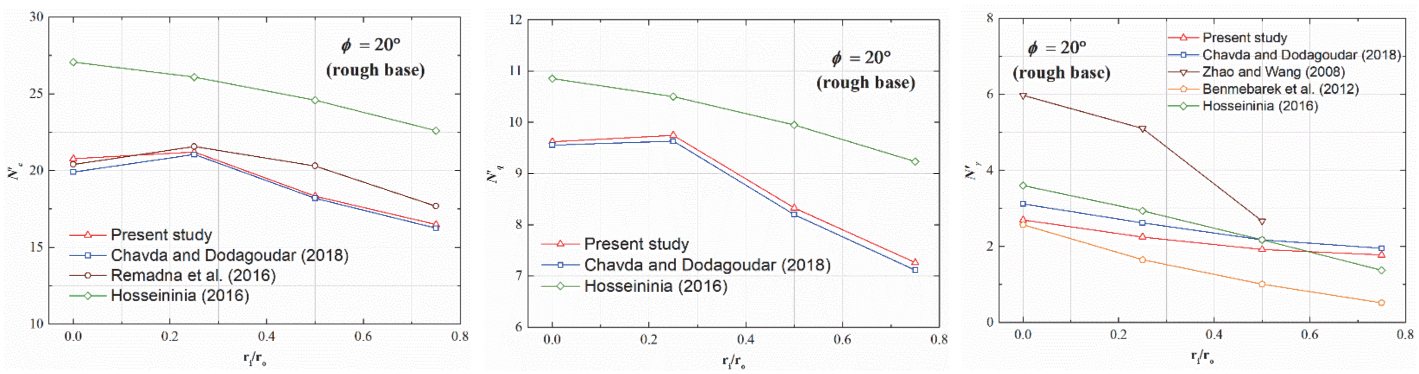
The FE analysis is carried out for ring footing on limited depth of soil by varying the depth of soil from $H = 1B$ to $5B$. The present study results are depicted as charts showing the variation of bearing capacity factors with varying friction angles of soil for each case of $H = 1B$ to $5B$ and the variation of bearing capacity factors with varying H/B for given range of friction angles ($\phi = 5°$-$30°$).

All the figures from Figs. 9 to 11 show the bearing capacity factors N'_c, N'_q, N'_γ of ring footings of radius ratio $r_i/r_o = 0.25$, 0.50, 0.75 increase with increase in friction angle and increase with decrease in H/B ratio. It is also observed that the effect of limited depth is mostly significant for $H = 1B$ and below and for higher friction angles ($\phi > 30°$) which is similar in the case of strip and



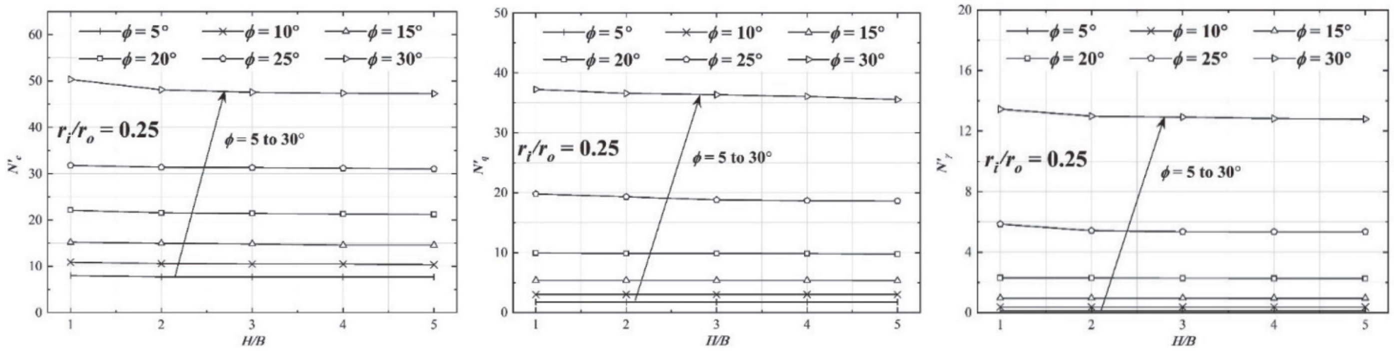
(a) N'_c (b) N'_q (c) N'_γ

Fig. 7 Variation of bearing capacity factors of circular footing with H/B



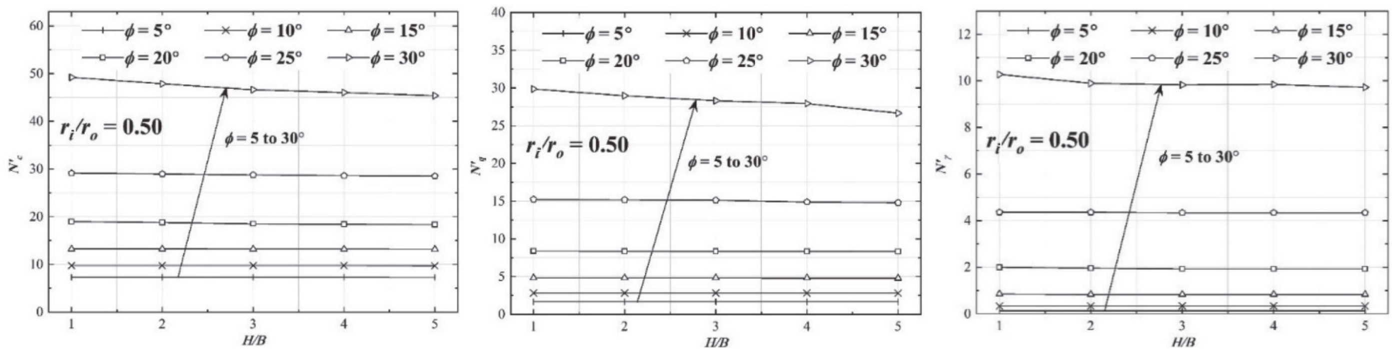
(a) N'_c (b) N'_q (c) N'_γ

Fig. 8 Comparison of bearing capacity factors of ring footing for $\phi = 20°$



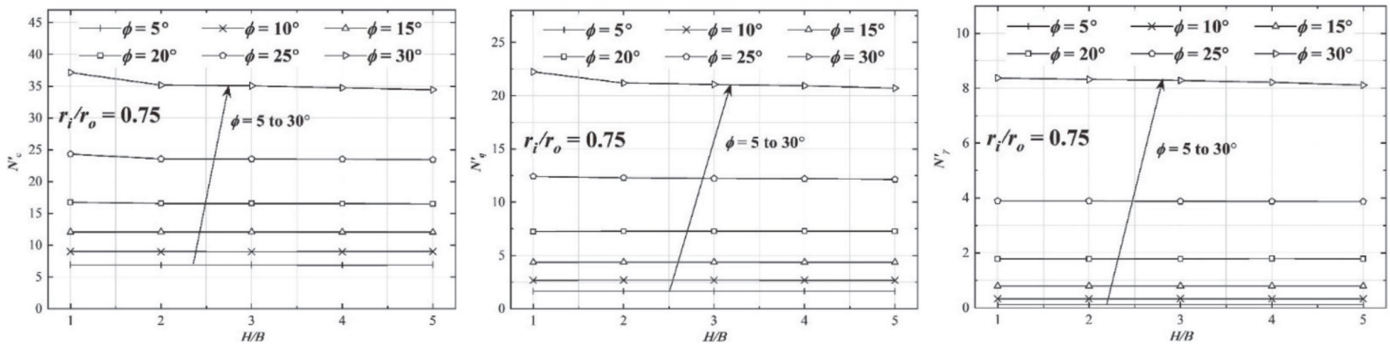
(a) N'_c (b) N'_q (c) N'_γ

Fig. 9 Variation of bearing capacity factors of ring footing (r_i/r_0 = 0.25) with varying H/B



(a) N'_c (b) N'_q (c) N'_γ

Fig. 10 Variation of bearing capacity factors of ring footing (r_i/r_0 = 0.50) with varying H/B



(a) N'_c (b) N'_q (c) N'_γ

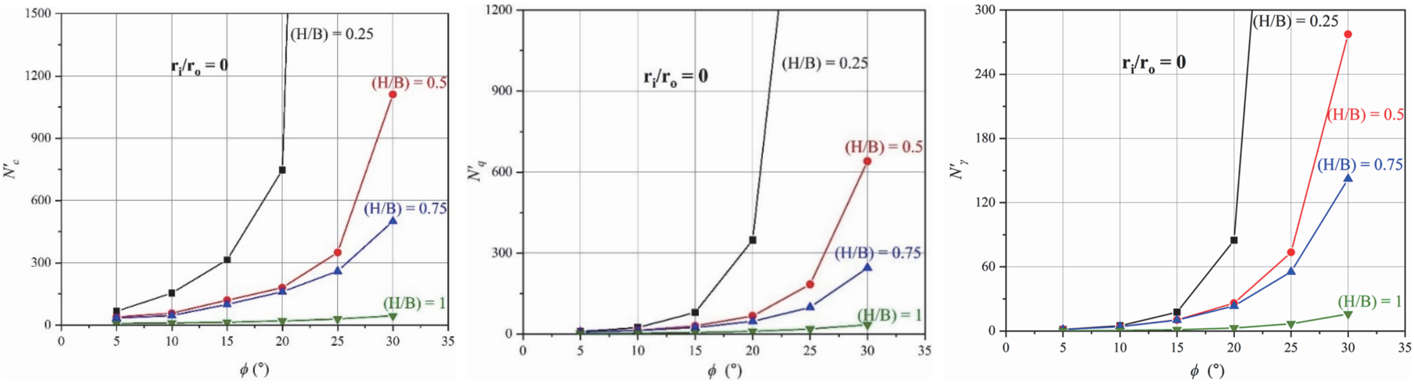
Fig. 11 Variation of bearing capacity factors of ring footing (r_i/r_0 = 0.75) with varying H/B

circular footings. And also, it is observed that the effect of limited depth is more significant for N'_c and N'_q than N'_γ and this effect increases with increase in radius ratio.

It is observed from the literature that the evaluation of bearing capacity factors for strip and circular footings resting on limited depth of cohesionless soil for $H < 3B$ were mostly performed. But in practice, if any rigid rough base is encountered at depths $H \leq 1B$ (like $H = 0.1B$, $0.3B$, $0.5B$, $1B$) then it is recommended to lay the foundation directly on the rigid base by removing the top layer which is of limited depth (H) of soil because in the case of shallow foundations, the minimum depth of excavation for concrete structures should be 0.5 m as per IS 1904-1986 (sec. 7.2) and 0.3 m as per IBC (2012) (sec. 1805.2) and normally laid at a depth of 3 m as per IS 1904-1986 (sec. 3.1). For example, if the width of footing is of 1 m (minimum recommended as per standard codes) and shallow depth of soil is at 1 m, then, in such case, authors recommend to remove 1 m layer of soil and place the footing directly on firm strata. This allows taking maximum advantage to get the maximum bearing capacity for the footing resting directly on firm strata, *i.e.,* rocks.

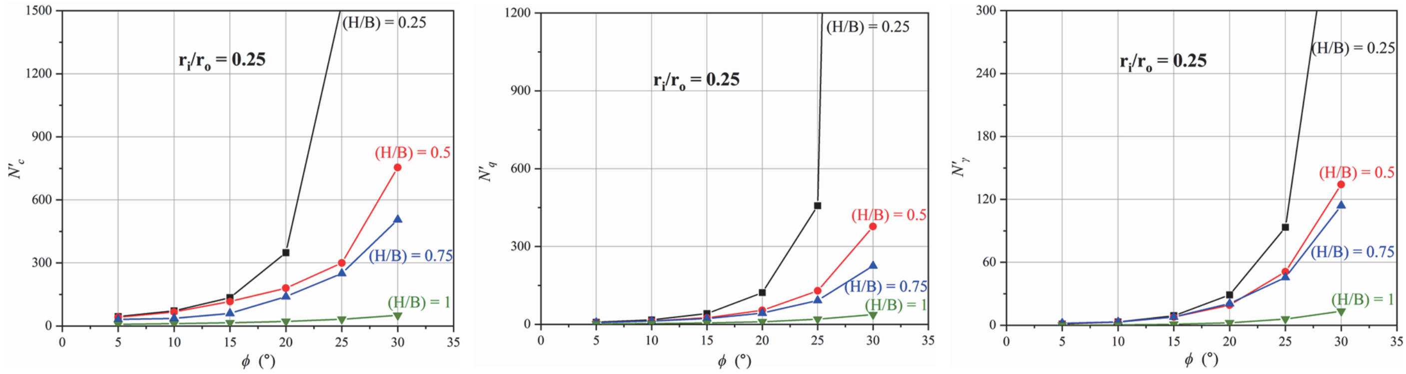
3.3.3 Ring Footing on Limited Depth of Soil, $H/B \leq 1$

The FE analysis is carried out for ring footing on the limited depth of soil by varying the depth of soil from $H = 1B$ to $0.25B$ along with the variation of friction angles of soil (ϕ = 5°-30°) to evaluate the bearing capacity factors. Figures 12-15 show the variation of the bearing capacity factors (N'_c, N'_q, and N'_γ) for ring foot-



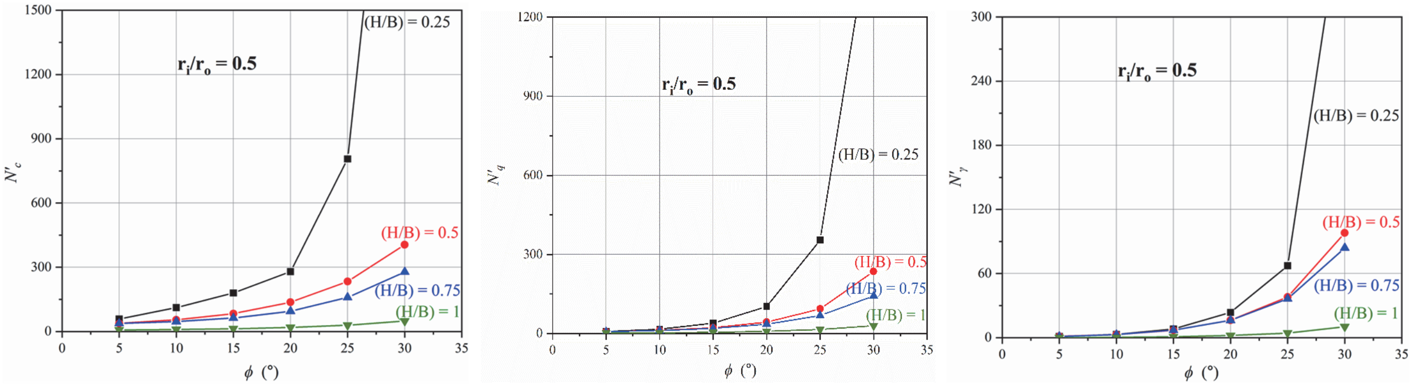
(a) N_c' (b) N_q' (c) N_γ'

Fig. 12 Variation of bearing capacity factors of ring footing for $r_i/r_0 = 0$ (circular footing) and $H/B \le 1$



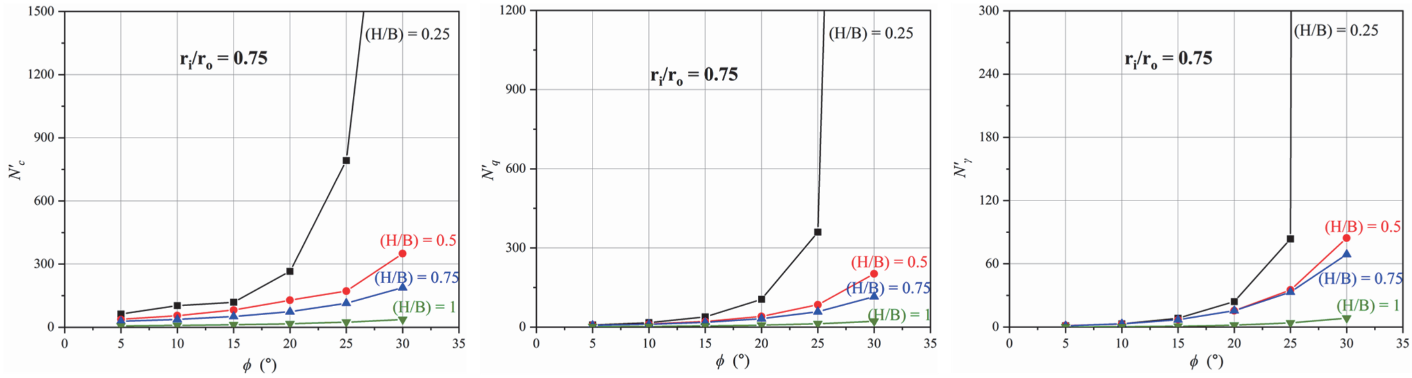
(a) N_c' (b) N_q' (c) N_γ'

Fig. 13 Variation of bearing capacity factors of ring footing for $r_i/r_0 = 0.25$ and $H/B \le 1$



(a) N_c' (b) N_q' (c) N_γ'

Fig. 14 Variation of bearing capacity factors of ring footing for $r_i/r_0 = 0.50$ and $H/B \le 1$



(a) N_c' (b) N_q' (c) N_γ'

Fig. 15 Variation of bearing capacity factors of ring footing for $r_i/r_0 = 0.75$ and $H/B \le 1$

ings having radius ratio $r_i/r_o = 0$, 0.25, 0.50, 0.75 with the variation of friction angles of soil as $\phi = 5°$-$30°$. It is observed from the figures that the values of N_c', N_q', and N_γ' of ring footings increase with an increase in ϕ and with decrease in H/B ratio from 0.25 to 1.0. Also, the effect of limited depth is mostly significant for $H = 0.25B$ and for $\phi \geq 15°$. Note that the effect of limited depth is more significant for N_c' and N_q' as compared with N_γ'.

3.3.4 Failure Planes for Ring Footing on Limited Depth of Soil

Figures 16-18 show the typical failure planes for the case of ring footing representing the failure mechanism corresponding to N_c', N_q', and N_γ' case, for the change in limited depth of soil, and for the change in radius ratio, respectively. Figure 16 depicts the failure planes for the N_c', N_q', and N_γ' cases of ring footing with $r_i/r_0 = 0.25$, limited depth of $H/B = 0.5$, and friction angle of $\phi = 15°$. It can be observed that the effect of limited depth of $H/B = 0.5$ and friction angle of $\phi = 15°$ is deeper and wider, *i.e.,* significant for N_c' and N_q' than N_γ'.

Figure 17 shows the variation of failure planes for the N_c' with varying limited depth, *i.e., H/B* = 0.25, 0.5, and 0.75. It is observed from the figure that the failure mechanism is significantly affected by the limited depth of $H/B = 0.25$, 0.5, and 0.75 and therefore, the bearing capacity factors increase with a decrease in the H/B ratio. Figure 18 shows the variation of failure planes for the N_c' with varying radius ratio, *i.e.,* $r_i/r_o = 0$, 0.25, 0.5, and 0.75. It is observed from the figure that the failure zones transform from axisymmetric failure mechanism to nearly plane strain failure mechanism with variation in the radius ratio of ring footing from 0 to 0.75. It is well known fact that when radius ratio of the ring footing increase the ring footing behaves more like strip footing (Chavda and Dodagoudar 2021)

4. CONCLUSIONS

In the present study, the finite element evaluation of bearing capacity factors for rough base strip, circular and ring ($r_i/r_o = 0.25$, 0.50, and 0.75) footings with respect to cohesion, surcharge and unit weight components of soil and resting on c-ϕ soil with limited depth varying from $H = 1B$ to $5B$ are evaluated. The bearing capacity factors are also evaluated for rough base ring footing resting

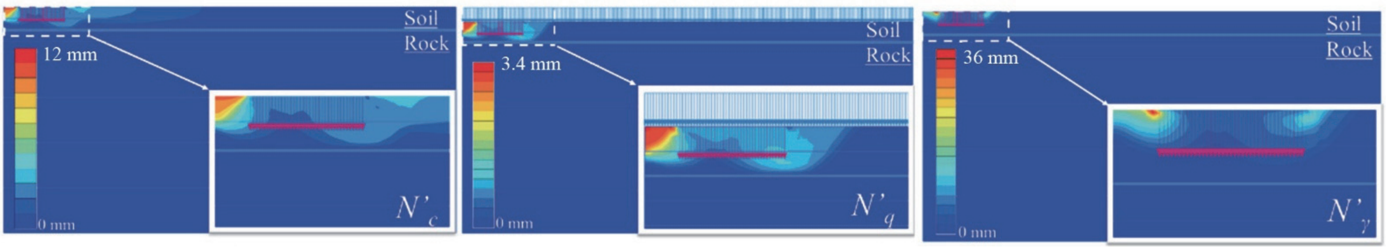


Fig. 16 Failure planes for ring footing with $r_i/r_o = 0.25$, $H/B = 0.5$, and $\phi = 15°$

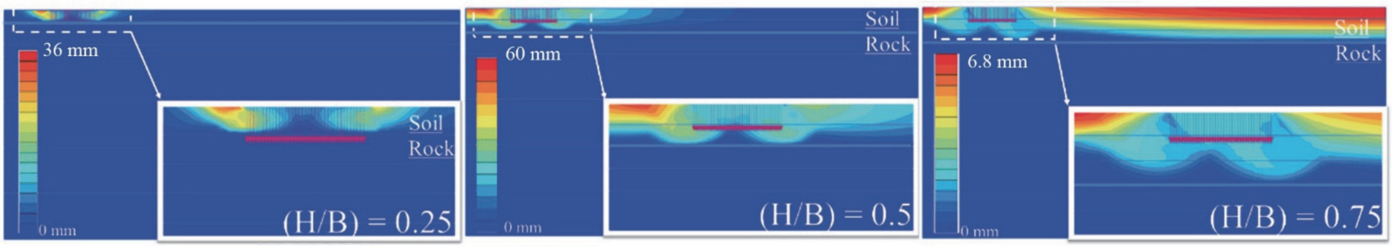


Fig. 17 Effect of H/B on N_c' for $r_i/r_o = 0.5$ and $\phi = 15°$

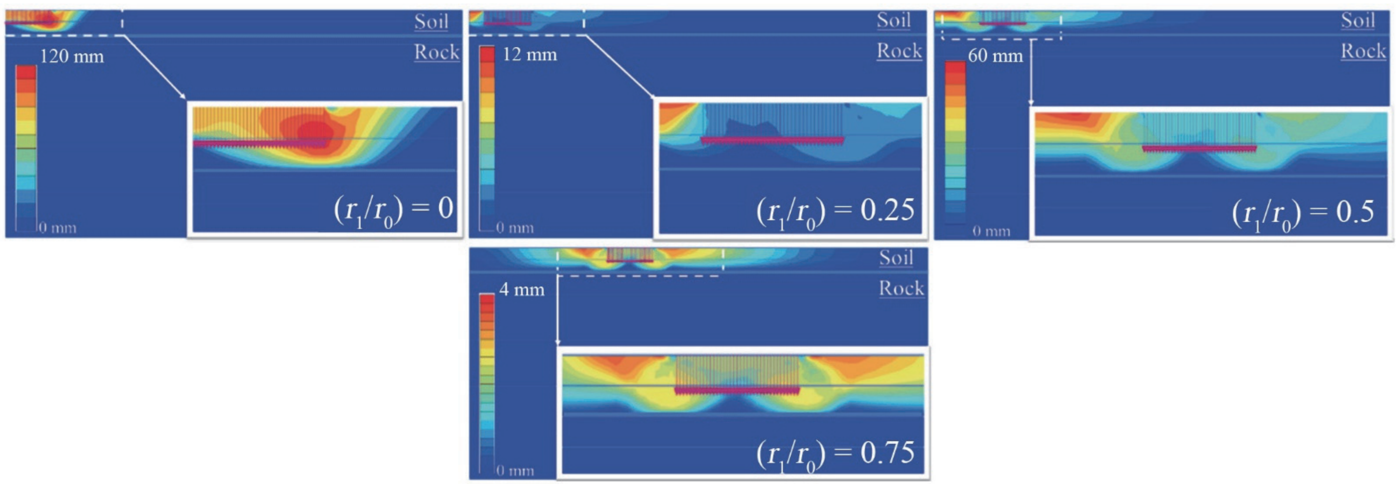


Fig. 18 Effect of r_i/r_o on N_c' for $H/B = 0.5$ and $\phi = 15°$

on c-ϕ soil with limited depth $H \leq 1B$. The bearing capacity factors are evaluated by Griffiths (1982) approach by redefining accordingly for strip, circular and ring footings. The mesh convergence study is carried out and fine mesh is selected in the FE analysis. Mohr-Coulomb material model is used and the effect of dilatancy is considered for higher friction angles ($\phi > 30°$). The method of defining the soil domain in layers is explained with which the errors are avoided due to no control over meshing in PLAXIS program. Based on the comparisons and inferences made in the present study, following conclusions are arrived at:

1. In the study, a new method of defining the material geometry to eliminate the error associated with varying mesh is attempted in conjunction with utilizing the advantage of symmetry to reduce calculation time and error associated with it.
2. The bearing capacity factors of strip footing increases with increase in friction angle of soil and increases with decrease in H/B ratio. The effect of limited depth is observed to be more significant for N_q than N_c and N_γ and are found to be more significant for higher friction angles ($\phi > 30°$).
3. The bearing capacity factors of circular footing increases with increase in friction angle of soil and increases with decrease in H/B ratio and the effect of limited depth is observed to be more significant for N_c' than N_q' and N_γ' and also for higher friction angles ($\phi > 30°$) which is similar in the case of strip footing. Also, the effect of limited depth is observed to be more predominant for strip footing than circular footing of same size/width.
4. The bearing capacity factors of ring footings increase with increase in friction angle of soil, increase with decrease in H/B ratio and increase with decrease in radius ratio and the effect of limited depth is observed to be mostly significant for $H = 1B$ and below and also for higher friction angles ($\phi > 30°$) which is similar in the case of strip and circular footings. Also, it is observed that the effect of limited depth is more significant for N_c' and N_q' than N_γ' and this effect is observed to be increasing with increase in radius ratio.
5. Therefore, it is clear that for the foundations on limited depth of soil, the bearing capacity factors are function of friction angle of soil and H/B ratio. From the study, the effect of limited depth is observed to be significant for $H \leq 1B$ and $\phi >$ 30°.
6. The typical failure planes for the case of ring footing are evaluated representing the failure mechanism corresponding to N_c', N_q', and N_γ' case, for the change in limited depth of soil, and for the change in radius ratio. It is inferred that the failure mechanism is significantly affected by the limited depth of H/B = 0.25, 0.5, 0.75 and therefore, the bearing capacity factors increase with a reduction in the H/B ratio. The failure zones transform from axisymmetric failure mechanism to nearly plane strain failure mechanism with variation in the radius ratio of ring footing from 0 to 0.75.
7. The effect of limited depth of soil on bearing capacity of footing is found effective for depth $H \leq 1B$. However, for such cases, if possible, it is recommended to lay the foundation directly on the rigid base (*i.e.,* rock layer) itself by removing the top layer which is of limited depth (H). As per the standard practice the footing with minimum width of 1 m is generally laid at 0.5 to 3 m in depth. Therefore, to get the maximum bearing capacity of footing, it is recommended to remove the limited depth of soil and place the footing directly on the firm strata. Whereas, in the situations like offshore foundations resting on soft soil where it is not possible to remove the top strata, it is opined that the effect of limited depth of soil shall be accounted in the design.

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DATA AVAILABILITY

The data and materials in this paper are available on request made directly to the corresponding author.

CONFLICT OF INTEREST STATEMENT

The authors declare that there is no conflict of interest.

REFERENCES

Alam, M., Chaallal, O., and Galy, B. (2021). "Flexible temporary shield in soft and sensitive clay: 3D FE modelling of experimental field test." *Modelling and Simulation in Engineering*, 1-15. https://doi.org/10.1155/2021/6626750

Benmebarek, S., Remadna, M.S., Benmebarek, N., and Belounar, L. (2012). "Numerical evaluation of the bearing capacity factor N'_γ of ring footings." *Computers and Geotechnics*, **44**, 132-138. https://doi.org/10.1016/j.compgeo.2012.04.004

Benmebarek, S., Saifi, I., and Benmebarek, N. (2017). "Undrained vertical bearing capacity factors for ring shallow footings." *Geotechnical and Geological Engineering*, **35**(1), 355-364. https://doi.org/10.1007/s10706-016-0110-y

Biarez, J., Burel, M., and Wack, B. (1961). "Contribution à l'étude de la force portent des foundation." *Proceedings of the 5th International Conference on Soil Mechanics and Foundation Engineering*, Paris, **1**, 603-609.

Bolton MD (1986). "The strength and dilatancy of sands." *Geotechnique*, **36**(1), 65-78. https://doi.org/10.1680/geot.1986.36.1.65

Bolton, M.D. and Lau, C.K. (1993). "Vertical bearing capacity factors for circular and strip footings on Mohr–Coulomb soil." *Canadian Geotechnical Journal*, **30**(6), 1024-1033. https://doi.org/10.1139/t93-099

Boushehrian, J.H. and Hataf, N. (2003). "Experimental and numerical investigation of the bearing capacity of model circular and ring footings on reinforced sand." *Geotextiles and Geomembranes*, **21**(4), 241-256. https://doi.org/10.1016/S0266-1144(03)00029-3

Cerato, A.B. and Lutenegger, A.J. (2006). "Bearing capacity of square and circular footings on a finite layer of granular soil underlain by a rigid base." *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, **132**(11), 1496-1501. https://doi.org/10.1061/(ASCE)1090-0241(2006)132:11(1496)

Chakraborty, D. (2016). "Bearing capacity of strip footings by incorporating a non-associated flow rule in lower bound limit analysis." *International Journal of Geotechnical Engineering*, **10**(3), 311-315. https://doi.org/10.1080/19386362.2016.1142272

Chakraborty, D. and Kumar, J. (2013). "Bearing capacity of foundations on slopes." *Geomechanics and Geoengineering*, **8**(4), 274-285. https://doi.org/10.1080/17486025.2013.770172

Chandrashekhara, K., Antony, S.J., and Mondal, D. (1998). "Semi-analytical finite element analysis of a strip footing on an elastic reinforced soil." *Applied Mathematical Modelling*, **22**(4-5), 331-349. https://doi.org/10.1016/S0307-904X(98)00011-0

Chavda, J.T. and Dodagoudar, G.R. (2018). "Finite element evaluation of ultimate capacity of strip footing: assessment using various constitutive models and sensitivity analysis. *Innovative Infrastructure Solutions*, **3**(1), 1-10. https://doi.org/10.1007/s41062-017-0121-4

Chavda, J.T. and Dodagoudar, G.R. (2019). "Finite element evaluation of vertical bearing capacity factors N_c', N_q', N_γ' for ring footings." *Geotechnical and Geological Engineering*, **37**(2), 741-754. https://doi.org/10.1007/s10706-018-0645-1

Chavda, J.T. and Dodagoudar, G.R. (2021). "On vertical bearing capacity of ring footings: finite element analysis, observations and recommendations." *International Journal of Geotechnical Engineering*, Vol (Issue), 1-13. https://doi.org/10.1080/19386362.2019.1648737

Choobbasti, A.J., Hesami, S.A.S.F., Najafi, A., Pirzadeh, S., Farrokhzad, F., and Zahmatkesh, A. (2010). "Numerical evaluation of bearing capacity and settlement of ring footing; case study of Kazeroon cooling towers." *International Journal of Research and Reviews in Applied Sciences*, **4**(2), 263-271.

Chouhan, K., Lai, V.Q., Chavda, J.T., Yoonirundorn, K., and Keawsawasvong, S. (2023a). "Evaluation of bearing capacity of ring footing with varying base roughness using finite element limit analysis." *Transportation Infrastructure Geotechnology*, 1-25. https://doi.org/10.1007/s40515-023-00286-2

Chouhan, K., Lai, V.Q., Chavda, J.T., Yoonirundorn, K., and Keawsawasvong, S. (2023b). "Evaluation of vertical bearing capacity factors for conical footing with varying base roughness using FELA and MARS model." *Ships and Offshore Structures*, 1-13. https://doi.org/10.1080/17445302.2023.2177030

Clark, J.I. (1998). "The settlement and bearing capacity of very large foundations on strong soils: 1996 RM Hardy keynote address." *Canadian Geotechnical Journal*, **35**(1), 131-145. https://doi.org/10.1139/t97-070

Drucker, D.C., Greenberg, H.J., and Prager, W. (1951). "The safety factor of an elastic-plastic body in plane strain." *Journal of Applied Mechanics*, **18**(4), 371-378. https://doi.org/10.1115/1.4010353

Erickson, H.L. and Drescher, A. (2002). "Bearing capacity of circular footings." *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, **128**(1), 38-43. https://doi.org/10.1061/(ASCE)1090-0241(2002)128:1(38)

Gholami, H. and Hosseininia, E.S. (2017). "Bearing capacity factors of ring footings by using the method of characteristics." *Geotechnical and Geological Engineering*, **35**(5), 2137-2146. https://doi.org/10.1007/s10706-017-0233-9

Griffiths, D.V. (1982). "Computation of bearing capacity factors using finite elements." *Geotechnique*, **32**(3), 195-202. https://doi.org/10.1680/geot.1982.32.3.195

Griffiths, D.V. (1989). "Computation of collapse loads in geomechanics by finite elements." *Ingenieur-Archiv*, **59**(3), 237-244. https://doi.org/10.1007/BF00532253

Hansen, B. (1961). "A general formula for bearing capacity." *Danish Geotechnical Institute, Bulletin*, **11**, 38-46.

Hansen, B. (1969). "Bearing capacity of shallow strip footings in clay." *Proceedings of the 7th International Conference on Soil Mechanics and Foundation Engineering*, Mexico City, 107-113.

Hataf, N. and Razavi, M.R. (2003). "Behavior of ring footing on sand." *Iranian Journal of Science and Technology*, *Transaction B: Engineering*, **27**, 47-56.

Hjiaj, M., Lyamin, A.V., and Sloan, S.W. (2005). "Numerical limit analysis solutions for the bearing capacity factor N_γ." *International Journal of Solids and Structures*, **42**(5-6), 1681-1704. https://doi.org/10.1016/j.ijsolstr.2004.08.002

Hosseininia, E.S. (2016). "Bearing capacity factors of ring footings." *Iranian Journal of Science and Technology, Transactions of Civil Engineering*, **40**(2), 121-132. https://doi.org/10.1007/s40996-016-0003-6

IBC, I. (2012). *International Building Code*. International Code Council, Washington DC, United States.

Ismael, N. F. (1996). "Loading tests on circular and ring plates in very dense cemented sands. *Journal of Geotechnical Engineering*, ASCE, **122**(4), 281-287. https://doi.org/10.1061/(ASCE)0733-9410(1996)122:4(281)

IS 1904-1986 (1987). *Indian Standard Code of Practice for Design and Construction of Shallow Foundations in Soils (Other than Raft, Ring and Shell)*. Bureau of Indian Standards, Ministry of Consumer Affairs, Food & Public Distribution, Government of India.

Kumar, J. and Chakraborty, M. (2015). "Bearing capacity factors for ring foundations." *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, **141**(10), 06015007. https://doi.org/10.1061/(ASCE)GT.1943-5606.0001345

Kumar, J. and Ghosh, P. (2005). "Bearing capacity factor N_γ for ring footings using the method of characteristics." *Canadian Geotechnical Journal*, **42**(5), 1474-1484. https://doi.org/10.1139/t05-051

Kumar, J. and Khatri, V.N. (2008). "Effect of footing roughness on lower bound N_γ values." *International Journal of Geomechanics*, ASCE, **8**(3), 176-187. https://doi.org/10.1061/(ASCE)1532-3641(2008)8:3(176)

Kumar, J. and Khatri, V.N. (2011). "Bearing capacity factors of circular foundations for a general c-ϕ soil using lower bound finite elements limit analysis." *International Journal for Numerical and Analytical Methods in Geomechanics*, **35**(3), 393-405. https://doi.org/10.1002/nag.900

Laman, M. and Yildiz, A. (2003). "Model studies of ring foundations on geogrid-reinforced sand." *Geosynthetics International*, **10**(5), 142-152. https://doi.org/10.1680/gein.2003.10.5.142

Lundgren, H. (1953). "Determination by the theory of plasticity of the bearing capacity of continuous footings on sand." *Proceedings of the 3rd ICSMFE,* **1**, 409-412.

Maheshwari, P. and Madhav, M.R. (2006). "Analysis of a rigid footing lying on three-layered soil using the finite difference method." *Geotechnical & Geological Engineering*, **24**(4), 851-869. https://doi.org/10.1007/s10706-005-7109-0

Mandel, J. and Salencon, J. (1972). "Force portante d'un sol sur une assise rigide (etude theorizue)." *Geotechnique*, **22**(1), 79-93. https://doi.org/10.1680/geot.1972.22.1.79

Martin, C.M. (2005). "Exact bearing capacity calculations using the method of characteristics." *Proceedings of the 11th International Conference on Analytical and Computational Methods in Geomechanics*, Turin, **4**, 441-450.

Meyerhof, G.G. (1963). "Some recent research on the bearing capacity of foundations." *Canadian Geotechnical Journal*, **1**(1), 16-26. https://doi.org/10.1139/t63-003

Meyerhof, G.G. (1974). "Ultimate bearing capacity of footings on sand layer overlying clay." *Canadian Geotechnical Journal*, **11**(2), 223-229. https://doi.org/10.1139/t74-018

Michalowski, R. (1997). "An estimate of the influence of soil weight on bearing capacity using limit analysis. *Soils and Foundations*, **37**(4), 57-64. https://doi.org/10.3208/sandf.37.4_57

Ohri, M.L., Purhit, D.G.M., and Dubey, M.L. (1997). "Behavior of ring footings on dune sand overlaying dense sand." *Proceedings of the International Conference of Civil Engineers,* Tehran, Iran, 4-6.

Remadna, M.S., Benmebarek, S., and Benmebarek, N. (2017). "Numerical evaluation of the bearing capacity factor N'_c of circular and ring footings." *Geomechanics and Geoengineering*, **12**(1), 1-13. https://doi.org/10.1080/17486025.2016.1153729

Saha, M.C. (1978). *Ultimate Bearing Capacity of Ring Footings on Sand*. Master Thesis of Engineering, University of Roorkee, Roorkee, India.

Saran, S., Bhandari, N.M., and Al-Smadi, M.M.A. (2003). "Analysis of eccentrically-obliquely loaded ring footings on sand." *Indian Geotechnical Journal*, **33**(4), 422-446.

Sargazi, O. and Hosseininia, E.S. (2017). "Bearing capacity of ring footings on cohesionless soil under eccentric load." *Computers and Geotechnics*, **92**, 169-178. https://doi.org/10.1016/j.compgeo.2017.08.003

El Sawwaf, M. and Nazir, A. (2012). "Behavior of eccentrically loaded small-scale ring footings resting on reinforced layered soil." *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, **138**(3), 376-384. https://doi.org/10.1061/(ASCE)GT.1943-5606.0000593

Sloan, S.W. (1988). "Lower bound limit analysis using finite elements and linear programming." *International Journal for Numerical and Analytical Methods in Geomechanics*, **12**(1), 61-77. https://doi.org/10.1002/nag.1610120105

Soubra, A.H. (1999). "Upper-bound solutions for bearing capacity of foundations." *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, **125**(1), 59-68. https://doi.org/10.1061/(ASCE)1090-0241(1999)125:1(59)

Tang, C. and Phoon, K.K. (2018). "Prediction of bearing capacity of ring foundation on dense sand with regard to stress level effect." *International Journal of Geomechanics*, ASCE, **18**(11), 04018154. https://doi.org/10.1061/(ASCE)GM.1943-5622.0001312

Terzaghi, K. (1943), *Theoretical Soil Mechanics*, John Wiley & Sons, New York.

Ukritchon, B., Whittle, A.J., and Klangvijit, C. (2003). "Calculations of bearing capacity factor N_γ using numerical limit analyses." *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, **129**(5), 468-474. https://doi.org/10.1061/(ASCE)1090-0241(2003)129:6(468)

Vesić, A.S. (1973). "Analysis of ultimate loads of shallow foundations." *Journal of the Soil Mechanics and Foundations Division*, **99**(1), 45-73. https://doi.org/10.1061/JSFEAQ.0001846

Yang, F., Zheng, X.C., Zhao, L.H., and Tan, Y.G. (2016). "Ultimate bearing capacity of a strip footing placed on sand with a rigid basement." *Computers and Geotechnics*, **77**, 115-119. https://doi.org/10.1016/j.compgeo.2016.04.009

Yin, J.H., Wang, Y.J., and Selvadurai, A.P.S. (2001). "Influence of nonassociativity on the bearing capacity of a strip footing." *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, **127**(11), 985-989. https://doi.org/10.1061/(ASCE)1090-0241(2001)127:11(985)

Zhao, L. and Wang, J.H. (2008). "Vertical bearing capacity for ring footings." *Computers and Geotechnics*, **35**(2), 292-304. https://doi.org/10.1016/j.compgeo.2007.05.005

Zhu, F. (1998). *Centrifuge Modelling and Numerical Analysis of Bearing Capacity of Ring Foundations on Sand*. Doctoral Dissertation, Memorial University of Newfoundland, Canada.

Zienkiewicz, O.C., Humpheson, C., and Lewis, R.W. (1975). "Associated and non-associated visco-plasticity and plasticity in soil mechanics." *Geotechnique*, **25**(4), 671-689. https://doi.org/10.1680/geot.1975.25.4.671