Bearing Capacity Estimation of Shallow Foundations on Layered Sand Strata Using Finite Elements Analysis

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Abstract. This paper presents bearing capacity estimation of rough strip and circular footings embedded in dense sand overlain by loose sand strata. Numerical study is carried out using finite element analysis (FE) wherein the soil was assumed to obey Mohr-Coulomb's yield criterion with either associated ($\psi=\phi$) or non- associated flow rule ($\psi<\phi$). The bearing capacity was computed for different values of soil friction angle of the top and bottom layer (ϕ_1 and ϕ_2 respectively), depth of the footing (D_f) from the surface and the thickness of top dense layer (H). The comparison were made with those of the available literatures wherever applicable.

Keywords: Finite element, Bearing capacity , Mohr-Coulomb, Conic programming.

1 Introduction

The concept of bearing capacity was first proposed by Terzaghi (1943), thereafter series of researchers contributed their findings towards estimating the bearing capacity of footings on stratified natural soil media or by placing dense sand over loose sand/ clay to increase the bearing capacity of the foundations. Many researchers focused on bearing capacity determination of footing on dense sand over clay (Meyerhof 1974; Hanna and Meyerhof 1980; Griffiths1982; Das and Dallo 1984; Michalowski and Shi 1995; Kenny and Andrews 1979; Burd and Frydman (1997); Okamura et al. (1998); Shiau et al. (2003); Qin and Huang (2008); Salimi et al. (2018). Relatively the studies with regard to the shallow foundations on layered sand strata has received less attention (Meyerhof 1978; Meyerhof and Hanna 1978; Hanna 1981, 1982; Das and Munoz 1984; Hanna 1987; Farah 2004; Kumar et al 2007; Khatri et al. 2017; Salimi et al. 2019). Among these listed studies, Meyerhof and Hanna (1978) used limit equilibrium method to determine the ultimate bearing capacity of strip and circular footings on layered sand subjected to vertical and inclined load. Hanna (1981, 1982) developed design charts to determine bearing capacity of strip and circular footings on layered sand. The results were compared with model tests on strip and circular footings. Das and Munoz (1984) estimated the bearing capacity of eccentrically loaded continuous foundations on layered sand experimentally.

Hanna (1978) carried out Finite element analysis and compared the results with theoretical and experimental values of Hanna (1981,1982).
Farah (2004) derived bearing capacity expressions for strip footing resting on layered sand media. Kumar et al. (2007) estimated the bearing capacity of dense sand overlying loose sand, with and without inclusion of geogrid. Khatri et al. (2017) estimated the bearing capacity of strip and circular footings with inclusion of dense sand layer over loose sand strata using lower and upper bound finite element limit analysis.

From the literature studies it can be concluded that less attention is given towards numerical approach for estimating the bearing capacity. Mostly the studies focused on laboratory tests and traditional approaches with certain assumptions and it was also noticed that the studies were limited to surface footing. Further, a limited studies were carried out for sand with non-associated flow rule ($\psi<\phi$) (Bolton 1986). Keeping this in mind, the present study tries to fill the gap. The present study deals with estimating the bearing capacity of strip and circular footing embedded in dense sand overlain by loose sand strata. The analysis was carried out using finite element analysis. The analysis was carried out for various thickness of top dense layer and friction angle of both top and bottom layer, the results are expressed in dimensionless manner for general applicability. The comparisons were made with the available literatures wherever applicable.

1.1 Problem Definition

A rigid rough strip and circular footing was embedded in the layered sand strata as shown in Figure 1. H, B, l and d are the thickness of the top dense layer, width/diameter of the footing, length and depth of the selected domain. ϕ_1 ,ϕ_2 and γ_1, γ_2 are the friction angle and unit weight of top and bottom layer respectively. The soil was assumed to be elastic- perfectly plastic, obeying either associated($\psi=\phi$) or non-associated ($\psi<\phi$) flow rule and Mohr- coulomb's yield criteria was considered. The material parameters considered in the parametric analysis were selected by following Salimi et al.(2019) and the same are reported in Table 1. The friction angle (ϕ) of the soil was varied from 30- 44°. The unit weight corresponding to the friction angle was considered to be 15.6-18.96 kN/m^3. The modulus of elasticity (E) was taken in the range of 20 to 62 MPa for variation of ϕ between 30°- 44°. It is intended to determine the ultimate load Q_u for footing with (i) different values of unit weight γ_1 and γ_2, friction angles, ϕ_1 and ϕ_2, of the upper and lower layers, respectively, (ii) different values of the H, and (iii) depth of the footing (D_f). It should be noted that for the case of embedded footing, instead of placing the footing at various depth(D_f), an equivalent surcharge was applied at surface for the analysis.

Table 1. Problem Parameters considered in parametric analysis.

Friction angle(ϕ)	Unit weight(γ) kN/m^3	E(MPa)	Poisson's ratio(ν)
30	15.60	20	0.20
32	16.00	26	0.22
35	16.80	35	0.25
40	18.00	50	0.30
44	18.96	62	0.34

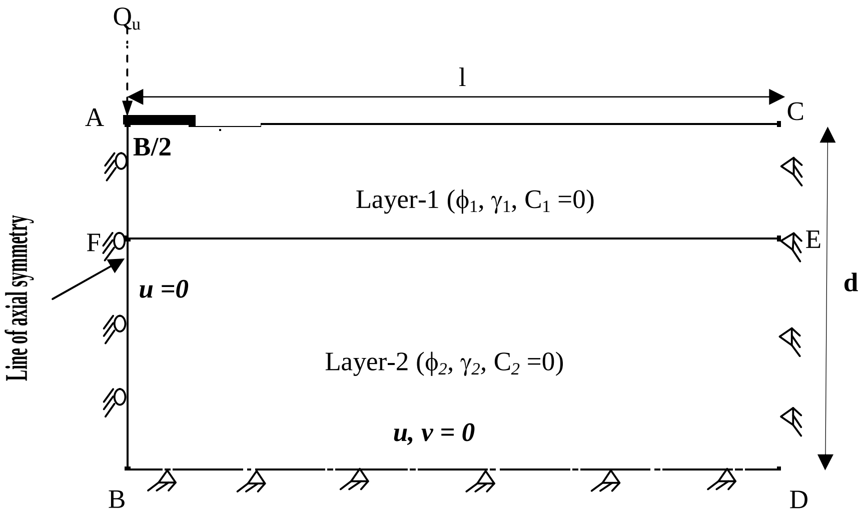
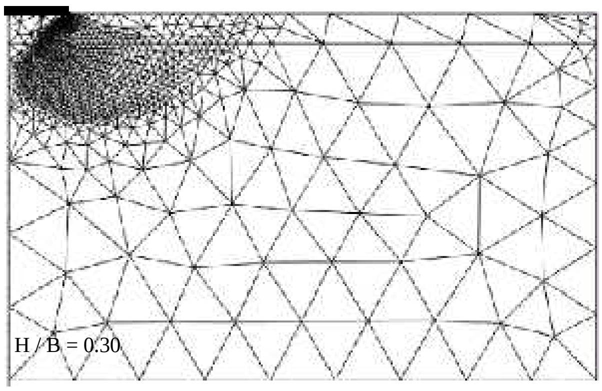


Fig. 1. Selected problem domain and associated boundary conditions

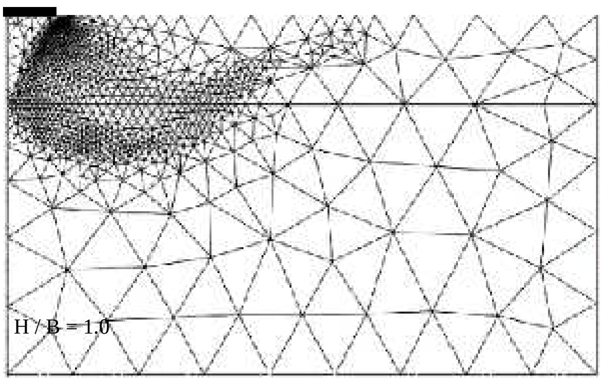
Problem Domain and Finite Element Model

In the present research work, the numerical study was performed by using a finite element module of OptumG2 software. The selected domain and the associated boundary conditions for the present problem is shown in Figure 1. For the sake of analysis, the width of footing (B) was taken as 3 m. Accordingly, the l and d value of 10B and 6B respectively were sufficient enough to contain the failure pattern within selected domain. On account of the axial symmetry, one half of the total domain in x-y and r-z plane for strip and circular footing respectively was considered and hence the horizontal displacement (u) along the line 'AB' was kept zero. Further the horizontal displacement (u) was made zero at the far-off boundary ‘CD’. Whereas horizontal and vertical displacement both were substituted as zero for bottom boundary BD.

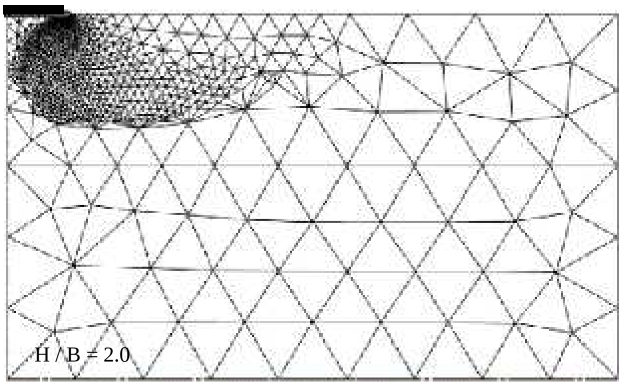
The soil and the footings are modelled using 6- node gauss element. Based on the convergence study (not reported here), the domain was subdivided into 10000 elements. Further during the analysis, the meshes were continuously updated on the basis of proxity of the state of stress within an element towards failure. Hence the region with finer elements in the mesh indirectly reflects a failure pattern. On this basis, the generated meshes for H /B = 0.3, 1.0 and 2.0 , ϕ_1 = 40° and ϕ_2 = 30°, are shown in Figure 2. From this figure once can notice that initially for smaller thickness of top dense layer (H/B), the failure pattern is extended in to both the layers, however with increase in H/B the failure pattern became confined to top layer only.



(a)



(b)



(c)

Fig. 2. Mesh details for footing on sand with ϕ_1 =40°, ϕ_2= 30° with (a) H/B =0.3, (b) H/B = 1.0 and (c) H/B =2.0.

2. Results and Discussions

The finite element analysis was performed for strip and circular footings for different normalized embedment depth (D_f/ B = 0, 0.5 and 1) and H/B ratio. The friction angle of the top dense layer was varied from 40 to 44° and the bottom loose layer was varied from 30 to 35°.The H/B was varied till the bearing capacity becomes constant. From the generated pressure settlement curve the bearing capacity in each case was determined. Further the bearing capacity for footing on layered sand case was expressed in non- dimensional manner, i.e. in terms of bearing capacity ratio (BCR), which is defined as the ratio of bearing capacity of the footing on layered sand media to the bearing capacity of footing on homogeneous sand layer (bottom layer). The variation of pressure settlement curve for few selected cases and that of BCR is described in subsequent paragraphs.

Variation of pressure-settlement curve with H/B

The variation of pressure with normalized settlement for footing embedded in layered sand with ϕ_1= 40° and ϕ_2 = 30° for $\psi=\phi$, $\psi<\phi$ are shown for strip and circular footing in Figure 3(a) - (c) and Figure 4 (a) - (c) respectively. From these figures it can be observed that the addition of top dense layer on the loose sand improves it's pressure-settlement behavior significantly as for given settlement higher pressure was observed for footing on layered sand cases in comparison to footing on homogenous loose sand layer. Further for given pressure the settlement in case of footing on layered sand was substantially smaller than footing on homogeneous sand layer. It implies that the densification of top layer not only improves the ultimate bearing capacity of footing but also reduces the settlement for given pressure. As anticipated the pressure-settlement

curve for non-associated ($\psi<\phi$) case plots lower than corresponding associated ($\psi = \phi$) case. These observations were consistent for various D_f/B ratios. A closure look at Figures 3 and 4 suggests that the increase in depth embedment (D_f) leads to increase in bearing pressure and settlement both.
In all the cases the computed bearing pressure was higher for circular footing than the corresponding strip footing.

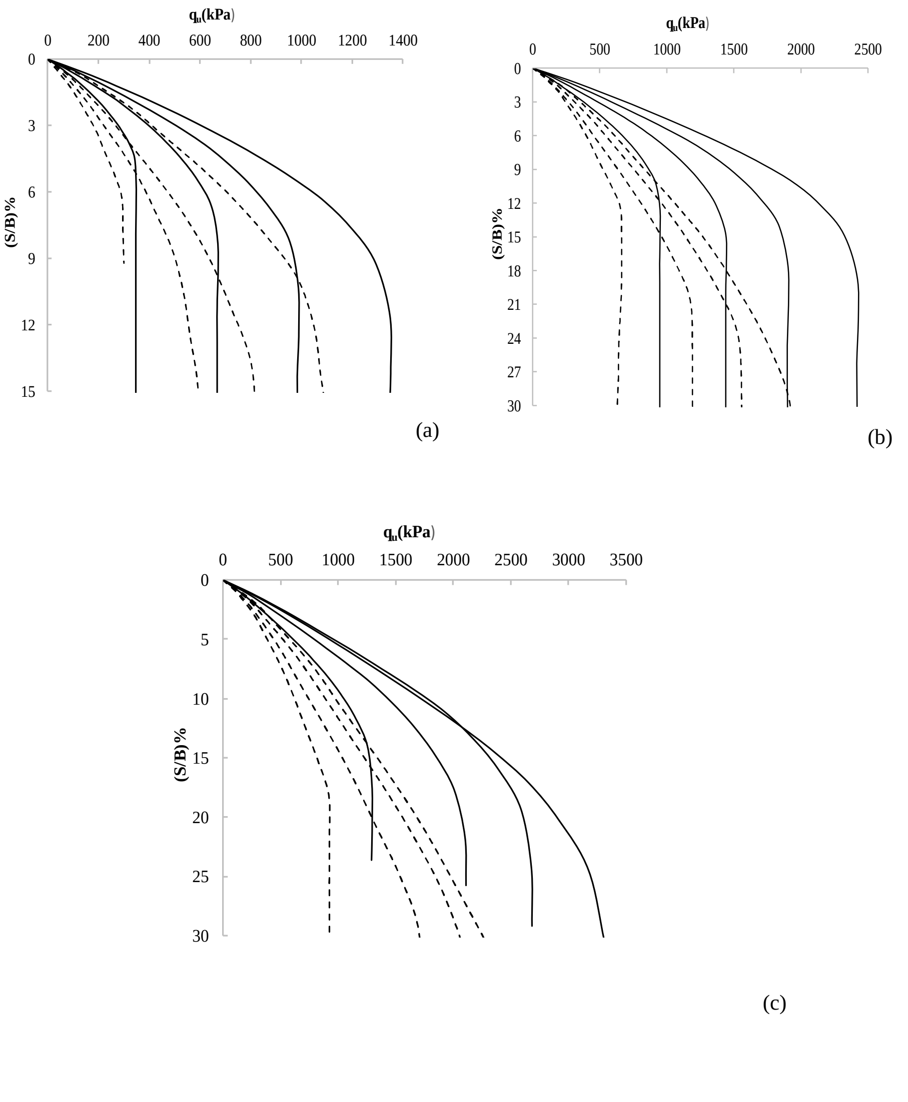


Fig. 3. The pressure-settlement plots for four different values of H/B considering strip footing with D_f/B equal to (a) 0; (b) 0.5; and (c) 1.

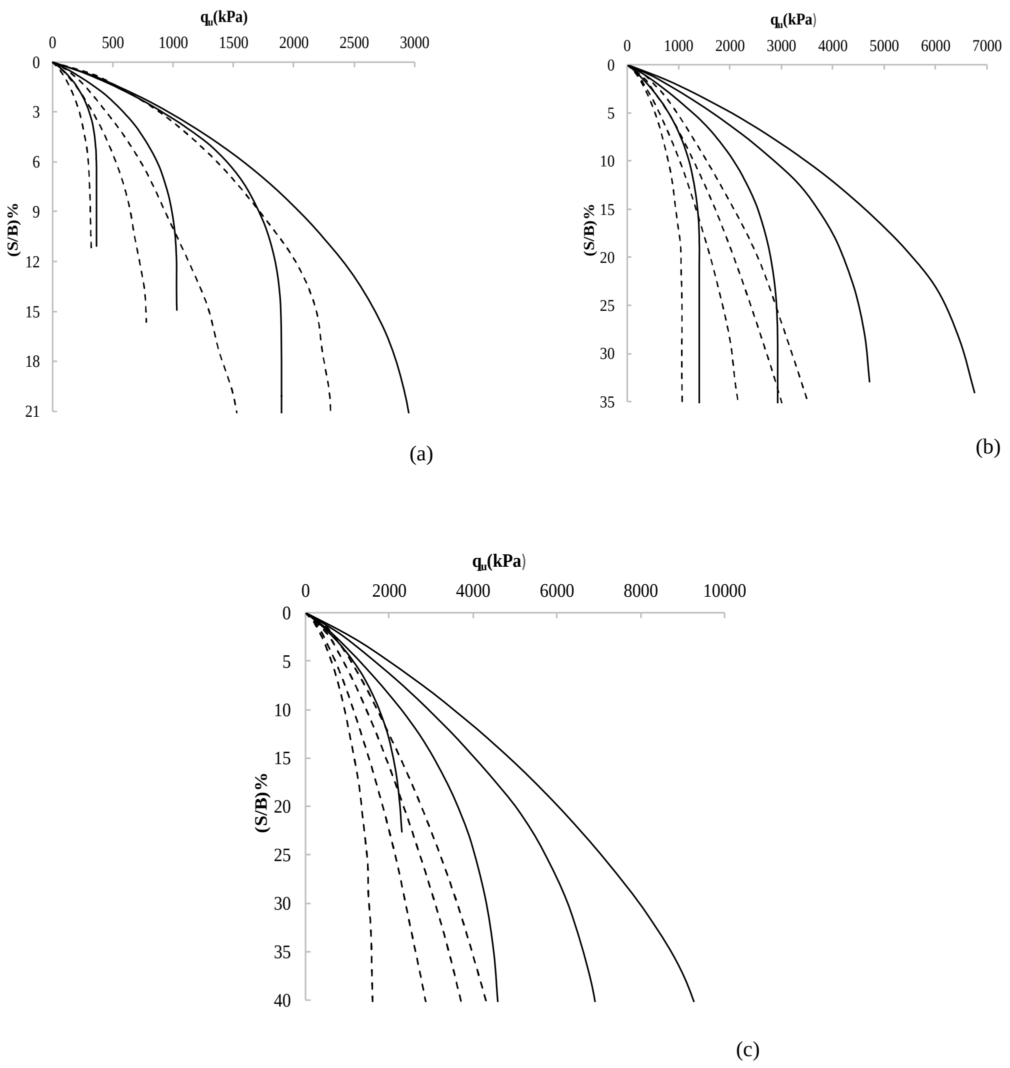


Fig. 4. The pressure-settlement plots for four different values of H/B considering circular footing with D_f/B equal to (a) 0; (b) 0.5; and (c) 1.

Table 2. Normalized bearing capacity for bottom homogeneous soil profile

Df/B	Friction angle(ϕ)	Strip		Circular	
		$\psi=\phi$ $q_u/(\gamma_2 B)$	$\psi<\phi$ $q_u/(\gamma_2 B)$	$\psi=\phi$ $q_u/(\gamma_2 B)$	$\psi<\phi$ $q_u/(\gamma_2 B)$
0		6.45	5.67	6.76	6.04
0.5	30	17.50	12.43	28.80	12.40
1.0		27.80	23.23	39.65	18.30
0		16.21	13.30	15.37	13.67
0.5	35	38.41	22.81	36.45	29.68
1.0		56.39	40.74	53.22	41.17

Variation of bearing capacity ratio (BCR) with H/B for different D_f/B

The variation of BCR with H/B for different normalized embedment depth (D_f/B) of footing are shown in Figure 5(a)-(d) and Figure 6(a)-(d) for strip and circular footing respectively. From these Figures, it is revealed that for a given D_f/B and ϕ_1,ϕ_2 the BCR is found to higher for surface footing ($D_f/B=0$) when compared to footing embedded in layered sand. For example, for $\phi_1=40°$, $\phi_2= 30°$ and H/B= 2 the BCR was found to be 6.70 for $D_f/B =0$ and it decreases to 4.50 and 3.70 for $D_f/B= 0.5$ and 1 respectively. It should be noted that though the BCR for embedded footing was observed smaller than the surface case the bearing capacity will be essentially higher since the rate of decrease of bearing capacity ratio for layered case is not significant. It is also observed that for a constant friction angle of the bottom layer (ϕ_2) the BCR increases with increases with increase in friction angle of top layer (ϕ_1). The improvement in BCR occurs when the top layer is very dense and the bottom layer is very loose.

For strip footing, the BCR increases continuously with increase in H/B thereafter becomes constant whereas for circular footing the BCR becomes constant earlier than in case of strip footing. The BCR with the use of associated flow ($\psi=\phi$) was higher in comparison to their non- associated flow ($\psi<\phi$) for different values D_f /B.

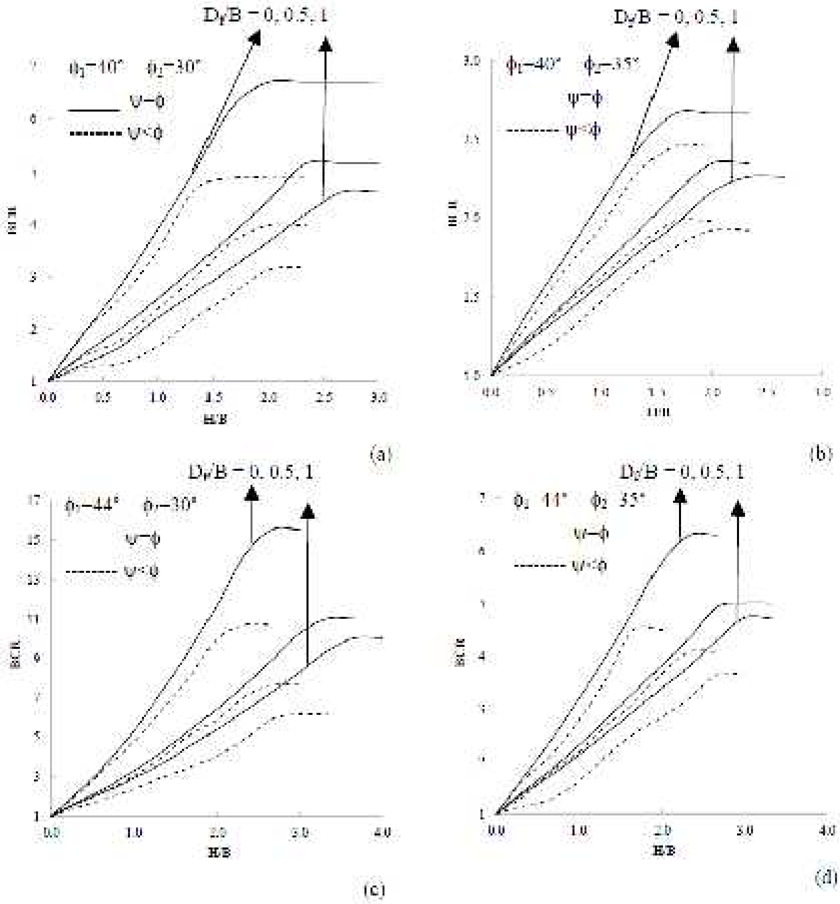


Fig. 5. Variation of BCR with H/B and D_f/B for (a) ϕ_1 =40°, ϕ_2 =30°(b) ϕ_1 =40° ϕ_2 =35° (c) ϕ_1 =44°, ϕ_2 =30°and (d) ϕ_1 =44°, ϕ_2 =35° (strip footing).

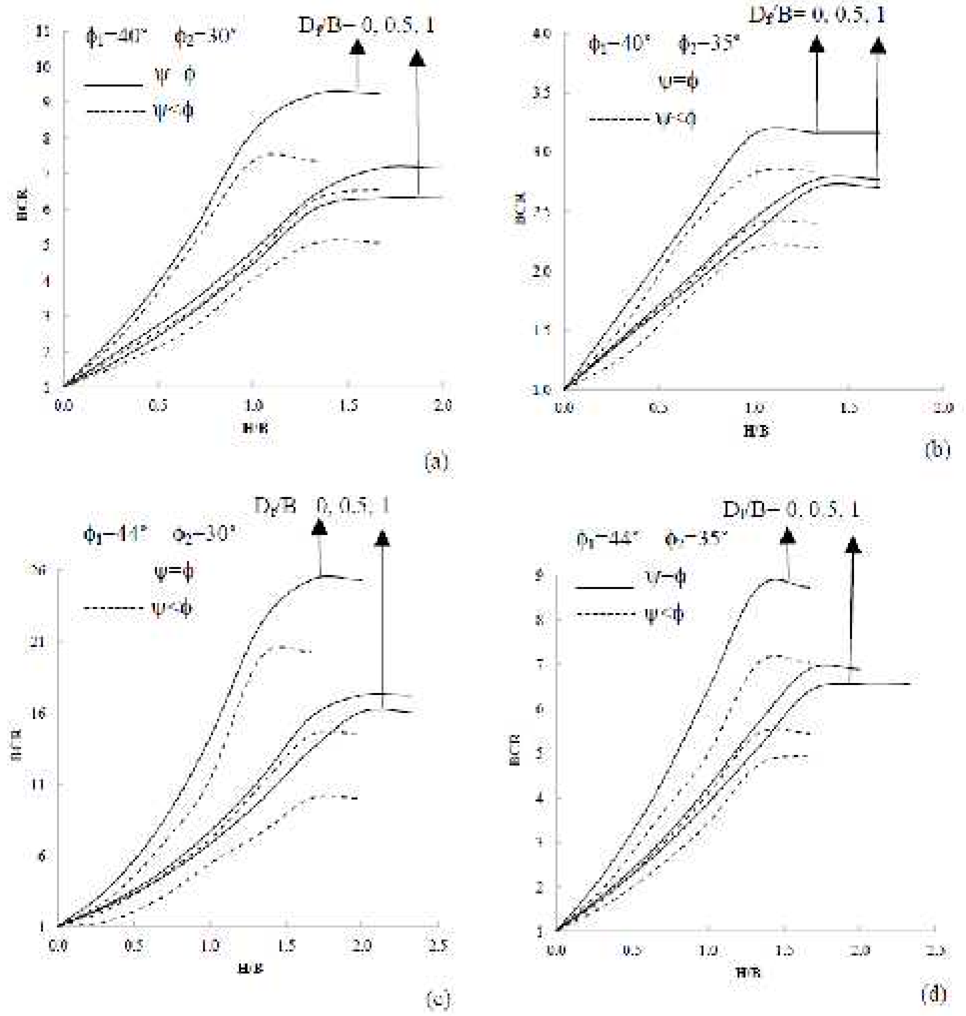


Fig. 6. Variation of BCR with H/B and D_f/B for (a) ϕ_1 =40°, ϕ_2 =30°(b) ϕ_1 =40° ϕ_2 =35° (c) ϕ_1 =44°, ϕ_2 =30°and (d) ϕ_1 =44°, ϕ_2 =35° (circular footing).

3. Comparison

In order to compare the results of present analysis with those available in literature, additional analysis was performed by taking the material properties from the relevant literature. The computed bearing capacity in various cases was expressed in normalized form by dividing with (γ_1B). Figure 7(a) shows a comparison of the present FE analysis with lower and upper bound finite elements limit analysis of Salimi et al. (2019) for strip footing. From this figure it can be noticed that the present $q_u/(\gamma_1 B)$ values for $\psi=\phi$ are in good agreement with Salimi et al. (2019) upper bound. However, $\psi<\phi$ values are lower than Salimi et al. (2019) lower and upper bound values.

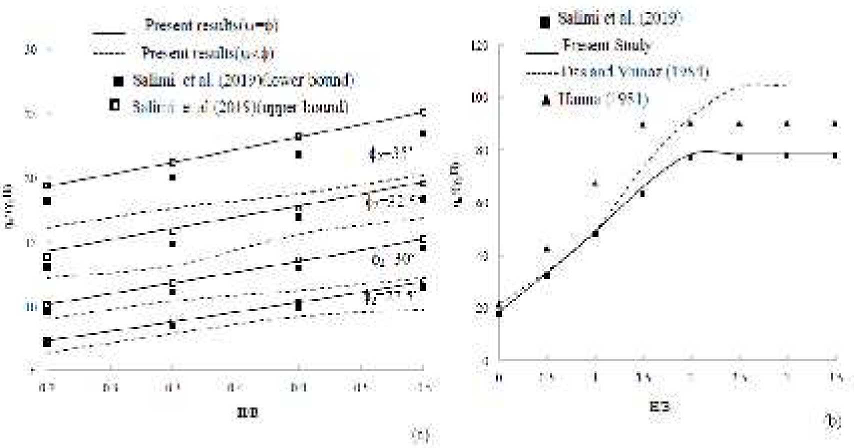


Fig. 7. Comparison of normalized bearing capacity for strip footing on layered sand with literature.

Further, the results of the present study for strip footing are compared with the semi-empirical solutions of Hanna (1981), experimental results of Das and Munoz (1984) and Finite element limit analysis (FELA) values of Salimi et al. (2019). The analysis was performed considering ϕ_1= 43° and ϕ_2= 36° with γ_1 and γ_2 = 17.06 and 15.25 kN/m^3 respectively. The same is shown in Figure 7(b). This Figure suggest that the normalized bearing capacity of present FEM analysis are very similar to Salimi et al. (2019) and agrees well with the experimental values of Das and Munoz (1984) for tests results of H/B ≤ 2. Moreover the values reported by Hanna (1981) are overestimated. Further the present BCR of circular footing compared well with FELA values of Khatri et al. (2017) for selected series of ϕ_1 = 40, 44° and ϕ_2 = 30°. The same is shown in Figure 8(a) and (b).

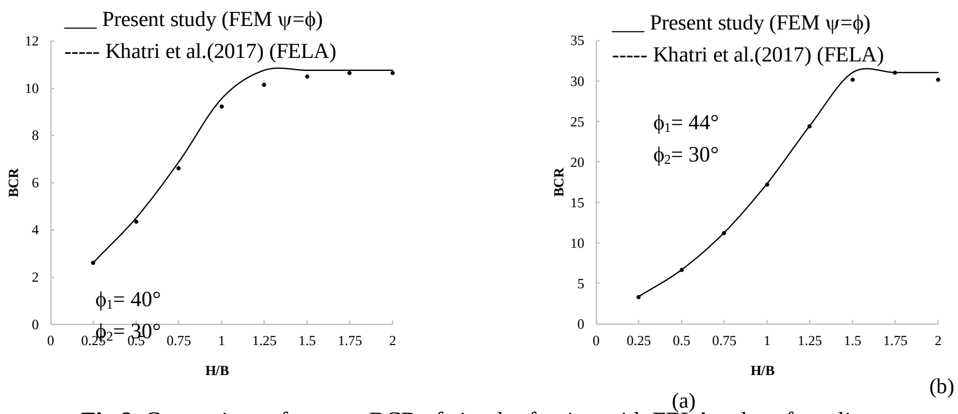


Fig.8. Comparison of present BCR of circular footing with FELA values from literature

4. Conclusions

The bearing capacity of strip and circular footings on dense on loose sand for different embedment depth was determined numerically by finite element analysis (FE). The bearing capacity was expressed in normalized form. The present study the brings forth the following conclusions.

1. For a given embedment depth, friction angle of top dense layer and bottom loose layer, the bearing capacity ratio increases with increase in the thickness of the top dense layer.
2. The bearing capacity ratio of footing is higher for ϕ_1 = 44 and ϕ_2= 30°. For strip footing of H/B= 2, the BCR was found to be 11.70, for D_f/B = 0. Similarly for circular footing of H/B = 2, and D_f/B = 0 the BCR was found to be 25.38. Hence, the bearing capacity ratio of circular footing is higher compared to strip footing.
3. With increase in embedded ratio, the maximum increase in bearing capacity for strip and circular footing was found to be 260% and 400% respectively.
4. The bearing capacity corresponding to non- associated flow rule is lower compare to the associated flow rule. With the use of non- associated flow rule, the maximum reduction in bearing capacity is 0.60 and 0.53 times associated for strip and circular footing respectively.

The present study suggests that the surface footing with inclusion of dense layer results in improvement of bearing capacity ratio but the bearing capacity increases with the increase in embedment depth.

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