

Bearing Capacity Factor of Circular Footings on Two-layered Clay Soils

Samir Benmoussa^{1, 2*}, Sadok Benmebarek¹, Naima Benmebarek¹

¹ Department of Civil and Hydraulic Engineering, NMISSI Laboratory, Biskra University, BP 145 Biskra 07000, Algeria.

² Department of Civil Engineering, University Batna 2, Fésdis, Batna 05078, Algeria.

Received 13 January 2021; Revised 10 April 2021; Accepted 17 April 2021; Published 01 May 2021

Abstract

Geotechnical engineers often deal with layered foundation soils. In this case, the soil bearing capacity assessment using the conventional bearing capacity theory based on the upper layer properties introduces significant inaccuracies if the top layer thickness is comparable to the rigid footing width placed on the soil surface. Under undrained conditions the cohesion increases almost linearly with depth. A few theoretical studies have been proposed in the literature in order to incorporate the cohesion variation with depth in the computation of the ultimate bearing capacity of the strip and circular footings. Rigorous solutions to the problem of circular footings resting on layered clays with linear increase of cohesion do not appear to exist. In this paper, numerical computations using FLAC code are carried out to assess the vertical bearing capacity beneath rough rigid circular footing resting on two-layered clays of both homogeneous and linearly increasing shear strength profiles. The bearing capacity calculation results which depend on the top layer thickness, the two-layered clays strength ratio and the cohesion increase rates with depth are presented in both tables and graphs, and compared with previously published results available in the literature. The critical depth for circular footing is found significantly less than for strip footing.

Keywords: Numerical Modeling; Circular Footing; Layered Clays; Bearing Capacity; Failure.

1. Introduction

For a surface strip footing resting on a single layer of homogeneous clay under undrained conditions, practitioners generally use Terzaghi's expression to compute ultimate footing loads. For a surface strip footing without a surcharge, the ultimate bearing capacity expression is reduced to:

$$q_u = N_c \cdot C_u \quad (1)$$

Equation 1 can be rewritten to include the effect of footing shape as follows:

$$q_u = N_c \cdot C_u \cdot S_c \quad (2)$$

The ultimate bearing capacity of circular footings resting on a single layer of homogeneous clay under undrained conditions can be estimated using Equation 2. In situ, natural soils are often deposited in layers. These layers are non-homogeneous in nature but can be assumed as distinct homogeneous layers for engineering purposes, although the

* Corresponding author: s.benmoussa@univ-batna2.dz

 <http://dx.doi.org/10.28991/cej-2021-03091689>



© 2021 by the authors. Licensee C.E.J, Tehran, Iran. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC-BY) license (<http://creativecommons.org/licenses/by/4.0/>).

strength properties of adjacent layers are generally quite different. If a footing is placed on the surface of a layered soil for which the top layer thickness is large compared to the footing width or diameter, then the realistic assessment of the bearing capacity may be obtained using conventional bearing capacity theory based on the properties of the upper layer. However, if the thickness of the top layer is comparable to the footing width, this approach may not be appropriate.

The effect of soil homogeneous layering for strip footings has been widely reported in the literature, particularly by Button [1], Meyerhof and Hanna [2], Merifield et al. [3], Gupta et al. [4], Chi and Lin [5], Rao et al. [6], Eshkevari et al. [7] and Das and khatri [8]. Circular piled raft on clay soil has been addressed by Karkush and Aljorany [9]. They showed the benefit effect of interaction between the soil and the circular raft foundation to support the load of digester tank. Experimental studies [10] on saturated normally consolidated and lightly overconsolidated clays indicate that the cohesion of soil mass under undrained conditions increases almost linearly with depth. A few theoretical studies have been proposed in the literature to incorporate the variation of cohesion with depth in the computation of the ultimate bearing capacity of strip and circular footings.

Using the stress characteristics method, Davis and Booker [11] have performed a series of solutions for both smooth and rough rigid strip footings on single clay layer with undrained cohesion increasing linearly with depth. Likewise, using the characteristics method, Reddy et al. [12] have obtained the solutions for both strip and circular smooth footings for the cases of footing placed at very shallow depths from the ground surface. Recently, using the lower bound limit analysis in conjunction with finite elements, the bearing capacity factor N_c for several rates of increase of cohesion with depth has been estimated by Khatri and Kumar [13]. Using a numerical approach by means of FLAC code (Fast Lagrangian Analyses of Continua) [14], the bearing capacity factor N_c of a strip footing resting on two layers with undrained cohesion increasing linearly with depth has been computed by Benmebarek et al. [15]. Lately, Chi and Lin [5] utilized limit analysis and FLAC numerical simulation to investigate the bearing capacity of a footing on single thick stratum or two-layered cohesive soils. They concluded that the partial punch-through shear failure was between the general shear failure and the full punch-through shear failure, depending on the strength ratio and the normalized layer thickness, the features of this failure mode was not apparent from the variations of bearing factor figures. However, the problem of circular and square footings resting on layered clays has been addressed by Merifield and Nguyen [16] only for layered clays with constant undrained shear strength. Therefore, with respect to investigations carried out so far, for layered soils, the effect of an increase of soil cohesion with depth has not been addressed in detail. Rigorous solutions to the problem of circular footings resting on layered clays with linear increase of cohesion do not appear to exist. Geotechnical engineers have addressed this issue by simply averaging layer strengths or adopting large safety factors to account for the uncertainty of soil layering.

The purpose of the present investigation is to take advantage of the numerical computation, which does not require in advance the specification of the failure mechanism surface needed for both limit equilibrium and limit analysis methods, to study the effect of two-layered clays with constant and linear increase of cohesion with depth on the bearing capacity beneath rigid circular footing subjected to axial static load. The computation results of the bearing capacity related to the strength ratio of the two-layered clays, the relative thickness of the top layer and the rates of the increase of soil cohesion with depth are presented in tables and graphs. The results are compared with previously published results available in the literature regarding circular footings [12, 13, 16, 17] to illustrate the sensibility of the bearing capacity and the failure mechanisms to the layered strength and layered thickness. A flowchart of the research methodology employed in this study is depicted in Figure 1.

2. Problem Definition

This paper deals with the numerical study of bearing capacity factor for circular footings on two-layered clays whose cohesion increases linearly with depth. A footing of diameter D is placed on an upper layer of clay with undrained shear strength C_{u1-0} and thickness H as shown in Figure 2. The latter is underlain by an infinite depth clay layer with undrained shear strength C_{u2-0} . Both cases of constant and linearly increase of cohesion are considered in this investigation.

It is assumed that the rate of cohesion increase is similar for both layers. The cohesion of the two soil layers increases linearly with depth in the following trend:

$$C_{u1} = \frac{m \cdot z}{D} C_{u1-0} + C_{u1-0} \quad (3)$$

$$C_{u2} = \frac{m \cdot z}{D} C_{u2-0} + C_{u2-0} \quad (4)$$

It should be noted that the ultimate bearing capacity for undrained loading of a footing is independent of the soil unit weight and elastic parameters. This implies that the undrained strength is assumed to be independent of the mean normal stress.

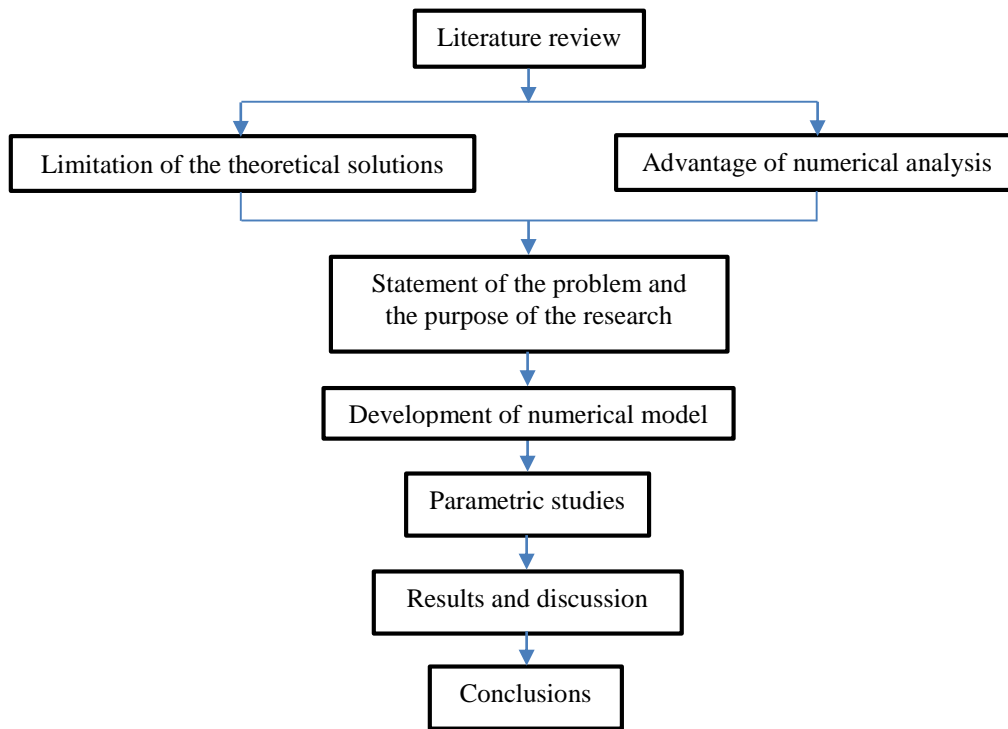


Figure 1. Research methodology flow chart

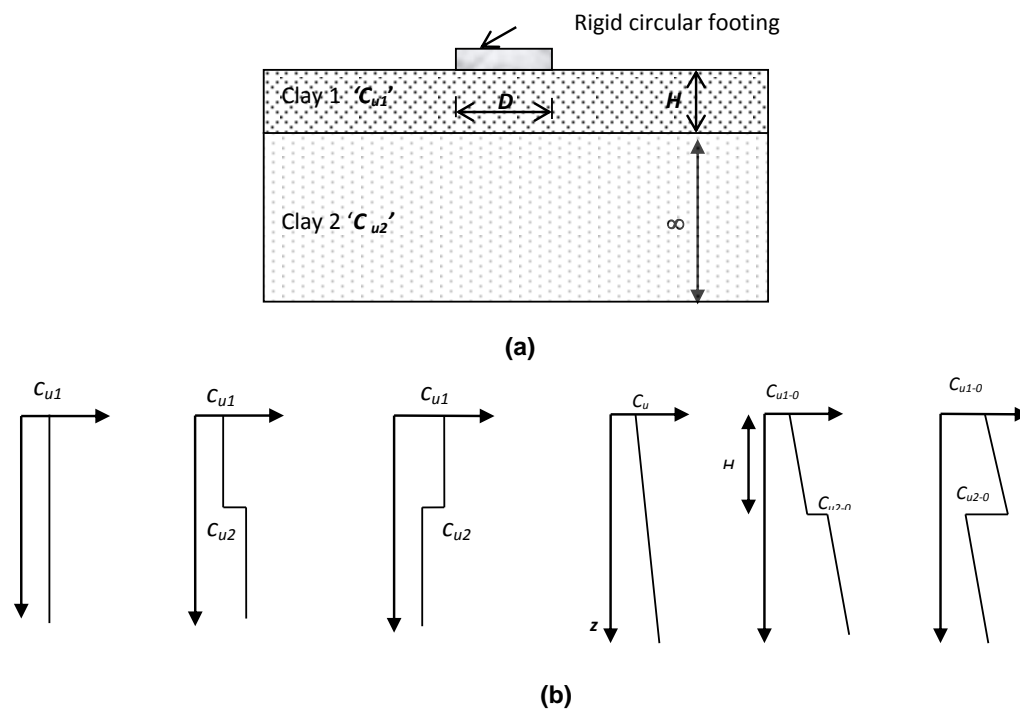


Figure 2. Studied cases: (a) Problem notation; (b) Cohesion variation with depth

In the case of a layered soil profile with constant undrained shear strength, it is convenient to rewrite Equation 1 in the form:

$$N_c^* = \frac{q_u}{C_{u1}} \tag{5}$$

In the case of layered clays with linearly increasing undrained shear strength, the equation can be written in the form:

$$N_c^* = \frac{q_u}{C_{u1-0}} \tag{6}$$

N_c^* is a modified bearing capacity factor which is a function of both H/D and C_{u1}/C_{u2} for constant undrained shear strength and is a function of H/D , C_{u1-0}/C_{u2-0} and m for linearly increasing undrained shear strength.

Solutions have been computed using FLAC code where H/D ranges from 0.125 to 1.5, C_{u1-0}/C_{u2-0} varies from 0.25 to 5 and for different values of m ($m = 0, 0.5, 1, 1.5, 2, 3, 4, 5$), these cover most problems of practical interest. It is noted that $(C_{u1-0}/C_{u2-0}) > 1$ corresponds to the common case of a strong clay layer over a soft clay layer, while $(C_{u1-0}/C_{u2-0}) < 1$ corresponds to the reverse case.

3. FLAC Simulations

For circular footings, the problem is axis-symmetric, therefore, only one half of the footing and soil mass was considered in the calculation scheme. Figure 3 shows the mesh and boundary conditions retained for this analysis. In the vicinity of the footing, the grid is refined to capture the large gradients in strain. The vertical and bottom boundaries were located at a distance of ten times the footing diameter in order to minimize boundary effects. The bottom boundary was assumed to be fixed, and the right vertical boundary was constrained in motion in the horizontal direction.

In order to be consistent with existing design expressions and the comparative studies described above, the elastic perfectly plastic Tresca model encoded in FLAC was used. Physical and mechanical characteristics assigned to the soil were: a shear modulus $G=30$ MPa, an elastic bulk modulus $K=50$ MPa, constant undrained strength, $C_{u1-0}=100$ kPa with internal friction $\phi_u = 0^\circ$. In order to develop an acceptable analysis scheme for later computations, preliminary simulations have been carried out, by testing the size of the domain and the grid refinement. It is noteworthy that the undrained bearing capacity of foundations is insensitive to the stiffness of soils [18, 19] and the soil unit weight as described by Housley and Martin (2003) [17] and verified in preliminary simulations.

The loading was modeled by the kinematically controlled indentation of the rigid footing. The solution was performed with velocities $1.0e-7$ m/step constant throughout the whole indentation process. Using a FISH function, the ultimate bearing capacity q_u was calculated by dividing the sum of the vertical footing nodal forces by the area of the footing, with its radius equal to the distance to the center of the first element outside the footing.

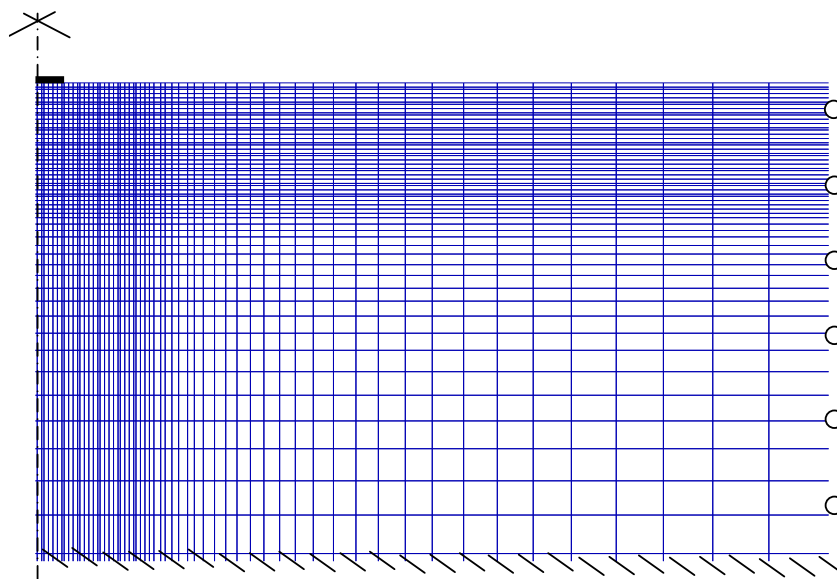


Figure 3. Mesh used and limit boundary conditions

4. Results and Discussion

4.1. Comparison with Existing Solutions

Before computing the bearing capacity of circular footings on two-layered undrained clays with constant and linearly increasing shear strength, first the case of single-layer was computed and compared with existing solutions available in the literature (Table 1): (i) The lower bound solutions on the basis of the three dimensional finite element limit analysis given by Salgado et al. [20], (ii) The method of characteristics solution of Housley and Martin [17], (iii) The lower bound limit analysis in conjunction with finite elements and linear programming reported by Khatri and Kumar [13] and (iv) The upper bound solution of Kusakabe et al. [21].

The results of the present study are well framed and compared to the solutions reported in the literature. This is clearly indicated in Figure 4 which presents the values of N_c^* versus m . Furthermore, the same trend is recorded (i. e. a smooth increase of N_c^* with m). The curve derived from this study is situated between that of Kusakabe et al. [21] and the other curves. In the range of $m = 0$ to 3 the same curve as that of Housley and Martin [17] and Khatri and Kumar [13] was obtained.

Table 1. Comparison of N_c^* values with the results derived by other authors for the case of a single layer clay with linearly increasing undrained shear strength

m	Present results	Kusakabe et al. [21]	Houlsby and Martin [17]	Khatri and Kumar [13]	Salgado et al. [20]	
					Lower bound	Upper bound
0	6.05	6.31	6.05	6.00		
1	7.00	7.39	6.95	6.88		
2	7.76	8.28	7.63	7.55		
3	8.47	9.02	8.21	8.12	5.856	6.227
4	9.15	9.78	8.73	8.64		
5	9.79	10.35	9.23	9.11		

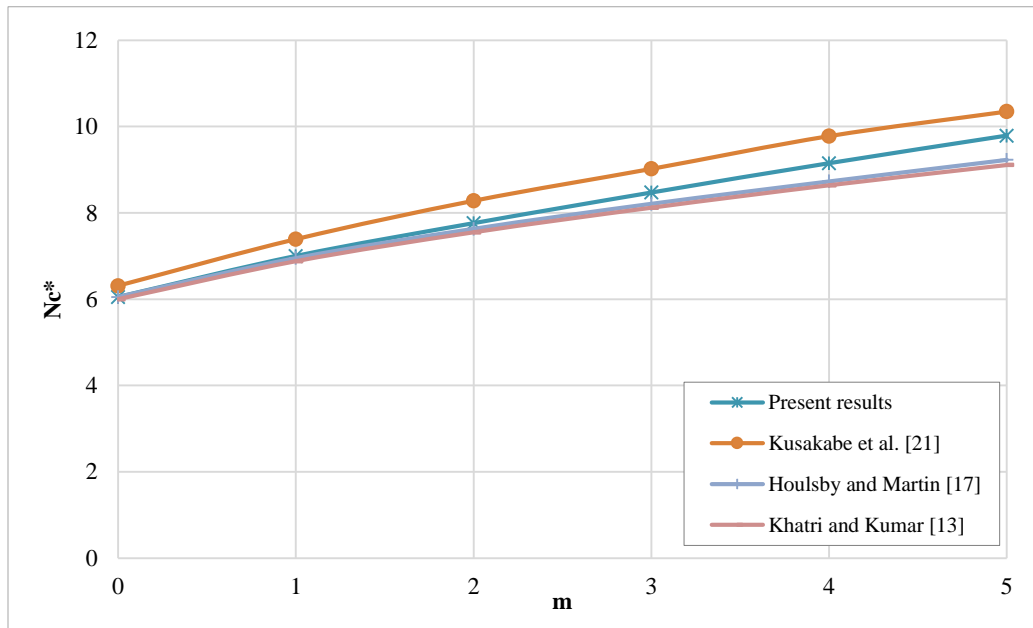


Figure 4. A comparison of N_c^* values with those from literature with different numerical solutions

In addition, the computed values of the modified bearing capacity factor for rough circular footings for the case of layered clays with constant undrained shear strength ($m = 0$) are plotted in Figure 5 and compared in Table 2 to the results given by Merifield and Nguyen [16] using finite elements ABAQUS code for each ratio of H/D and C_{u1-0}/C_{u2-0} solutions.

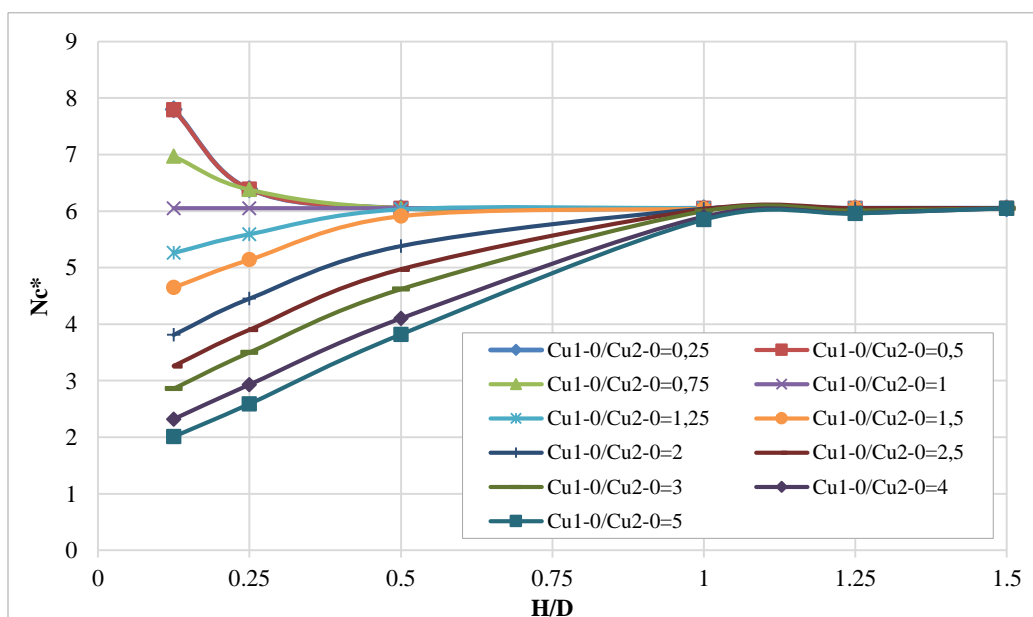


Figure 5. Variation of N_c^* for all combinations of $\frac{H}{D}$ for constant cohesion in the case of layered clay

Table 2. Comparison of N_c^* values with the results derived by other authors for the case of layered clays with constant undrained shear strength ($m = 0$)

$\frac{H}{D}$	$\frac{C_{u1-0}}{C_{u2-0}}$	0.25	0.5	0.75	1	1.25	1.5	2	2.5	3	4	5
0,125	Present study	7.8	7.79	6.97	6.05	5.26	4.65	3.81	3.26	2.86	2.32	2.01
	Merifield et al. [16]	7.95	7.89	6.85	6.05	5.27	4.66	3.85	3.32		2.41	2.07
0,25	Present study	6.39	6.39	6.38	6.05	5.59	5.14	4.45	3.90	3.50	2.93	2.59
	Merifield et al. [16]	6.36	6.36	6.34	6.05	5.59	5.17	4.51	4.02		3.13	2.78
0,5	Present study	6.05	6.05	6.05	6.05	6.03	5.91	5.38	4.97	4.62	4.10	3.82
	Merifield et al. [16]	6.04	6.04	6.04	6.05	6.02	5.90	5.58	5.23		4.39	4.03
1	Present study	6.05	6.05	6.05	6.05	6.05	6.04	6.04	6.03	6.00	5.90	5.85
	Merifield et al. [16]	6.03	6.03	6.03	6.05	6.05	6.05	6.06	6.06		6.04	5.94
1,5	Present study	6.05	6.05	6.05	6.05	6.05	6.05	6.05	6.05	6.05	6.05	6.05
	Merifield et al. [16]	6.04	6.04	6.03	6.05	6.04	6.04	6.04	6.04		6.04	6.03

The comparison between the present N_c^* and the results of Merifield and Nguyen [16] seems quite coherent. The same value of 6.05 was obtained for a single homogeneous layer. The present N_c^* values remain a little lower with a difference of less than 7%. Finally, the effect of increasing cohesion linearly with depth is investigated for different values of m ($m = 0, 0.5, 1, 1.5, 2, 3, 4, 5$). These cover most problems of practical interest. The results are listed presented in Table 3.

Table 3. N_c^* values of bilayers clay where undrained shear strength increases linearly with depth

H/D	C_{u1-0}/C_{u2-0}	m = 0	m = 0.5	m = 1	m = 1.5	m = 2	m = 3	m = 4	m = 5
0.125	0.25	7.8	8.09	8.28	8.51	8.78	9.22	9.72	10.19
	0.5	7.79	8.04	8.32	8.52	8.75	9.23	9.72	10.19
	0.75	6.97	7.45	7.85	8.22	8.56	9.16	9.68	10.18
	1	6.05	6.53	7.00	7.38	7.76	8.47	9.15	9.79
	1.25	5.26	5.78	6.22	6.48	6.83	7.51	8.14	8.68
	1.5	4.65	5.14	5.58	5.97	6.26	6.84	7.46	8.00
	2	3.81	4.25	4.64	5.01	5.35	5.85	6.37	6.92
	2.5	3.26	3.66	4.01	4.34	4.65	5.24	5.60	6.11
	3	2.86	3.23	3.55	3.86	4.13	4.68	5.18	5.42
	4	2.32	2.64	2.70	2.86	3.19	3.63	4.04	4.43
0.25	5	2.01	2.26	2.49	2.50	2.71	3.10	3.47	3.82
	0.25	6.39	6.77	7.15	7.51	7.83	8.51	9.19	9.79
	0.5	6.39	6.77	7.15	7.51	7.83	8.51	9.19	9.79
	0.75	6.38	6.79	7.15	7.52	7.83	8.51	9.19	9.79
	1	6.05	6.53	7.00	7.38	7.76	8.47	9.15	9.79
	1.25	5.59	6.09	6.60	7.05	7.47	8.26	8.99	9.66
	1.5	5.14	5.71	6.18	6.67	7.13	7.98	8.73	9.40
	2	4.45	5.07	5.48	5.97	6.42	7.27	8.05	8.79
	2.5	3.90	4.55	4.90	5.40	5.82	6.68	7.47	8.17
	3	3.50	3.97	4.47	4.99	5.35	6.16	6.89	7.60
0.5	4	2.93	3.40	3.81	4.23	4.60	5.31	5.99	6.70
	5	2.59	3.02	3.41	3.75	4.11	4.77	5.40	6.01
	0.25	6.05	6.56	7.00	7.40	7.77	8.48	9.16	9.79
	0.5	6.05	6.56	7.00	7.40	7.77	8.48	9.16	9.79
	0.75	6.05	6.56	7.00	7.40	7.77	8.48	9.16	9.79
	1	6.05	6.53	7.00	7.38	7.76	8.47	9.15	9.79
	1.25	6.03	6.56	7.01	7.36	7.77	8.47	9.15	9.79
	1.5	5.91	6.53	7.00	7.40	7.77	8.48	9.15	9.79
	2	5.38	6.26	6.96	7.39	7.78	8.45	9.15	9.79
	2.5	4.97	5.89	6.65	7.27	7.76	8.48	9.17	9.78
0.5	3	4.62	5.56	6.30	6.99	7.61	8.48	9.17	9.79
	4	4.10	4.94	5.77	6.47	7.12	8.26	9.17	9.80
	5	3.82	4.59	5.33	5.99	6.65	7.81	8.91	9.78

	0.25	6.05	6.52	7.00	7.38	7.76	8.47	9.15	9.79
	0.5	6.05	6.52	7.00	7.38	7.76	8.47	9.15	9.79
	0.75	6.05	6.52	7.00	7.38	7.76	8.47	9.15	9.79
	1	6.05	6.52	7.00	7.38	7.76	8.47	9.15	9.79
	1.25	6.05	6.52	7.00	7.38	7.76	8.47	9.15	9.79
1	1.5	6.04	6.52	7.00	7.38	7.76	8.47	9.15	9.79
	2	6.04	6.52	7.00	7.38	7.76	8.47	9.15	9.79
	2.5	6.03	6.52	7.00	7.38	7.76	8.47	9.15	9.79
	3	6.00	6.52	7.00	7.38	7.76	8.47	9.15	9.79
	4	5.90	6.52	7.00	7.38	7.76	8.47	9.15	9.79
	5	5.83	6.52	7.00	7.38	7.76	8.47	9.15	9.79
<hr/>									
	0.25	6.05	6.52	7.00	7.38	7.76	8.47	9.15	9.79
	0.5	6.05	6.52	7.00	7.38	7.76	8.47	9.15	9.79
	0.75	6.05	6.52	7.00	7.38	7.76	8.47	9.15	9.79
	1	6.05	6.52	7.00	7.38	7.76	8.47	9.15	9.79
	1.25	6.05	6.52	7.00	7.38	7.76	8.47	9.15	9.79
1.25	1.5	6.05	6.52	7.00	7.38	7.76	8.47	9.15	9.79
	2	6.05	6.52	7.00	7.38	7.76	8.47	9.15	9.79
	2.5	6.05	6.52	7.00	7.38	7.76	8.47	9.15	9.79
	3	6.01	6.52	7.00	7.38	7.76	8.47	9.15	9.79
	4	5.96	6.52	7.00	7.38	7.76	8.47	9.15	9.79
	5	5.96	6.52	7.00	7.38	7.76	8.47	9.15	9.79
<hr/>									
	0.25	6.05	6.52	7.00	7.38	7.76	8.47	9.15	9.79
	0.5	6.05	6.52	7.00	7.38	7.76	8.47	9.15	9.79
	0.75	6.05	6.52	7.00	7.38	7.76	8.47	9.15	9.79
	1	6.05	6.52	7.00	7.38	7.76	8.47	9.15	9.79
	1.25	6.05	6.52	7.00	7.38	7.76	8.47	9.15	9.79
1.5	1.5	6.05	6.52	7.00	7.38	7.76	8.47	9.15	9.79
	2	6.05	6.52	7.00	7.38	7.76	8.47	9.15	9.79
	2.5	6.05	6.52	7.00	7.38	7.76	8.47	9.15	9.79
	3	6.05	6.52	7.00	7.38	7.76	8.47	9.15	9.79
	4	6.05	6.52	7.00	7.38	7.76	8.47	9.15	9.79
	5	6.05	6.52	7.00	7.38	7.76	8.47	9.15	9.79

4.2. Layered Clays with Constant Undrained Shear Strength

4.2.1. Footing on Strong Clay Overlying Soft Clay ($\frac{C_{u1-0}}{C_{u2-0}} > 1$)

For cases of layered clays with constant undrained shear strength ($m = 0$) where the top layer is stronger than the bottom layer ($(C_{u1-0}/C_{u2-0}) > 1$), the present results of N_c^* given in Table 3 are shown graphically in Figure 5 for comparison purposes. These indicate that N_c^* increases as H/D increases and approaches 6.05 for all cases up to a depth ratio of $H/D = 1.5$. Thereafter, the value of N_c^* becomes almost constant and equal to 6.05 which indicates that the failure mechanism is limited in the top layer and the whole soil can be treated as homogenous using the properties of the top layer only. For strong clay overlying soft clay profile, the larger the ratio C_{u1-0}/C_{u2-0} is, the larger the critical depth will be. This critical depth ($H/D = 1.5$) for circular footing is significantly less than the $H/B \approx 2-2.5$ for strip footing found by some investigators [2, 3, 10].

For $H/D < 1.5$, the present results show that N_c^* decreases with both the increase of the ratio C_{u1-0}/C_{u2-0} and the decrease of the top layer depth ratio H/D . For instance, the values of N_c^* are reduced to 2.01 for $(C_{u1-0}/C_{u2-0}) = 5$ and $H/D = 0.125$ while for the same conditions, the value is reduced to 1.40 in the case of a strip footing [15]. As the top layer becomes very strong compared to the bottom layer, full punching shear through the top layer occurs typically for ratios of $H/D \leq 0.5$ as illustrated in Figure 6 for the case of $H/D = 0.25$ and $(C_{u1-0}/C_{u2-0}) = 5$.

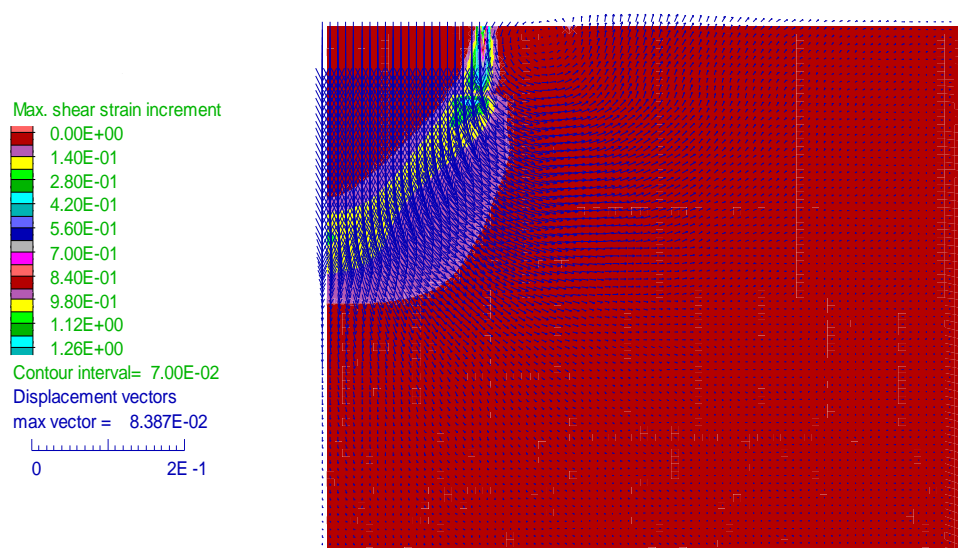


Figure 6. Failure mechanism visualized by the distribution of maximum shear strain rates and displacement field vectors for $\frac{H}{D} = 0.25$ and $\frac{C_{u1-0}}{C_{u2-0}} = 5$

4.2.2. Footing on Soft Clay Overlying Strong Clay ($\frac{C_{u1-0}}{C_{u2-0}} < 1$)

For cases of layered clays with constant undrained shear strength ($m = 0$) where the top layer is weaker than the bottom layer, the results presented in Table 3 indicate that N_c^* decreases as H/D increases until a value of 0.5 is reached. For $H/D = 0.125$, it is equal to 7.80 when the ratio $(C_{u1-0}/C_{u2-0}) = 0.25$. For $H/D = 0.25$ and $(C_{u1-0}/C_{u2-0}) = 0.25$, the bottom layer is slightly affected by the failure mechanism as illustrated by the shear strain increments and field displacement vectors (Figure 7). However, for the ratios of $H/D \geq 0.5$, the results (Table 3) show no increase in the bearing capacity of circular footings corresponding to the failure surface fully contained within the top layer as illustrated by the concentration of the shear strain increments and field displacement vectors (Figure 8). Consequently, the whole soil can be treated as homogenous soil using the properties of the top soil only. For soft clay overlying strong clay profile, the critical depth seems to be a constant around $0.5D$ which is less than the case of strong clay overlying soft clay profile.

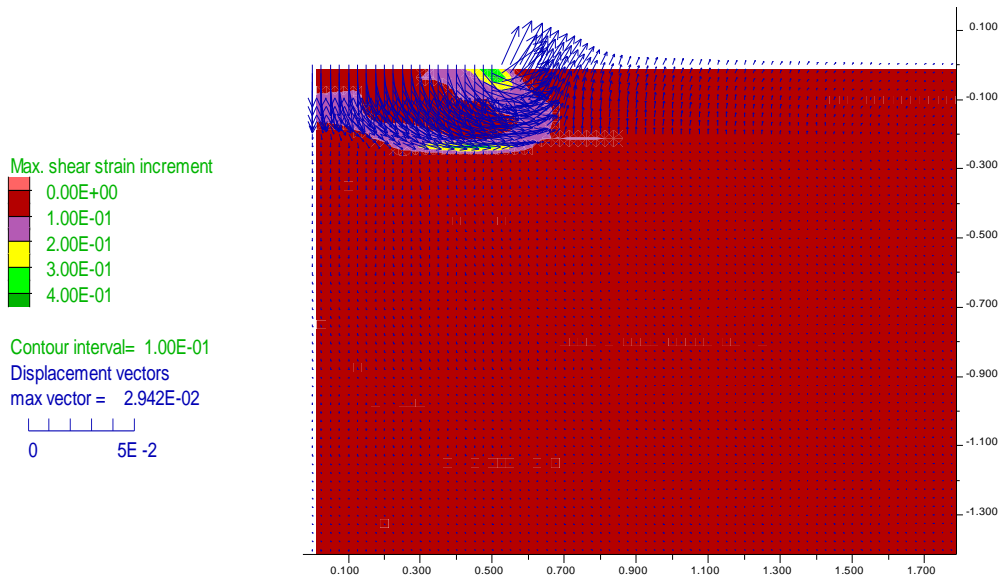


Figure 7. Failure mechanism visualized by distribution of maximum shear strain rates and displacement field vectors for footing with $\frac{H}{D} = 0.25$ and $\frac{C_{u1-0}}{C_{u2-0}} = 0.25$

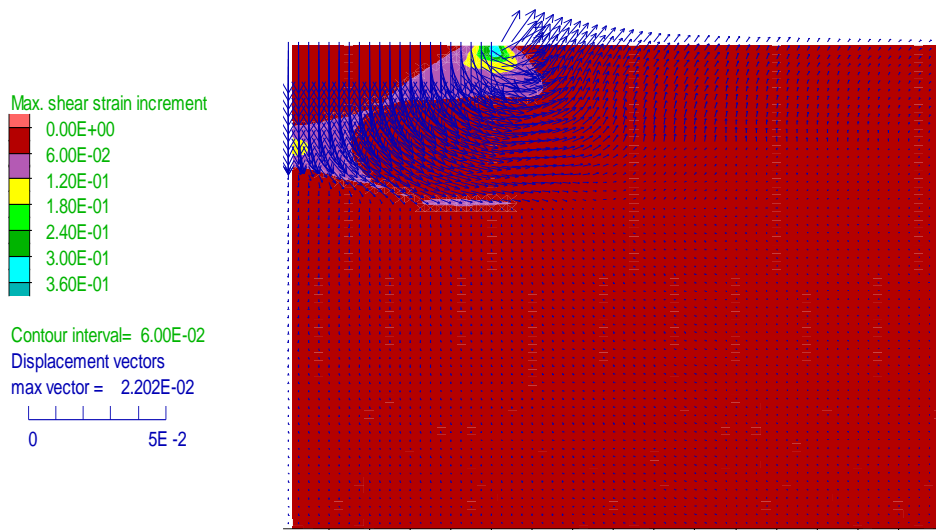


Figure 8. Failure mechanism visualized by distribution of maximum shear strain rates and displacement field vectors for footing with $\frac{H}{D} = 0.5$ and $\frac{C_{u1-0}}{C_{u2-0}} < 1$

4.3. Layered Clays with Linearly Increasing Undrained Shear Strength

The computed values of the modified bearing capacity factor N_c^* for two layered clays with undrained shear strength increasing linearly with depth are presented in Table 3. The results show a significant increase in N_c^* values with an increase in the value of m for all combinations of H/D and C_{u1-0}/C_{u2-0} . Figures 9 and 10 illustrate the effects of m and H/D for two extreme cases respectively: strong-over-soft clay profile with $(C_{u1-0}/C_{u2-0}) = 5$ and soft-over-strong clay profile with $(C_{u1-0}/C_{u2-0}) = 0.25$.

Figure 9 indicates that regarding the influence of m , there is a clear increasing trend with m for each value of H/D . Furthermore, for each value of m , an increase in the bearing capacity factor for strong-over-soft clay profile occurs up to the critical depth ratio $H/D = 1$ beyond this threshold there is no effect. However, for $H/D = 0.5$, N_c^* increases as m increases and converges to the envelope curve for $m = 5$. This indicates that critical depth decreases as m increases and reaches $H/D = 0.5$ for $m = 5$. For $H/D < 0.5$, the effect of the increase of m is less sensible with the diminution of H/D . However, for soft-over-strong clay profile, the results indicate that an increase in bearing capacity (Figure 10) is more pronounced for $H/D = 0.125$ than $H/D \geq 0.25$. The difference decreases with the increase of m . However, for the ratios of $H/D \geq 0.5$, the results (Table 3) show no increase in the bearing capacity of circular footings corresponding to the failure surface fully contained within the top layer as illustrated by the concentration of the shear strain increments and field displacement vectors (Figure 8). So, the whole soil can be treated as a homogenous soil using the properties of the top soil only. For soft clay overlying strong clay profile, the critical depth seems to be a constant around $0.5D$ which is significantly less than the case of strong clay overlying soft clay profile.

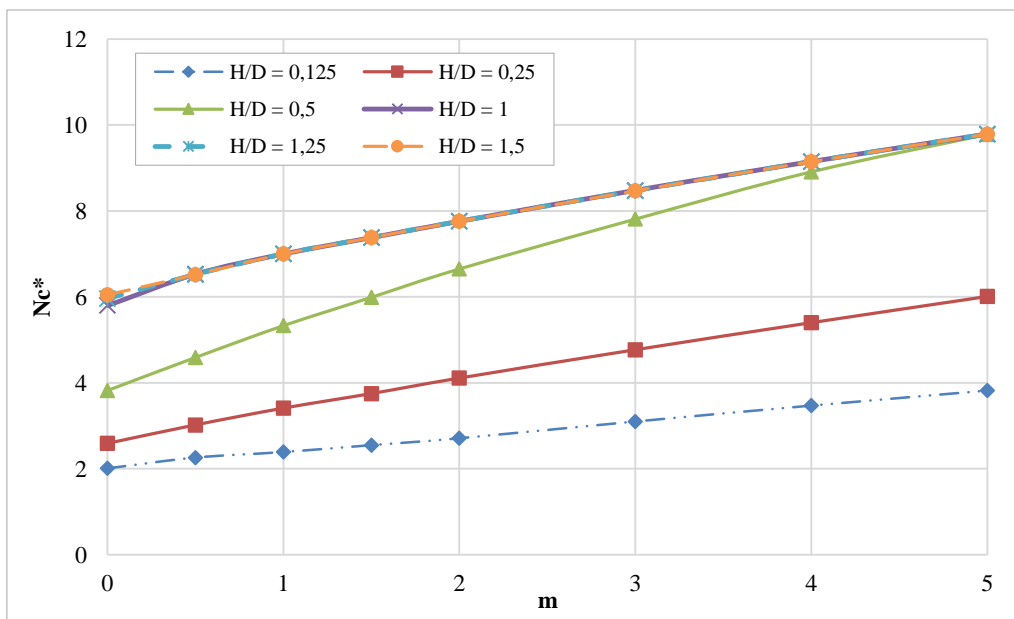


Figure 9. Variation of N_c^* with $\frac{H}{D}$ and m for $\frac{C_{u1-0}}{C_{u2-0}} = 5$

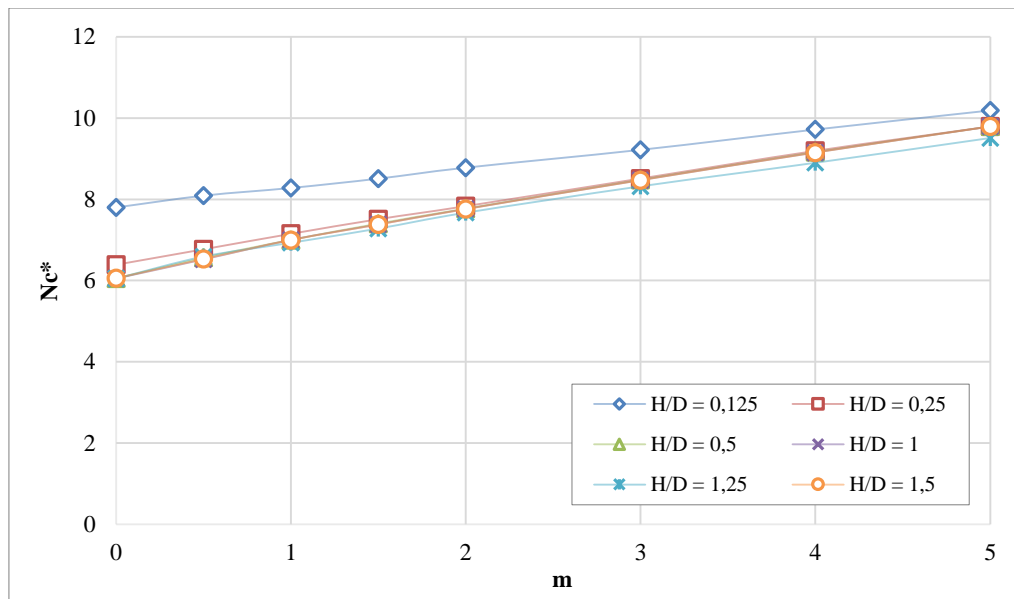


Figure 10. Variation of N_c^* with $\frac{H}{D}$ and m for $\frac{C_{u1-0}}{C_{u2-0}} = 0.25$

5. Conclusions

Numerical computations of the bearing capacity of rigid and rough circular footings on a two-undrained layered clays profile with both constant and linear increase of cohesion with depth have been performed using FLAC code. The results obtained have been presented in terms of a modified bearing capacity factor N_c^* in both tabular and graphical forms to facilitate their use in solving practical design problems. A number of conclusions may be drawn from this investigation:

- For a single layer clay profiles, the present numerical computations of N_c^* compare well with previously reported analytical and finite-element solutions. N_c^* is found to increase continuously with the rate of increase of the cohesion according to depth.
- For a strong-over-soft clay profile:
 - ✓ For constant undrained shear strength ($m = 0$), the results show a critical depth ratio $H/D = 1.5$ for circular footing. This critical depth is significantly less than $H/B \approx 2-2.5$ for strip footing. For $H/D < 1.5$, N_c^* decreases with both the increase of the ratio C_{u1-0}/C_{u2-0} and the decrease of the top layer depth ratio H/D . For $H/D \geq 1.5$, failure mechanism occurs within the top layer, and the bearing capacity is independent of the bottom layer, as well;
 - ✓ For linearly increasing undrained shear strength, the results indicate that the increase of the m reduces the critical depth noticed by the reduction of the bearing capacity occurring up to depth ratios $H/D = 1$ and 0.5 for $m = 0.5$ and 5 respectively unlike the case of strip footing which occurs for $H/D = 2, 1.5$ and 1 for $m = 0, 0.5$ and 1.5 respectively
- For a soft-over-strong clay profile:
 - ✓ The bearing capacity increases with the increase of the factor m and the decrease of the depth ratio H/D ;
 - ✓ The critical depth ratio is around $H/D = 0.5$ which is much less than the case of strong clay overlying soft clay profile for circular footing,
 - ✓ It can also be noted that increasing the m value reduces the critical depth observed by reducing the bearing capacity occurring up to the depth ratio $H/D = 0.25$ for $m = 5$.

6. Declarations

6.1. Data Availability Statement

The data presented in this study are available in article.

6.2. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

6.3. Acknowledgements

The authors express their gratitude to the Directorate General for Scientific Research and Technological Development of Algeria.

6.4. Conflicts of Interest

The authors declare no conflict of interest.

7. References

- [1] Button, S. J. "The bearing capacity of footings on a two-layer cohesive subsoil." In: Proceeding of the 3rd International Conference on Soil Mechanics and Foundation Engineering, Zurich (1953): 332–335.
- [2] Meyerhof, G. G., and A. M. Hanna. "Ultimate Bearing Capacity of Foundations on Layered Soils under Inclined Load." *Canadian Geotechnical Journal* 15, no. 4 (November 1, 1978): 565–572. doi:10.1139/t78-060.
- [3] Merifield, R. S., S. W. Sloan, and H. S. Yu. "Rigorous Plasticity Solutions for the Bearing Capacity of Two-Layered Clays." *Géotechnique* 49, no. 4 (August 1999): 471–490. doi:10.1680/geot.1999.49.4.471.
- [4] Gupta, Arushi, Rakesh Kumar Dutta, Rajnish Shrivastava, and Vishwas Nandkishor Khatri. "Ultimate Bearing Capacity of Square/Rectangular Footing on Layered Soil." *Indian Geotechnical Journal* 47, no. 3 (March 29, 2017): 303–313. doi:10.1007/s40098-017-0233-y.
- [5] Chi, Chao-Ming, and Zheng-Shan Lin. "The Bearing Capacity Evaluations of a Spread Footing on Single Thick Stratum or Two-Layered Cohesive Soils." *Journal of Marine Science and Engineering* 8, no. 11 (October 29, 2020): 853. doi:10.3390/jmse8110853.
- [6] Rao, Pingping, Ying Liu, and Jifei Cui. "Bearing Capacity of Strip Footings on Two-Layered Clay under Combined Loading." *Computers and Geotechnics* 69 (September 2015): 210–218. doi:10.1016/j.compgeo.2015.05.018.
- [7] Salimi Eshkevari, Seyednima, Andrew J. Abbo, and George Kouretzis. "Bearing Capacity of Strip Footings on Sand over Clay." *Canadian Geotechnical Journal* 56, no. 5 (May 2019): 699–709. doi:10.1139/cgj-2017-0489.
- [8] Das P. P. and V. N. Khatri. "Bearing Capacity Estimation of Shallow Foundations on Layered Sand Strata Using Finite Elements Analysis." *Conf. Construction in Geotechnical Engineering*, Editors: Latha Gali, Madhavi, Palapati, Raghuvveer Rao (2020): 1-13.
- [9] Karkush, Mahdi O, and Ala N. Aljorany. "Numerical Evaluation of Foundation of Digester Tank of Sewage Treatment Plant." *Civil Engineering Journal* 5, no. 5 (May 22, 2019): 996–1006. doi:10.28991/cej-2019-03091306.
- [10] Bishop, A. W. "The Strength of Soils as Engineering Materials." *Géotechnique* 16, no. 2 (June 1966): 91–130. doi:10.1680/geot.1966.16.2.91.
- [11] Davis, E. H., and J. R. Booker. "The Effect of Increasing Strength with Depth on the Bearing Capacity of Clays." *Géotechnique* 23, no. 4 (December 1973): 551–563. doi:10.1680/geot.1973.23.4.551.
- [12] Reddy, A. Siva, Anil K. Singh, and Suresh S. Karnik. "Bearing Capacity of Clays Whose Cohesion Increases Linearly with Depth." *Journal of Geotechnical Engineering* 117, no. 2 (February 1991): 348–353. doi:10.1061/(asce)0733-9410(1991)117:2(348).
- [13] Khatri, Vishwas N., and Jyant Kumar. "Bearing Capacity Factor N_c Under $\Phi=0$ Condition for Piles in Clays." *International Journal for Numerical and Analytical Methods in Geomechanics* 33, no. 9 (November 25, 2008): 1203–1225. doi:10.1002/nag.763.
- [14] Itasca. "Fast Lagrangian Analysis of Continua." Minneapolis: ITASCA Consulting Group, Inc. (2018).
- [15] Benmebarek, S., S. Benmoussa, L. Belouar, and N. Benmebarek. "Bearing Capacity of Shallow Foundation on Two Clay Layers by Numerical Approach." *Geotechnical and Geological Engineering* 30, no. 4 (April 18, 2012): 907–923. doi:10.1007/s10706-012-9513-6.
- [16] Merifield, R. S., and V. Q. Nguyen. "Two- and Three-Dimensional Bearing-Capacity Solutions for Footings on Two-Layered Clays." *Geomechanics and Geoengineering* 1, no. 2 (August 31, 2006): 151–162. doi:10.1080/17486020600632637.
- [17] Houlsby, G. T., and C. M. Martin. "Undrained Bearing Capacity Factors for Conical Footings on Clay." *Géotechnique* 53, no. 5 (June 2003): 513–520. doi:10.1680/geot.2003.53.5.513.
- [18] Yun, Gijae, and M Fraser Bransby. "The Horizontal-Moment Capacity of Embedded Foundations in Undrained Soil." *Canadian Geotechnical Journal* 44, no. 4 (April 1, 2007): 409–424. doi:10.1139/t06-126.
- [19] Shiau, J. S., R. S. Merifield, A. V. Lyamin, and S. W. Sloan. "Undrained Stability of Footings on Slopes." *International Journal of Geomechanics* 11, no. 5 (October 2011): 381–390. doi:10.1061/(asce)gm.1943-5622.0000092.
- [20] Salgado, R., A. V. Lyamin, S. W. Sloan, and H. S. Yu. "Two- and Three-Dimensional Bearing Capacity of Foundations in Clay." *Géotechnique* 54, no. 5 (June 2004): 297–306. doi:10.1680/geot.2004.54.5.297.
- [21] Kusakabe, Osamu, Hiroyuki Suzuki, and Akio Nakase. "An Upper Bound Calculation on Bearing Capacity of a Circular Footing on a Non-Homogeneous Clay." *Soils and Foundations* 26, no. 3 (September 1986): 143–148. doi:10.3208/sandf1972.26.3_143.