DETERMINATION AND PREDICTION OF THE ULTIMATE BEARING CAPACITY OF A STRIP FOOTING ON UNDRAINED CLAYEY SLOPES

DOLOČANJE IN NAPOVED MEJNE NOSILNOSTI PASOVNIH TEMELJEV NA NEDRENIRANIH GLINENIH POBOČJIH

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DOI https://doi.org/10.18690/actageotechslov.16.2.50-65.2019

Keywords

bearing capacity ratio, cohesive soil, cohesionless soil, edge distance, footing, slope

Abstract

In the present study, a footing resting on clayey slopes is analysed using finite element analysis, and the results are further used for predicting the bearing capacity of the footing using statistical analyses. The absolute bearing capacity increases with an increase in the embedment depth of the footing, the edge distance and the soil undrained strength. However, the rate of increase of the bearing capacity with the footing depth on the slope is, relatively, less than the level ground. The critical edge distance is found to increase with an increase in the embedment depth of the footing and the slope inclination. In contrast to cohesionless soil slopes, the critical edge distance decreases and the bearing-capacity ratio increases with an increase in the soil strength for a given slope geometry and footing depth. The magnitude of the critical edge distance is found to vary from 0.5 to 5 times the footing width in cohesive soil, which is relatively very small when compared to cohesionless soil. A number of differences have been observed between the failure mechanism of a footing resting on a cohesive soil slope and a cohesionless soil slope, which contributes to the differences in their behaviour. The soil strength and the slope inclination are found to be the two most important factors affecting the bearing capacity of a footing on slopes. The predicted values of the bearing capacity are compared with the existing experimental and theoretical values.

Ključne besede

razmerje nosilnosti, vezljiva zemljina, nevezljiva zemljina, razdalja med robovi, temelj, naklon

Izvleček

V tej študiji je s pomočjo metode končnih elementov analiziran temelj na glinastih pobočjih. Rezultati analiz so nato s pomočjo statističnih analiz uporabljeni za napovedovanje nosilnosti temeljev na pobočju. Absolutna nosilnost narašča s povečanjem globine vpetja, razdalje do roba pobočja in nedrenirane trdnosti zemljine. Stopnja povečanja nosilnosti z globino vpetja na pobočju je relativno manjša kot pri temeljih na ravnih tleh. Ugotovljeno je, da se kritična razdalja do roba temelja poveča s povečanjem globine vpetja temelja in naklona pobočja. Za določeno geometrijo pobočja in globino osnove temelja, se, v nasprotju s pobočji nekoherentnih zemljin, kritična razdalja do roba zmanjšuje in razmerje nosilnosti narašča s povečanjem trdnosti tal. Ugotovljeno je tudi, da se obseg kritične razdalje do roba giblje od 0,5 do 5-kratne širine temelja v vezljivi zemlji, kar je v primerjavi z nevezljivo zemljino relativno majhno. Ugotovljene so bile številne razlike med porušnim mehanizmom temelja na piobočju iz vezljivih in nevezljivih zemljin, ki prispevajo k razlikam v obnašanju tal. Nadalje je ugotovljeno, da sta trdnost tal in naklon pobočja najpomembnejša dejavnika, ki vplivata na nosilnost temelja na pobočju. Napovedane vrednosti nosilnosti so bile primerjane z obstoječimi eksperimentalnimi in teoretičnimi vrednostmi.

1 INTRODUCTION

A foundation located on a slope or adjacent to a slope crest possesses a lower bearing capacity than level ground as it lacks the confinement from the slope side. Footings resting precisely on the slope crest possess the minimum bearing capacity [1]. However, the bearing capacity improves with an increase in the edge distance (b) between the footing and the slope crest, an increase in the soil strength and also with an increase of the embedment depth of the footing [1].

The majority of earlier studies were carried out on cohesionless soil. The range of critical edge distances is found to vary from 2 to 12 times the footing width (B) in cohesionless soils [2-3]. A number of studies investigated the footing resting adjacent to cohesive slopes. Meyerhof [1] assumed a uniform mobilization of the soil on the slope side and the level side, and found that the critical edge distance ranged from B to 4.5B. Kusakabe et al. [4] found that $c_u/(\gamma B)$ is an important factor affecting the bearing capacity and the failure mechanism. In a few cases the critical edge distance was found to be more than 5B. DeSimone [5] used a boundary integral equation to study the bearing capacity of the footing on a clay slope without considering the effect of the edge distance in the analysis. Jao et al. [6] found that the effect of the slope inclination and the edge distance is relatively less in purely cohesive soils than in silty clay and cohesionless soil. Georgiadis [7] analyzed the cohesive soil slope using an upper-bound analysis and found the critical edge distance to be 2B without a consideration of the slope height. Al-Jubair & Abbas [8] and Abbas and Sabbar [9] used 2D Plaxis and observed that the influence of the slope became insignificant at an edge distance of 1.5B. Georgiadis and Chrysouli [10] varied the edge distance from 0 to B and found that the bearing capacity decreases linearly with the horizontal seismic acceleration. Gill et al. [11-12] found that the efficiency of the reinforcement reduces with an increase in the edge distance. Farzaneh et al. [13] determined the seismic bearing capacity of a footing on a slope for a maximum edge distance of 1B. Mirzababaei et al. [14] also constrained the edge distance to 3B. Luo and Bathurst [15] performed a reliability analysis for the bearing capacity of a footing resting on a cohesive slope crest. Baazouzi et al. [16-17] determined the effect of slope inclination on the undrained bearing capacity. Aminpour et al. [18] determined the effect of surcharge loading slope behaviour. Acharya and Dey [19] found the critical edge distance to be 4B in c-ϕ soils for an isolated footing. Leshchinsky and Xie [20] analysed a number of cases of a footing resting on a c-φ slope, but the edge distance was not determined in the analysis. Acharya and Dey [21] developed an interaction mechanism for a multiple footing resting on a slope based on a displacement pattern. A number of studies have also been carried out to analyse cohesive soil slopes using soft computing [19, 22-24]. However, most of these studies are limited to a determination of the slope's stability. It is observed from the literature that a consensus over the critical edge distance is also missing in the case of a footing resting over a cohesive slope. In the majority of studies the edge distance was found to vary from B to 3B. However, some studies found the values to be on the very high side. Kusakabe et al. [4] and Meyerhof [1] found this distance to be approximately 4B–5B. Zhao and Wei [25] found that the bearing capacity is increasing continuously, even up to an edge distance of 10B. However, these values cannot be considered as a true value of the critical edge distance as most of the studies were limited to a particular soil and a limited range of other parameters. The surcharge loading is triangular on the slope side; however, most of the earlier studies considered it as a uniform loading.

In this study, a series of finite element analyses were performed to determine the effect of various factors, such as the slope geometry, soil strength, edge distance, and embedment depth on the bearing capacity of a footing resting on cohesive soil slopes. The differences in the failure mechanism of a footing resting on clayey soil and cohesionless soil are identified and presented in detail. The use of conventional limit equilibrium methods to determine the bearing capacity is time consuming. Therefore, a limit analysis has been used in the present study. Additionally, a nonlinear multiple regression analysis (NMRA) and an artificial neural network (ANN) have been used to predict the bearing capacity factor as well as the BCR. The predicted values are compared with the earlier theoretical and experimental studies.

2 NUMERICAL MODELLING OF THE PROBLEM

The finite-element program OptumG2 [26] was used to perform the analysis. A typical model used in the analysis is presented in Fig. 1. A horizontal displacement is not allowed along the vertical boundary and no displacement is allowed along the bottom boundary. However, along the slope edge, the displacement is allowed in both the directions. The gradient of the soil slope is kept uniform throughout the slope. Based on the edge distance and the slope geometry, the area of the domain was selected as large enough to avoid the boundary effect. The minimum height and width of the domain are restricted to 8B and 16B, respectively. The width domain is increased to 25B on gentle slopes. A

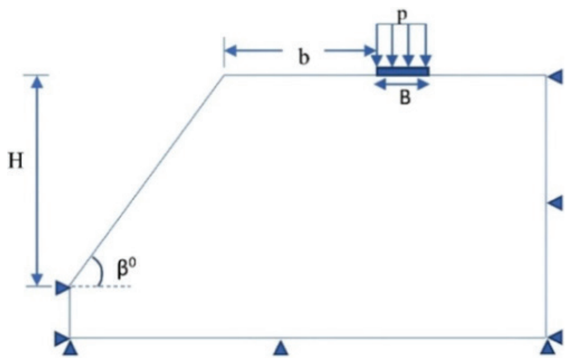


Figure 1. Representation of the foundation and the slope with boundary conditions.

number of iterations were performed to achieve stable results, and in every iteration the mesh was re-refined in the critical area to avoid the unnecessary refining of the mesh all over the domain area.

The strip footing has been modeled as a "plate" element. Under the plain-strain condition, the elastic plate element behaves like a standard Euler-Bernoulli beam element. To model the rigid footing, the stiffness of the plate has to be kept very high, compared to the soil. The clay was modelled using the elastic/perfectly-plastic Mohr-Coulomb model. The unconfined strength of the soil is assumed to be constant throughout the depth of the soil strata.

Three type of elements, namely, three-noded triangular elements for the lower bound analysis, six-node triangular elements for the upper bound, and a 15-node mixed Gauss element were used to model the soil. The lower-bound (UB) analysis follows the formulation of Makrodimopoulos and Martin [27-28], and the upper bound (UB) follows the formulation of Krabbenhøft et al. [29-30] in association with second-order cone programming. The lower-bound element of the three nodes uses a linear change in the stresses between the junction nodes. The lower-bound elements are linked by two zero-thickness elements to produce the statically admissible stress discontinuity between the junction nodes. For the maximum lower bound limit, the collapse load is evaluated by finding a collapse load that satisfies a statically admissible stress field defined by the stress equilibrium equations for triangular elements. Similar to the lower-bound element, the six-nodded upper-bound element uses the linear interpolation of the stresses, while unknown displacements were determined using quadratic interpolation. The displacements are continuous between the elements. The minimum upper-bound limit load satisfies a kinematic velocity field defined by the compatibility and the associated flow-rule equations for triangular elements and velocity discontinuities for soil-skirt interfaces. It is observed that the 15-node mixed Gauss element gives results very close to the average of the UB and LB analyses. Therefore, the analysis was carried out on a 15-node mixed Gauss element.

A total 5000 elements were initially used in the domain and this was increased to 70,000 in the final iteration. The element uses a cubic interpolation and quartic interpolation functions for the stresses and displacements, respectively. The footing is modeled as a perfectly rigid plate, which possesses an infinite stiffness. The six-node zero-thickness element was used to model the interface of the soil and the footing. The interface factor value was varied from 0.5 to 1, to consider the effect of the roughness of the footing. The interface factor is assumed to be 0 for a footing with a perfectly rough base. It was observed that the bearing capacity of a footing resting on a clay slope is changing noticeably with the interface-factor value. However, the change in BCR with the interface friction is very small.

The loading was applied in terms of a load multiplier directly over the footing, and it is increased continuously until the bearing capacity failure Before performing the bearing capacity analysis, a slope-stability analysis was performed to check the stability of the slope. The present study determined the bearing capacity considering the ultimate failure of the footing. Therefore, the settlement criterion has not been considered in the present study due to the inability of a limit analysis. The details of the modeling and the analysis are presented in a manual [26, 31].

3 PARAMETERS CONSIDERED IN THE ANALYSIS

All the parameters that influence the bearing capacity of a footing resting near the slope crest are considered in the analysis. These parameters include, the slope inclination, the edge distance, the average undrained shear strength of the soil and the footing properties. Earlier studies used ranges of undrained shear strength to represent the various consistencies of the cohesive soils [32]. Based on previous studies, a large range of undrained strength values are selected to reflect all the possible ranges of consistency. The ranges of the considered parameters are presented in Table 1. The unit weights of the soil are assumed to be 14–17 kN/m^3. The stiffness of the soil increases with an increase in the consistency of the soil. Therefore, the stiffness of the soil is also assumed to be varying from 2500 kN/m^2 to 14000kN/m^2 with the soil unconfined strength [33]. The edge distance (b) and the embedment depth (D) are normalized with respect to the footing width and stated as the edge-distance ratio (b/B) and the depth ratio (D/B), respectively.

Table 1. Range of various parameters considered in the study.

c_u (kPa)	Consis-tency	$c_u/(\gamma B)$	(b/B)	$\beta°$	(D/B)	No. of analysis
20	Soft	0.7	0, 1, 2, 3, 5	0–15	0, 0.5,1.0	60
40	Medium	1.4	0, 1, 2, 3, 5	0–35	0, 0.5,1.0	120
80	Stiff	2.8	0, 1, 2, 3, 4	0–45	0, 0.5,1.0	150
160	Very stiff	5.7	0, 1, 2, 3, 4	0–55	0, 0.5,1.0	180
320	Hard	10.6	0, 1, 2, 3	0–80	0, 0.5,1.0	204

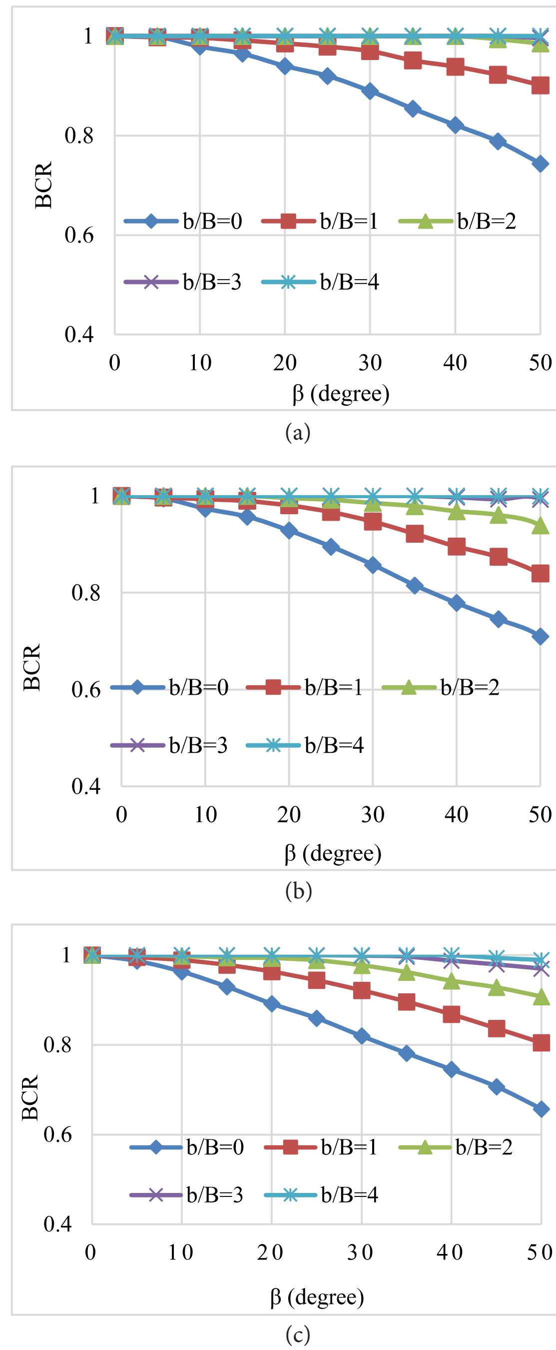


Figure 2. Effect of slope inclination on the BCR: (a) D/B=0, (b) D/B=0.5, (c) D/B=1.

4 RESULTS AND DISCUSSION

The variation in the bearing capacity with each of the factors is presented in detail and discussed separately. The change in the bearing capacity is determined in terms of the bearing capacity ratio (BCR). The BCR is defined as the ratio of the bearing capacity (or the bearing capacity factor) of a footing resting over the slope to the bearing capacity (or the bearing capacity factor) of the same footing resting over level ground under identical soil conditions. This means that the BCR also represents the relative bearing capacity of a footing resting on a slope to level ground.

4.1 The effect of the slope gradient

The typical variation in the bearing capacity ratio (BCR) with the change in the slope inclination for a footing with various embedment ratios (0, 0.5 and 1) resting on soil ($c_u/(\gamma B)$=2.85) is presented in Fig. 2. The bearing capacity as well as the BCR decreases nonlinearly with the increase in the slope inclination. The adverse effect of the slope on the BCR decreases with an increase in the edge distance. For a larger edge distance, the decrease in the BCR with the slope inclination is either very nominal or negligible. It is also observed that the decrease in the BCR with the slope inclination is relatively large in the footings resting below ground level compared to the footing resting on the ground surface.

The effect of slope inclination on the failure mechanism (shear dissipation contours) for a footing resting at an edge distance of 3B is presented in Fig. 3. It shows that the failure mechanism is independent of the slope inclination for gentle slopes and it is similar to the footing resting on level ground. These cases are similar to the failure mechanism assumed by Terzaghi. However, the interaction between the slope and the footing increases with an increase in the slope inclination, which decreases the mobilization of the soil strength on the level side of the footing and decreases the bearing capacity of the footing (Fig. 3 c-f). Consequently, there is a decrease in the BCR, as observed in Fig. 2. Cure et al. [34] have also observed similar trends for cohesionless soils. For gentle slopes, the failure is bearing-capacity failure (Fig. 3 a-c). For a very steep slope (50–70°), the slope failure is not representative (Fig. 3 e-f). In moderate-to-steep slopes (35–45°), a combined failure

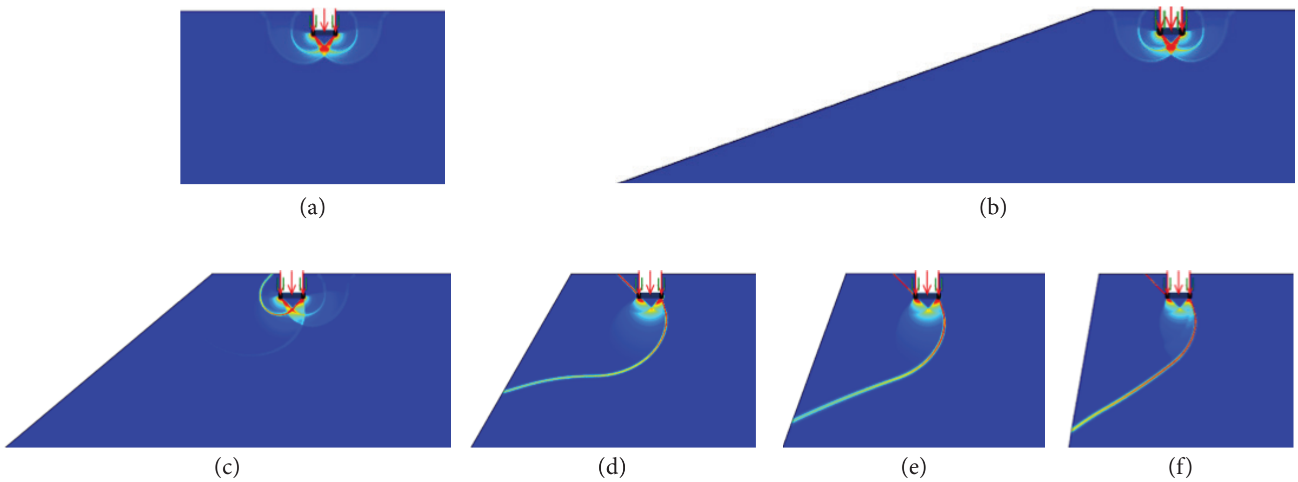


Figure 3. Effect of slope inclination on the failure mechanism: (a) β=0°, (b) β=20°, (c) β=30°, (d) β=40°, (e) β=50°, (f) β=70°.

mechanism coexists, where the slope failure as well as the bearing capacity failure occur together (Fig. 3 d). Even a footing on a steep slope can be stable if it is resting at a large edge distance, as it remains intact and unaffected by the slope. However, soil near to the slope edge and along the slope surface may fail and causes to the local slope failure.

4.2 The effect of the embedment depth of a footing

Fig. 4 shows the effect of the embedment depth of a footing on the BCR for a cohesive soil of $c_u/(\gamma B)$=2.85. Though the bearing capacity increases with an increase in the embedment depth of the footing, the BCR decreases with an increase in the depth of the footing.

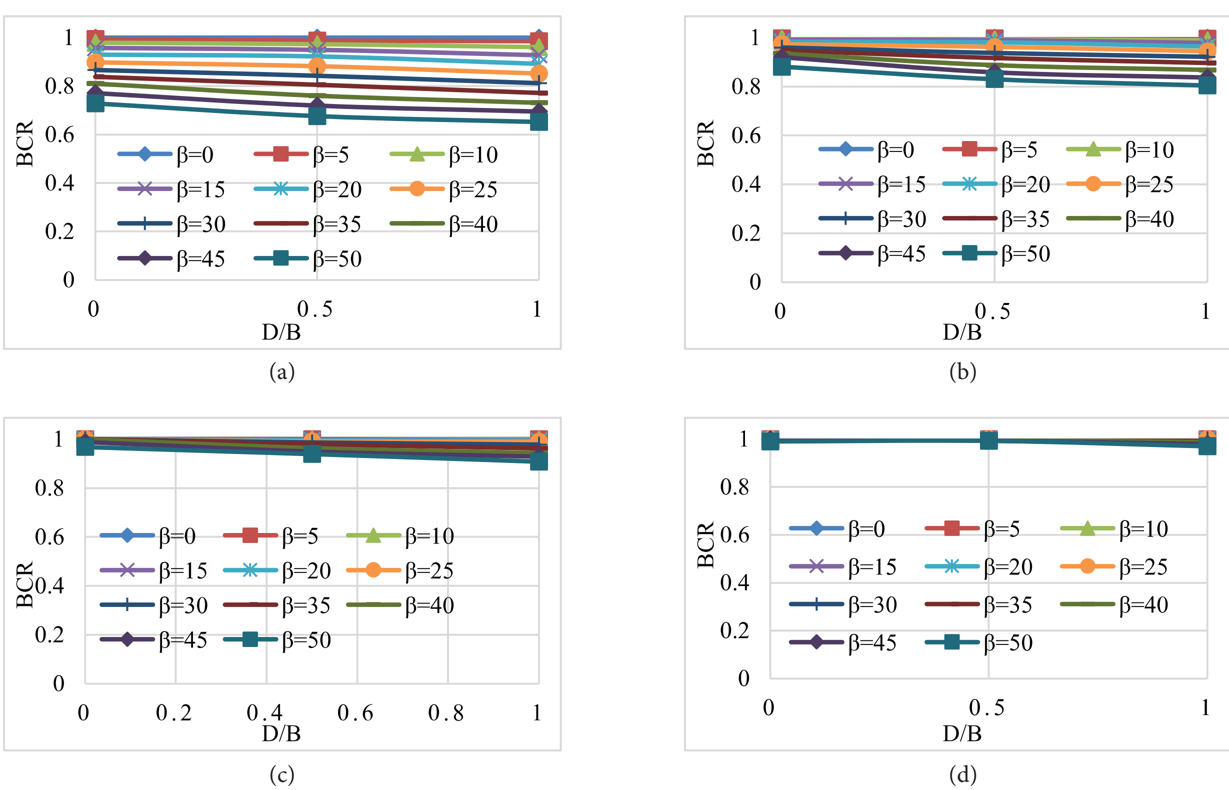


Figure 4. Effect of embedment depth of the footing on the BCR: (a) b/B=0, (b) b/B=1, (c) b/B=2, (d) b/B=3.

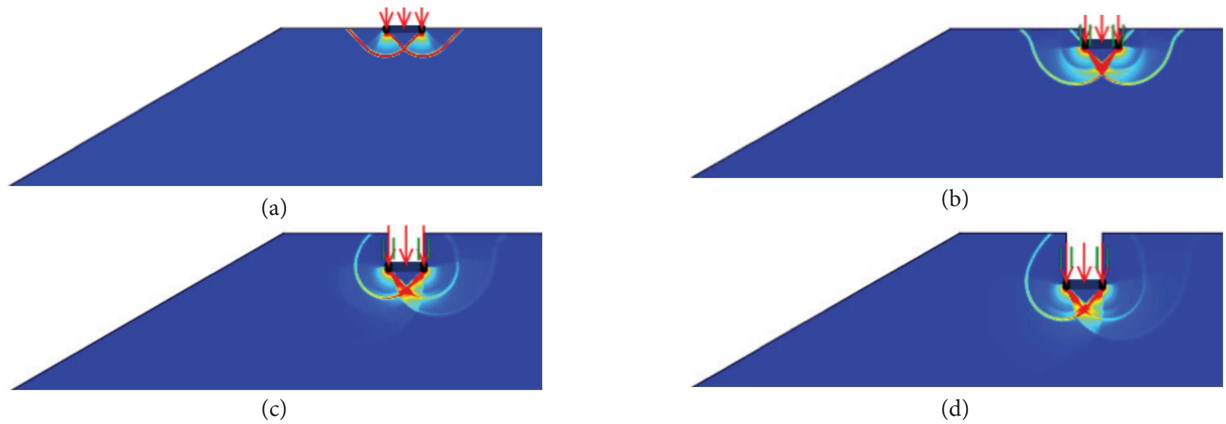


Figure 5. Effect of the embedment depth of a footing on the shear dissipation (a) D/B=0.0, (b) D/B=0.5, (c) D/B=1.0, D/B=1.5.

The influence of the footing depth becomes more noticeable with an increase in the steepness of the slopes, but reduces with an increase in the edge distance. The rate of decrease in the BCR with the depth of the embedment is relatively high when the depth ratio increases from 0 to 0.5, but it reduces when the depth ratio increases from 0.5 to 1. It is expected that the rate of decrease in the BCR with the depth of the footing will decrease further with an increase in the depth of the footing from 1 to 1.5. The contribution of the surcharge loading to the bearing capacity is a maximum for level ground and it reduces with an increase in the slope inclination. Narita and Yamaguchi [35] also found that the effect of the embedment depth of the footing is significant for steep slopes and a low setback distance.

The effect of the embedment depth on the failure mechanism is presented in Fig. 5. At a shallow depth (D/B=0 and 0.5), the failure mechanism of the footing resting on a slope is similar to Terzaghi's failure mechanism (Fig. 4 a, b). However, with an increase in the footing depth, the difference in the failure mechanism becomes significant. The footing resting on the ground surface possesses a small load-carrying capacity and a very small area of foundation soil involves and contributes to the bearing capacity (Fig. 5 a). Therefore, the bearing capacity is independent of the slope (Fig. 5 a). While in the case of a greater embedment depth, the large soil area contributes to the bearing capacity. The failure surface also extends in the lateral direction and a large edge distance is required to cover that much area to mobilize the soil strength optimally (Fig. 5 b, c). Therefore, the BCR reduces with an increase in the embedment depth of the footing, as depicted in Fig. 4.

The influence of the embedment depth on the BCR becomes less evident with an increase in the edge distance. This is due to the fact that for an edge distance, more than or equal to the critical edge distance, the BCR remains almost constant, irrespective of the slope inclination and the depth ratio of the footing. Narita and Yamaguchi [34] have made similar observations for cohesionless soils.

4.3 Effect of the soil strength

The typical variation in the normalized bearing capacity (BCR) with soil strength for a footing with an embedment ratio (D/B) of 1 is presented in Fig. 6. It shows that the BCR increases with an increase in the $c_u/(\gamma B)$. The change in BCR is significant when $c_u/(\gamma B)$ increases from 1.4 to 2.8, but a further increase in $c_u/(\gamma B)$ only makes a negligible improvement in the BCR. Similar observations have been made for the other embedment ratios (D/B=0, 0.5 and 1.5). However, it was observed that the effect of the soil strength on the BCR is increasing marginally with the footing depth. It can also be observed that the effect of the soil strength is more prominent in a steep slope, but it reduces with a decrease in the steepness of the slope. The effect of the soil strength on the BCR reduces with a further increase in the edge distance. With an increase in the edge distance, the footing becomes independent of the slope and the condition becomes similar to level ground. Therefore, the influence of the strength becomes negligible with a decrease in the slope inclination, and it increases the BCR close to 1, irrespective of the slope inclination.

The typical effect of soil strength on the failure mechanism for a footing with an embedment ratio of 1 resting over a soil slope of 300 at an edge distance of 2B is presented in Fig. 7. At low strength ($c_u/(\gamma B)$=0.7), the failure is a global slope failure. However, with an increase in the strength of the soil, the failure mode changes to bearing-capacity failure. The contribution of the soil located on the level side of the footing to the bearing capacity increases with an increase in the soil strength, and the failure becomes a bearing capacity

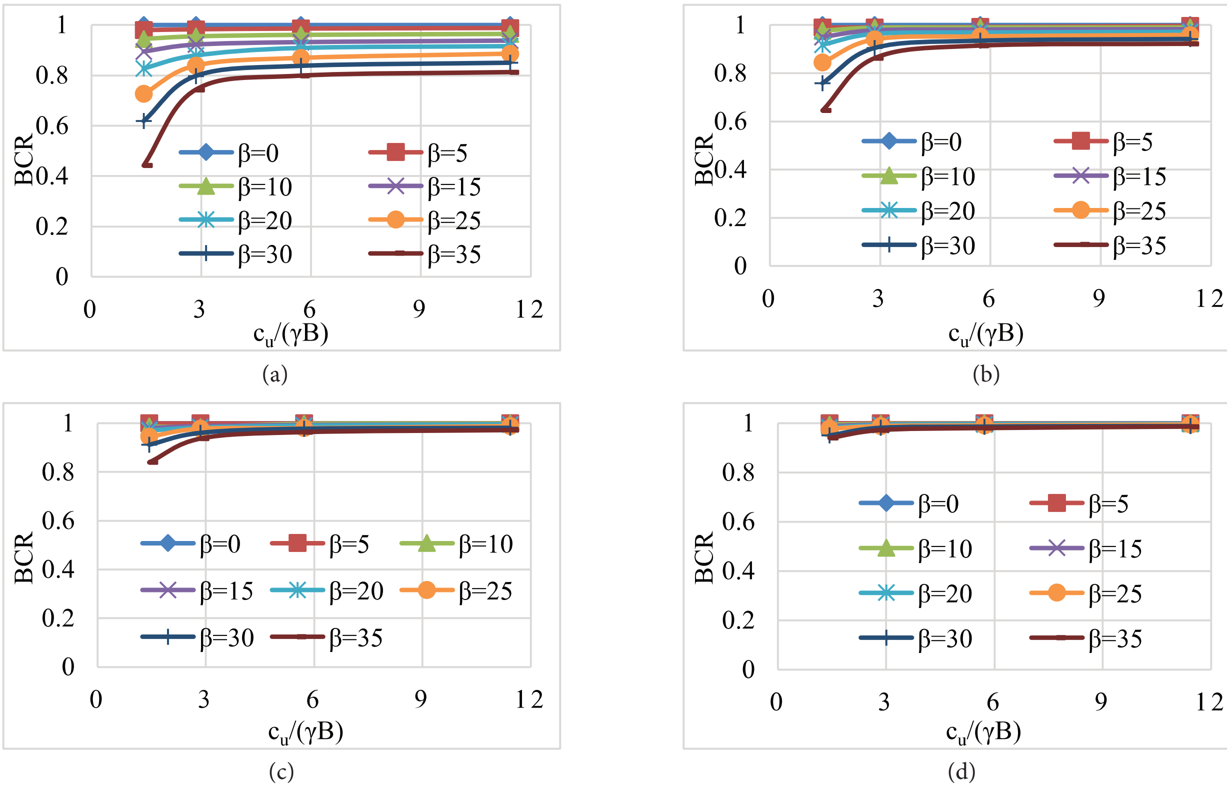


Figure 6. Effect of soil strength on the relative bearing capacity: (a) b/B=0, (b) b/B=1, (c) b/B=2, (c) b/B=3, (c) b/B=4.

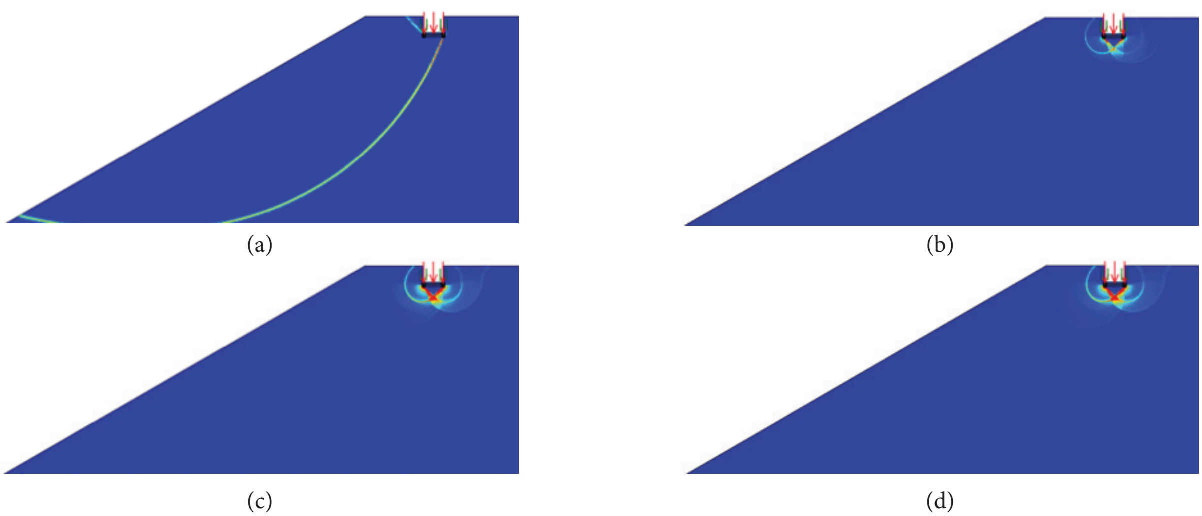


Figure 7. Effect of soil strength on the failure mechanism: (a) $c_u/(\gamma B)$ =0.7, (b) $c_u/(\gamma B)$ =1.4, (c) $c_u/(\gamma B)$ =2.8, (d) $c_u/(\gamma B)$ =5.7.

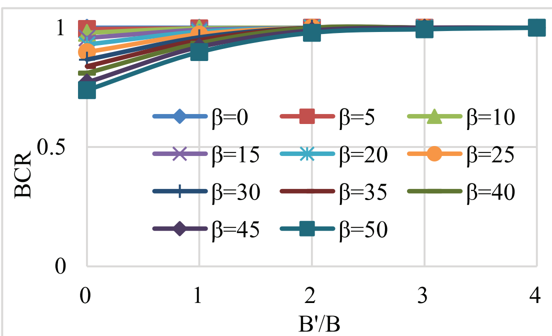
failure. It can also be stated that the severe effect of the slope decreases with an increase in the strength of the soil. Therefore, the edge distance at which the strength of the soil mobilizes optimally decreases with the increase in the soil strength. Although the magnitude of the safe slope inclination increases with the soil strength, the critical edge distance is found to decrease.

4.4 Effect of the edge distance

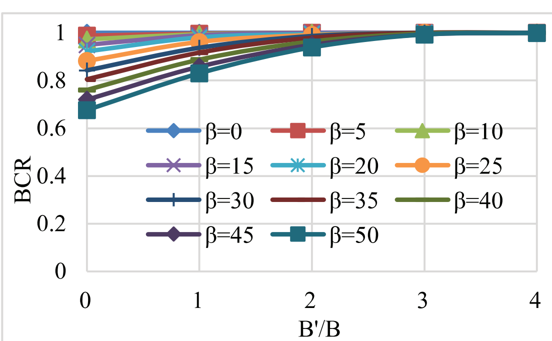
The typical variation in the BCR with edge distance is presented in Fig. 8 for a footing of different embedment ratios resting over a soil having $c_u/(\gamma B)$=2.85. The degree of strength mobilization of the soil located on the level side increases with an increase in the edge distance.

Consequently, it increases the bearing capacity and the stability of the footing. The footing located near to the slope fails due to the local shear failure and the mode of failure changed to general shear or punching shear failures with an increase in the edge distance.

At a particular edge distance, both sides of the soil contribute with an equal amount and the footing behaviour becomes independent of the slope. At this critical edge distance, the failure pattern becomes symmetrical about the footing axis. At a small edge distance and a steep slope, the failure is one sided (slope side only), and the soil on the side of the level ground does not fully contribute to the bearing capacity. Therefore, the measured BCR is small for a footing resting precisely on a slope crest or near to the slope crest. The degree of strength mobilization of the soil located on the level side increases with an increase in the edge distance (Fig. 9). The passive resistane increases with an increase in the edge distance, resulting in the increases in the bearing capacity [36]. Varzaghani and Ghanbari [37] also stated that the stiffness of the foundation increases with the setback distance increases, which leads to an increase in the bearing capacity of the soil.



(a)



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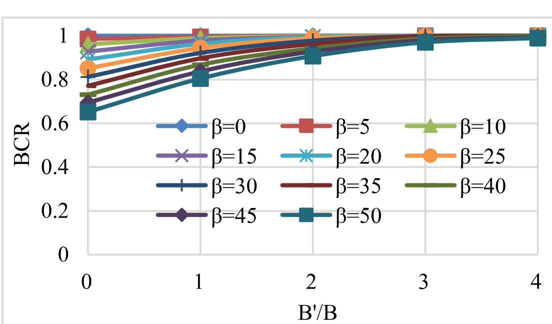
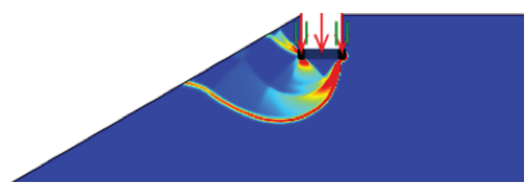


(c)

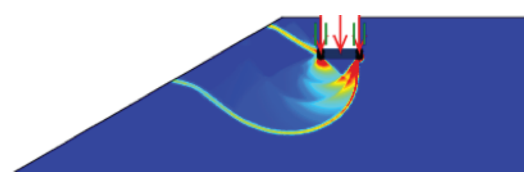
Figure 8. Effect of edge distance on the bearing capacity enhancement for a footing: (a) D_f/B=0, (b) D_f/B=0.5, (c) D_f/B=1.0.

The typical effect of edge distance on the failure mechanism is shown in Figure 9. It shows that the failure mechanism changes significantly with an increase in the edge distance. The elastic wedge below the footing is unsymmetrical for a small setback and becomes a symmetrical and higher edge distance. Also, the shear dissipation on the level side of the footing also increases with an increase in the edge distance. The footing becomes independent of the slope with an increase in the edge distance, and at a particular edge distance, the footing becomes independent of the slope inclination.

On the basis of the numerical analyses, the limiting edge distance is identified for the various combinations



(a)



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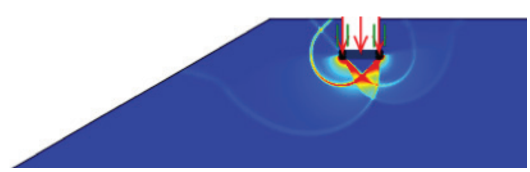

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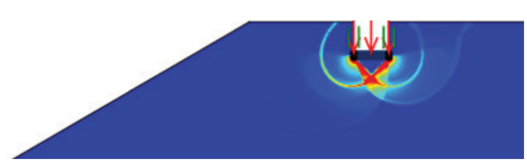


(d)

Figure 9. Effect of edge distance on the failure mechanism: (a) b/B=0, (b) b/B=1, (c) b/B=2, (d) b/B=3.

of parameters. The limiting edge distance evaluated in the present study is presented in Table 2. The increase in the critical edge distance is primarily observed (Table 2) due to the increased slope inclination in the soils, rather than an increase in the soil strength as even a steep slope is stable in cohesive soils due to the higher strength.

Table 2. Limiting edge distance for strip footing on a cohesive soil slope.

Undrained shear c_u (kPa)	$c_u/(\gamma B)$	β°	Depth ratio (D/B)	Critical b/B	Optimum b/B
20	*0.7*	0–20	0–1.0	1–5.0	1.0–2.5
40	1.4	0–35	0–1.0	1.0–4.5	1.0–2.0
80	2.8	0–50	0–1.0	1.0–4.5	1.0–1.5
160	5.7	0–55	0–1.0	0.5.0–4.0	0.5–1.0
320	11.4	0–80	0–1.0	0.5.0–3.0	0.5

The International Residential Code [38] and the Uniform Building Code [39] suggest the maximum edge distance can be a minimum of H/3 and 12 m. The Indian standard IS: 1904-1986 recommends maintaining a minimum distance of 0.9 m from the slope surface. However, the code does not provide any guidelines to locate a footing resting near to the slope crest (edge distance). In the present study, the critical edge distance is found to vary from 1 m to 9 m (or 0.05H to 0.45H). However, from the present numerical study, it is observed that the critical setback distance depends not only on the slope height, but also on the slope inclination, the depth of footing, the width of footing, and the strength of the soil ($c_u/(\gamma B)$).

However, in practice, it is not always possible to locate a footing at a critical setback distance. Therefore, an optimum value of the edge distance needs to be identified, at which the reduced bearing capacity (due to the slope effect) is reasonably negligible. In the present study, the optimum value of the edge is determined by considering a BCR value equal to 0.75–0.8 and varies from 0.5B to 2.5B (0.05H to 0.05H), depending on the footing depth, the soil strength and the slope inclination. The obtained values of the optimum setback (0.05H to 0.05H) are significantly less than the values suggested in the codes. The significant difference highlights the fact that a constant value of the edge distance, as suggested in the standards/codes, irrespective of the soil properties, foundation characteristics and slope geometry is not appropriate, and needs to be improved.

5 COMPARISON WITH THE BEHAVIOUR OF A FOOTING RESTING ON COHESIONLESS SOIL SLOPES

The results of the present study have been compared with the results of Shukla and Jakka [2], where footings resting on cohesionless soil slopes were studied in detail. From the comparison of the results, it is observed that the BCR decreases with an increase in the slope inclination and the embedment depth in both cohesive and cohesionless soil slopes. However, the influence of the soil strength on the critical edge and the BCR is the opposite in cohesive and cohesionless soils. Unlike cohesionless soils, the critical edge distance decreases with an increase in the strength of the cohesive soils. Furthermore, the range of the critical edge distance is found to be narrow (1B to 5B) in cohesive soils, compared to cohesionless soil, where it is varying from 2B to more than 12B. Despite the increase in the bearing capacity with the soil strength in cohesive soil, as well as cohesionless soils, the BCR increases with the soil strength in cohesive soil and decreases in cohesionless soil.

The effect of the strength parameters (φ, $c_u/(\gamma B)$) on the BCR and the bearing capacity factor for a footing resting at an edge distance of 1B is presented in Fig. 10. Further discussions are made here to understand the reasons for the observed opposite trends in the case of the critical edge distance and the BCR. The bearing capacity factor ($N_{\gamma q}$) in cohesionless soil increases exponentially with the soil strength in cohesionless soils, especially for level ground (Fig. 10 a), while its increase rate is moderate or low for steep slopes. As the BCR represents the normalized bearing capacity with respect to level ground, the BCR decreases with an increase in the soil strength due to a large and sharp increase in the bearing capacity in level ground compared to the slopes (Fig. 10 a). However, in clayey slopes, the bearing capacity factor (N_{cq}) increases sharply for steep slopes in comparison to gentle slopes (Fig. 10 b). This opposite observation in cohesionless soil and cohesive soil leads to a difference in the observations made in the BCR (Fig. 10 c-d).

To further understand the contradictory observations, the failure mechanisms of footings in both types of soil have been studied. The variation in the failure mechanism for cohesive soil and cohesionless soil is presented in Figs. 7 and 11, respectively. The area contributing to the bearing capacity increases with the increase in the internal friction of cohesionless soil and the undrained strength of cohesive soil. The increase in the area within the rupture surface leads to an increase in the bearing-capacity factor. The contribution from the level side of

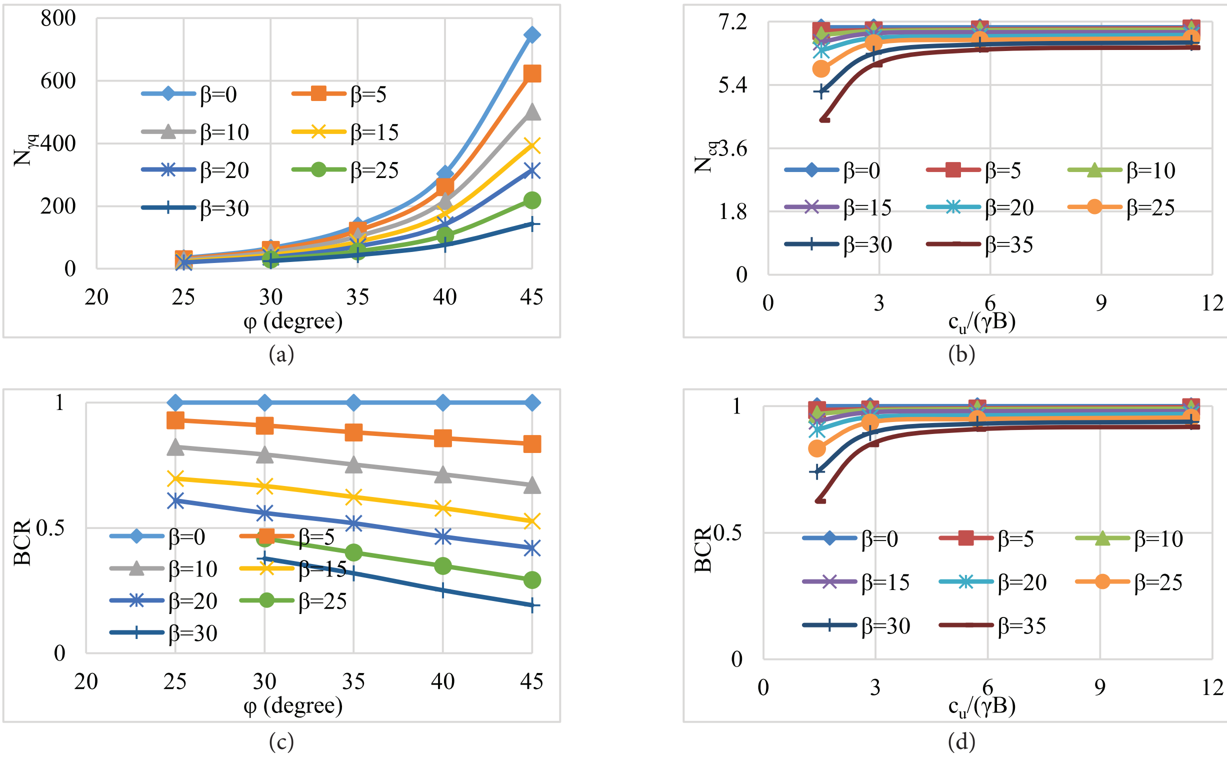


Figure 10. Effect of strength parameters: (a) on the bearing capacity factor in cohesionless soil, (b) on the bearing capacity factor in cohesive soil, (c) on the bearing capacity ratio in cohesionless soil, (d) on the bearing capacity ratio in cohesive soil.

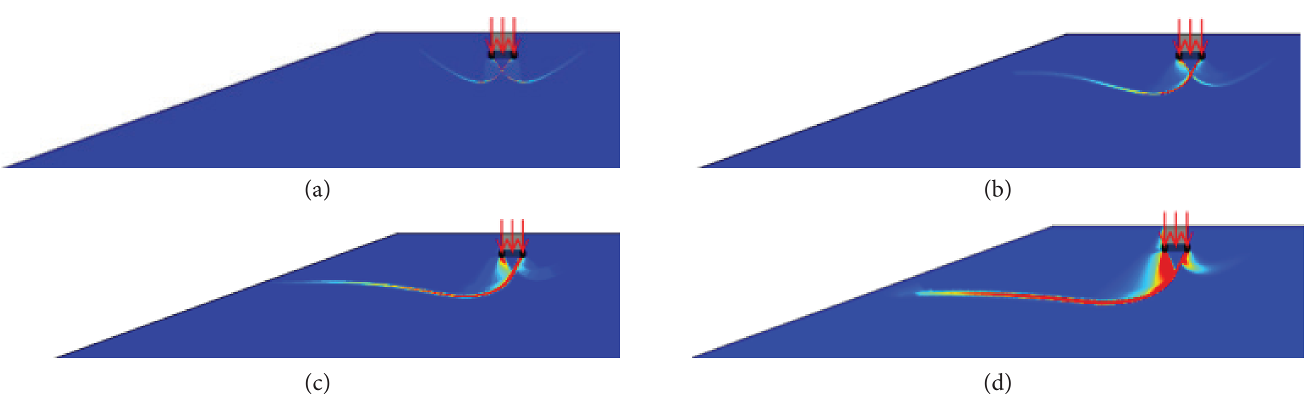


Figure 11. Effect of the angle of internal friction on the failure mechanism: (a) φ=25°, (b) φ=30°, (c) φ=35°, (d) φ=40°.

the footing reduces sharply in cohesionless soils (Fig. 11 a-d). The reduction in the area of the shear zone on the level side of the footing contributes to a reduction in the BCR with an increase in the angle of the internal friction of the soil. This means that the adverse effect of the slope reduces with an increase in the soil-strength parameter in cohesive soil, unlike in the cohesive soil.

In cohesionless soils, the slip surface is a log spiral and extends to longer lateral dimensions and greater depths than the cohesive soil. This contributing area increases significantly with the angle of the shearing resistance of the soil. Therefore, a larger edge distance is required in cohesionless soils. In cohesive soils, the failure surface is circular and only a small area contributes to the bearing capacity. The slip surface extends to a very small area beyond the footing width in cohesive soils. Also, the failure mechanism changes from slope failure to bearing-capacity failure with an increase in the strength for a given edge distance. Therefore, the critical edge distance decreases with an increase in the soil strength in cohesive soils.

6 PREDICTION OF THE BEARING CAPACITY

The numerical analysis results were used to carry out a regression analysis and an artificial neural network (ANN). The purpose of using both of the methods is to predict the BCR and the bearing-capacity factor accurately. It is observed from the numerical analyses that a total of four independent variables (i.e., b, β, $c_u/(\gamma B)$ and D/B) influences the bearing capacity factor of a footing resting near to the slope crest. The linear multiple regression (LMR) analysis was carried out initially to predict the BCR and N_{cq} . The regression coefficient (R^2) is found to be 0.81 and 0.68 for N_{cq} and BCR, respectively. This means that LMR is not efficient to model and predict the bearing capacity of a footing on a slope as the relationship between the independent variables and the dependent variable is nonlinear. Therefore, it is necessary to consider the nonlinearity in developing regression equations. To consider the nonlinearity, it is assumed that Ncq and BCR are dependent not only on these four variables, but also upon a number of other variables. These other variables are a function of the initially assumed four independent variations. Considering these derivatives, a nonlinear multiple regression analysis (NMRA) and correlation analysis, along with other statistical tests, were performed to derive an equation to predict the bearing-capacity factor (N_{cq}) considering the combined effect of the soil cohesion and the surcharge loading above the footing base. Another equation is also developed to determine the change in the bearing capacity (BCR).

Various types of functions, such as linear, exponential and polynomial functions, were initially assumed, and finally the best relationship was used to develop the equation. Initially, a total of 24 variables, which are functions of four independent variables, were considered in the regression analysis to develop equations to compute BCR and N_{cq}. Co-linearity can produce serious problems and ordinary least-squares approximations can be very different from the true values. Therefore, the degree of multi-collinearity was used to remove the insignificant variables. It was found that only eight variables out of 24 affect the N_{cq}) significantly. Later, these eight variables were used to develop an equation to predict N_{cq}. It was found that R^2 reduces from 0.994 to 0.975, when a number of insignificant variables were removed from the analysis. This reduces the number of variables in the regression equation significantly, without reducing the R^2 value by much. It ensures that all the assumed dependent variables are not affecting the bearing capacity significantly with respect to those assumed in the initial phase of the regression analysis. Similarly, 13 derivatives were used in the development of an equation to predict the normalized bearing relative to the level ground (BCR) out of 32 derivatives. It reduces the regression coefficient from 0.992 to 0.953. The ultimate bearing capacity of a footing located adjacent to a slope can be determined precisely by using either Eqn. 4 or Eqn. 5. Therefore, it is suggested to use the BCR values (using Eqn. 2) and Eqn. 4 to determine the effect of the slope geometry on the footing bearing capacity of a footing on a slope.

In equations (1) to (5) c_u is the undrained cohesion of the soil, N_{cq} is the bearing-capacity factor, β is the slope inclination in radians, D is the depth of the footing, B is the width of the footing, γ is the unit weight of the soil and b is the edge distance.

$$N_{cq} = 5.18 - 2.2\beta + \frac{b}{B}\beta(1 - 0.016\frac{b}{B} + 0.27\frac{D}{B}) + 3.6\frac{D}{B}(1 - 0.48\frac{D}{B} - 0.28\beta) + \frac{c_u}{\gamma B}\beta(0.4 - 0.03\frac{c_u}{\gamma B})$$
$$-1.85\beta^2(1 - 0.18\beta - 0.04\frac{c_u}{\gamma B} - 0.14\frac{D}{B}) \quad (1)$$

$$BCR = 1 - 0.4\beta + 0.065\frac{c_u}{\gamma B}\beta(1 - 0.068\frac{c_u}{\gamma B}) + 0.17\frac{b}{B}\beta(1 - 0.15\frac{b}{B}) - 0.28\beta^2(1 - 0.038\frac{c_u}{\gamma B} - 0.2\beta - 0.12\frac{D}{B})$$
$$-0.072\frac{D}{B}\beta(1 - 0.22\frac{b}{B}) \quad (2)$$

$$\mathrm{N}_{cq} \text{ on slope} = N_{cq} \text{ on level ground (BCR)} \quad (3)$$

$$\text{Ultimate bearing capacity}_{(slope)} = N_{cq(slope)} c_u \quad (4)$$

$$\text{Ultimate bearing capacity}_{(slope)} = (5.16c_u + \gamma \mathrm{D})\mathrm{BCR} \quad (5)$$

Hansen [40] and Vesic [41] have also developed equations considering the slope inclination and $c_u/(\gamma B)$ only. Later, Bowles [42] also developed an equation and the soil strength was considered in the developed equation. Recently, Georgiadis [7] proposed an equation to calculate Nc (slope) based on a rigorous finite element analysis. However, the developed equation is complex and does not consider the effect of the footing depth that is an important factor affecting the bearing capacity. The presented Eqns. 1 and 2, consider the effects of all these factors together in single equation to determine the effect of the slope inclination on the bearing capacity. The slope height was not considered in the presented equation as only the foundation failure was considered in the analysis, not the slope failure (toe and base failure). Initially, the slope height (H/B) was also considered in the analysis, but it was observed that its effect is very nominal with respect to the bearing capacity. However, in marginally stable slopes, the slope height has a significant influence. In a marginally stable slope, the slope failure induced by the footing loading governs the capacity, not the shear failure, which can be clearly seen from Figs. 3(f) and Fig. 7(a).

A linear multiple regression analysis was also performed to determine the critical factors affecting the bearing capacity. Based on the P values, the order of significant factors affecting the bearing capacity is also evaluated. The order of the factors is $c_u/(\gamma B)$ > Slope inclination > Embedment depth of footing > Edge distance. The relative importance of all these factors was again assessed based on Garson's algorithm [43], and a similar order was obtained in this case also. The relative importance of these variables is presented in Table 3. Acharyya and dey [19] have also provided a similar rating for the c-φ soil slope based on an ANN. This indicates that the bearing

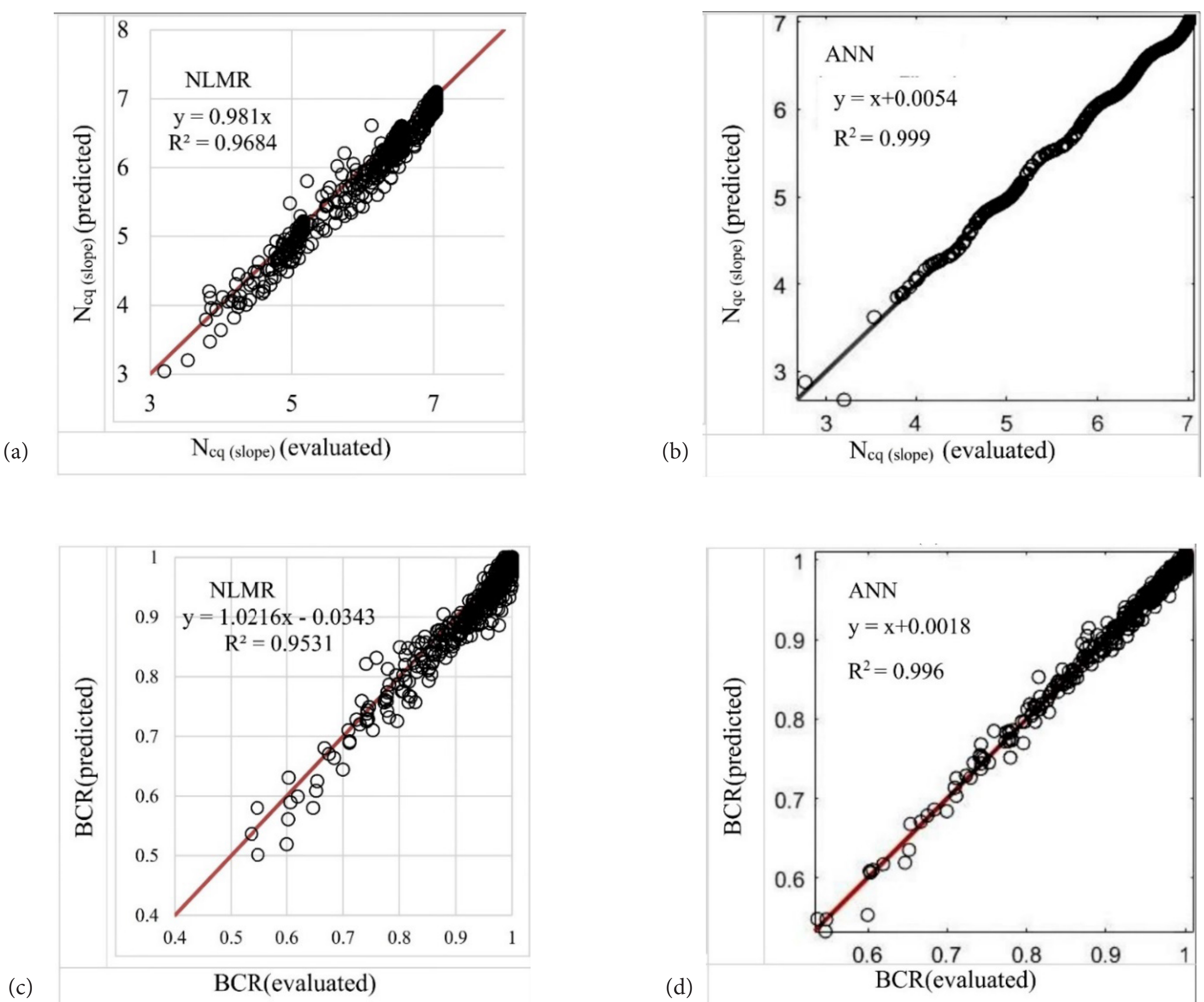


Figure 12. Comparison of the predicted values with the determined values:
(a) N_{cq}(slope) using NLMR analysis, (b) N_{cq}(slope) using ANN, (c) BCR using NLMR analysis, (d) BCR using ANN.

capacity is greatly affected by the soil strength, followed by the steepness of the slope, which is a destabilizing factor, and the embedment depth of the footing and the edge distance have the least influence on the BCR. In contrast to cohesive soils, the influence of the depth ratio is found to be less than the edge distance in cohesionless soils. This is due to the fact that the slip line/fracture surface spread over a larger lateral extent in the cohesionless soil than in the cohesive soil, which makes the lateral dimension (edge distance) more important than the vertical dimension (depth of footing).

Table 3. Relative importance of all four variables.

Factors	*Rating*	Relative importance
$c_u/(\gamma B)$	1	45.6 %
Slope inclination (β)	2	40.5 %
Depth ratio (D/B)	3	8.5 %
Edge distance (b/B)	4	5.4 %

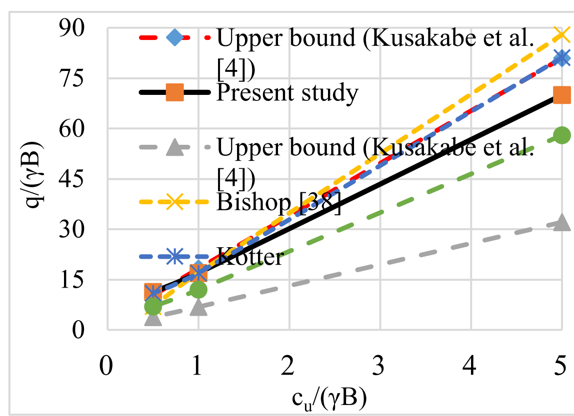
An artificial neural network (ANN) model was also developed to determine the bearing capacity of the footing on the slope using the Levenberg-Marquardt algorithm and MATLAB. The ANN was added to compare the efficiency of the regression analysis with a regression analysis. In the model, 70% of the data (420) was used for training purposes and the remaining 30% of the data (180) was used for testing and validation purposes. Similar to the regression analysis, a total of four independent variables (i.e., b, β, $c_u/(\gamma B)$ and D/B) were used as the input, and BCR and Ncq were the output variables. Eight hidden layers were used in the study. Each hidden layer had 10 hidden neurons, which is based on the formula $2(n + 1)$. Here, 'n' is the number of input variables, which is equal to four in the present cases. A comparison of the predicted values with the determined values of N_{cq} with a nonlinear multiple regression analysis (NLMR) and the ANN is presented in Figs. 12 (a) and 12 (b), respectively. Similarly, a comparison of the predicted values with the determined values of the BCR with the NMRA and ANN is presented in Figs. 12 (c) and 12 (d), respectively.

Both methods predict the N_{cq} and BCR accurately (as R^2 is relatively high for both methods); however, the efficiency of the ANN of is found to be relatively higher than the NMRA. This means the ANN modeled the nonlineariarity more accurately than the MMRA. However, the ANN method has many limitations due the black-box approach [44]. NLMR also has an advantage over ANN, as it gives simple equations to predict the bearing capacity factor and BCR, which can be easily used by researchers and engineers.

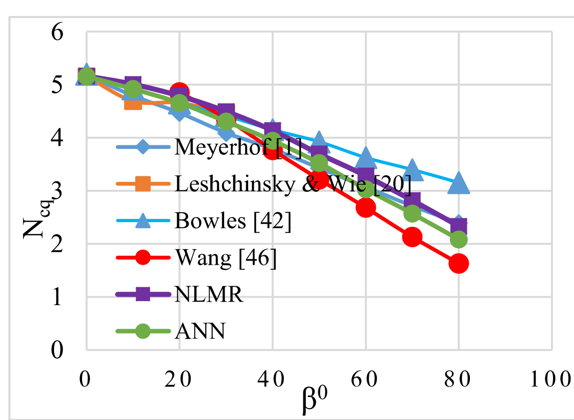
7 VALIDATION OF THE PROPOSED EQUATION

To validate the presented equation, the predicted values are compared with the results of previous studies and are presented in Fig. 13. Fig. 13 (a-b) presents the normalised bearing capacity ($q/\gamma B$) for various values of $c_u/(\gamma B)$ for cohesive soil. These plots show that the bearing-capacity values are close to those determined by Kusakabe et al. [4]. Kusakabe et al. [4] also presented the ($q/\gamma B$) values determined by other researchers, i.e., Bishop [45], Kotter and Bishop. These values have also been used for comparison purposes. As seen from Fig. 13 (a), the solution obtained with the presently used finite element model is less than the upper-bound solution of Kusakabe et al. [4], Bishop [45] and Kotter's solution. However, the values of the present study are found to be always greater than the lower-bound solution of Kusakabe et al. [4] and Fellenius's solution.

Fig. 13 (b) shows that the bearing capacity factor values predicted from the NLMR analysis are close to those determined in the numerical analysis and the previ-



(a)



(b)

Figure 13. Comparison of the predicted values with previous studies: (a) Effect of $c_u/(\gamma B)$, (b) Effect of slope inclination.

ously determined values of Meyerhof [1], Bowles [42] and the experimental study of Wang [46]. The values of the predicted bearing capacity factor are close to the experimental study result of Wang [46] for a small slope inclination. However, the predicted values are slightly higher than the experimentally determined values of Wang [46] and lower than the values of Bowles [42]. The predicted bearing capacity factors are found to be close to the values proposed by Meyerhof [1]. However, for steep slopes ($\beta > 40°$), the values are lower than the Meyerhof [1] values. This similar observation was made in previous studies of a cohesionless soil slope [47-48]. The values predicted from the ANN are less than the earlier studies, except for the experimentally determined values of Wang et al. [40]. Similar to the present study, a number of other studies also found that small-scale model testing generally underestimates the bearing capacity of a footing on a slope [49].

8 CONCLUSION

The presence of a slope, close to a footing, influences the bearing capacity of the footing. The severity of the slope effect depends on the footing location, the soil strength and the slope geometry. However, the slope effects are found to be independent of the soil strength in the case of a stable slope (in the case of bearing-capacity failure). The bearing capacity is a minimum when the footing is resting exactly on the slope crest and it increases with the increase in the edge distance. The critical edge distance varies from 1B to 5B, depending on various factors. In contrast to the present finding, currently codes suggest the critical setback distance mainly based only on the slope inclination and the slope height. The range of critical setbacks in cohesive soils is significantly less than in cohesionless soils. The increase in the bearing capacity with the edge distance is relatively large and non-linear in the case of the steep slopes and footings of the higher depth of the embedment. The critical value of the edge distance is identified in the present study and it is found to increase with an increase in the slope inclination and the embedment depth of the footing.

In gentle slopes, shear failure governs the footing capacity. Two failure mechanisms, i.e., slope failure and bearing-capacity failure, can co-exist in steep slopes. In a few cases, the slope fails due to the stress generated from the footing loading itself. The influence of the strength parameter on the BCR and the critical edge distance is different in cohesive soils, compared to cohesionless soils. The BCR decreases with an increase in the strength of a cohesionless soil, whereas it increases with an increase in the undrained strength in cohesive soils. In contrast to cohesionless soils, the critical edge distance is found to decrease with an increase in the undrained strength of the cohesive soil. This contradictory behavior is ascribed to the differences in the failure mechanisms of the cohesive and noncohesive soils. The range of the critical edge distance is found to vary from 1B to 5B in cohesive soil.

Both the ANN and NLMR analyses were used to predict the BCR and Ncq (slope). The developed nonlinear regression equations are found to be efficient in predicting the bearing capacity factor on the slope and the BCR accurately. However, the ANN is found to be relatively more efficient at predicting the BCR and the N_{cq} (slope) values, compared to the NLMR analysis.

Acknowledgment

Authors are thankful to the anonymous reviewers for their valuable suggestions. Authors are also grateful to the Optum Computational Engineering for providing the OptumG2 program free of cost and their constant support throughout the study.

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