CRITICAL SETBACK DISTANCE FOR A FOOTING RESTING ON SLOPES

Rajesh Prasad Shukla
IIT Roorkee,
Department of Earthquake Engineering
Roorkee, India
E-mail: rpshukla.2013@iitkalumni.org

Ravi Sankar Jakka *(corresponding author)*
IIT Roorkee,
Department of Earthquake Engineering
Roorkee, India
E-mail: rsjakka@iitr.ac.in

Keywords

bearing capacity ratio, cohesionless soil, footing, setback distance, slopes

Abstract

Structures are often constructed on slopes in hilly regions, which results in a lack of soil support on the sloping side of the footings. This causes a reduction in the bearing capacity of the footings. Though there are number of studies about foundations on slopes, most of these studies are confined to surface footings only (i.e., without the depth of embedment). Furthermore, there is no consensus in the literature over the influence of the setback distance on bearing capacity. This paper presents the results of finite-element analyses on a strip footing resting on stable slopes. A very large number of possible soil slopes with different footing depths were analysed. From the results it is found that the critical setback distance increases with an increase in the internal friction angle of soil, the depth of the footing and the slope gradient. The critical setback distance is varying between 2 to 4 times the footing width for soils with a low internal friction angle, while it is more than 10 times the footing width for soils with a higher internal friction angle. A regression equation is also developed based on the outcomes of the study. The developed equation is able to predict the influence of various parameters affecting the bearing capacity of a footing resting over the slopes. The results are compared with earlier experimental and numerical studies.

1 INTRODUCTION

Structures are often built on or near a slope for several reasons, such as the unavailability of level ground, to make the structure more appealing, to construct a foundation for bridges, etc. The presence of a slope significantly affects the load-carrying capacity of a footing [1]. A footing constructed on slopes, lacks soil support on one side, which results in the failure of the foundation at a lower load compared to the identical foundations on level ground. This means that the ability of soil to support structures (i.e., bearing capacity) reduces. An estimation of the bearing capacity after accounting for the slope and foundation geometry is difficult. In these cases, the determination of the bearing capacity is different from general cases, as various additional factors influence the bearing capacity.

For foundations located on a slope, the plastic zone on the side of the slope is relatively smaller than those of similar foundations on level ground [2]. Thus, the ultimate bearing capacity of the foundation is correspondingly reducing in almost all cases. The soil strength on the slope side is fully mobilised before the complete mobilization of the soil strength on the side of the level ground, and consequently the footing fails without reaching its ultimate collapse load. The geometry of the slopes and the soil characteristics are important factors influencing the mobilization of soil strength on either side of the slope. The geometry of the slope includes the setback distance (B'), the slope gradient (horizontal: vertical) and its height. The soil characteristics include the type of soil and the strength parameters of the soil (c and φ).

A number of studies considered the effect of the slope on bearing capacity of the footings. Some of the studies considered the effect of the setback distance on bearing capacity of the footing. Meyerhof [2] proposed bearing-capacity factors for a footing resting near slopes. Hansen [3] presented slope-correction factors for a footing resting precisely on the slope crest. However, the presented solution cannot be used for a footing resting with some distance from the slope crest. Shields et al. [4] experimentally evaluated the resultant bearing-capacity factor, $N_{\gamma q,}$ (the combined effect of overburden resistance and soil self-weight), for a footing resting over a slope gradient of 2 Horizontal: 1Vertical (2H:1V) and 1.5H:1V in cohesionless soil. It was reported that Meyerhof [2] overestimates the bearing capacity factors for a footing resting near the slope. This is due to fact that Meyerhof [2]considered equal mobilization of the soil strength on both sides of the slope. Kusakabe et al. [5] used the upper bound to estimate the bearing capacity. Model tests were also conducted, but the maximum setback distance was restricted to the footing width (B). Graham et al. [6] used method of stress characteristics to determine the bearing capacity, but the study was limited to a setback of 2B. Tatsuoka et al. [7] found the study results of Graham et al. [6] to be on the unsafe side. Bowles [8] considered a graphical approach to incorporate the effect of slopes, but the variation in the failure geometry with the slope angles and setback distance are not considered in the analysis. Saran et al. [9] used upper bound analysis and the limit-equilibrium method to determine the ultimate load. The critical setback was evaluated separately for bearing-capacity factors (N_c, N_q, and N_γ). The critical setback distance was found to range from 1.88B to 4.88B. The mechanism adopted in the upper-bound analysis is inconsistent with the assumed soil model as an inadmissible failure mechanism was adopted in the study [10]. Narita and Yamaguchi [11] extended the study of Kusakabe et al. [5] to the clay slope, but both studies neglected the mobilization of the shear strength of the soil on the level side of the footing. De Buhan and Garnier [12] evaluated the bearing capacity of a rectangular shallow foundation located near a slope or an excavation by using yield design theory.

Lee and Manjunath [13] constrained the maximum setback distance to 5B. However, the test results clearly showed that the bearing capacity is increasing continuously, even at 5B. Huang and Kang [14] used the limit-equilibrium method and found that the critical setback distance is varying from 2.1 to 7.1B for the soil of internal friction 30 to 45°, respectively. Castelli and Motta [15] used the limit equilibrium and found that the critical setback is varying from 1.5B to 5.5B. El Sawwaf and Nazir [16] conducted tests on loose sand and found that the enhancement in bearing capacity becomes constant for a setback of 3B. Naeini et al. [17] conducted a study on a slope of 1H: 1V and found that the bearing capacity reaches the level ground at a setback of 10B. Gill et al. [18] observed in the experimental studies that the effect of the slope is significant up to a setback of 3B in coal ash slopes. Nouri [19] found the critical setback distance to be equal to 8B for soil of internal friction 35° and it can be even more than 8B for the soil of higher values of internal friction. Rostami and Ghazavi [20] used the limit-equilibrium method and found that the critical setback distance is varying between 3.1 and 5.4B.

There is no consensus over the critical value of the setback distance in the literature. A few studies concluded that the setback distance does not affect the bearing capacity beyond a B'/B of 2 and 3 [6, 8, 16, 18, 21-24]. However, other studies found this value to vary up to 5 and 6 [2, 4, 9, 13, 14, 25-27]. Some studies found the B'/B values to be even more than 7–8 [14, 17, 19]. The strength contribution from the soil on the level side of a footing, the effect of the slope angle on the failure surface, the effect of driving forces acting on the sloping side and the effect of embedment depth of footing have been neglected in most of the studies. Furthermore, these studies do not incorporate the non-uniformity of the surcharge loading, especially on the slope side of the footing. Another common limitation in most of the studies is that these were restricted up to a setback distance of 5B in the analyses, even though there is a significant improvement in the bearing capacity from a setback of 4B to 5B. This means that the true value of the critical setback distance remains undetermined in the earlier studies.

In the present study extensive finite-element analyses have been carried out to study the effect of the setback distance on the bearing capacity of a footing resting near the slope crest for various possible slopes and footing geometries, including the depth of the embedment. Based on the study, bearing-capacity-reduction factor (BCR) is proposed for a combination of parameters. The BCR factor is defined as the ratio of the bearing capacity of a footing resting on a slope to the bearing capacity of an identical footing resting over level ground. A regression equation is also developed to directly estimate the reduction in the bearing capacity of footings resting over the slope.

2 PARAMETERS CONSIDERED IN THE ANALYSIS

All the different parameters affecting the performance of a strip footing resting near the slopes, such as the soil friction angle, the slope inclination, the depth of the footing and the setback distance were considered in the analysis. The ranges of the parameters used in the study are summarized in Table 1. It is commonly accepted that the angle of internal friction of soil can vary between 27° and 42° [28]. But to maintain the uniformity in the results, the present study considered a range of friction angles varying from 25^0 to 45^0. The slope angle considered in the analysis depends on the friction angle of the soil. To ensure the stability of the soil slope, the slope angle is assumed to be always less than the angle of internal friction of the soil. Additionally, slope-stability analyses were carried out to avoid unstable slopes. Two unit weights, 16 and 17 kN/m^3, are considered in the analysis. The stiffness and the Poisson's ratio of the soil are assumed to be 12500 kN/m^2 and 0.3, respectively. The normalized parameters, depth ratio and setback ratio are defined and used for the interpretation of the results. The depth ratio is defined as the depth of the foundation normalized with respect to the width of the footing, while the setback ratio is the setback distance for a footing normalized with respect to the width of the footing. After considering the variation in the different parameters, a total of 528 cases have been analysed.

3 METHOD OF ANALYSIS

The finite-element analysis was performed using a two-dimensional finite-element program. A plain-strain analysis was used to simulate the strip footing resting near the slope. A software programmeOptumG2 was used for the FEM analysis. Fig. 1 shows a typical finite-element model used in the study. It was assumed that the slope gradient is uniform along the length of the footing.

The model domain was kept large enough to minimize the boundary effects. The area of the domain was selected based on the slope geometry and the setback distance. For a larger slope gradient and setback distance, a larger area of domain was selected to minimize the effect of the boundaries on the results of analysis.

The number of elements in the analysis and the area of the model domain were varied with the slope gradient and the setback distance. Fifteen nodded gauss elements were used in the analysis. The elements use a cubic interpolation of the stresses and the quartic interpolation of the displacements. A small number of elements are sufficient for steep slopes with a smaller setback distance, whereas a larger number of elements are required for gentle slopes with a larger setback distance. The optimum number of elements were worked out by

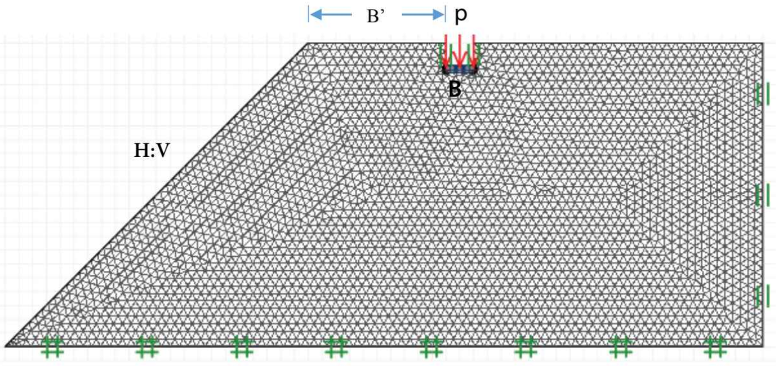

Figure 1. A typical finite-element model used in the study.

Table 1. Ranges of different parameters considered in the analysis.

Friction angle (φ^0)	Slope gradient, G (V/H)	Depth ratio (D/B)	Setback ratio (B'/B)	No. of tests
25	1/10, 1/7, 1/5, 1/4, 1/3	0, 0.5 and 1	0, 1, 3, 5 and 7	75
30	1/10, 1/7, 1/5, 1/4, 1/3 and 1/2	0, 0.5 and 1	0, 1, 3, 5 and 7	90
35	1/10, 1/7, 1/4, 1/3, 1/2 and 1/1.5	0, 0.5 and 1	0, 1, 3, 5,7 and 9	108
40	1/10, 1/7,1/4, 1/3, 1/2, 1/1.5 and 1/1.4	0, 0.5 and 1	0, 1, 3, 5, 7 and 9	108
45	1/10, 1/7, 1/4, 1/3, 1/2, 1/1.5 and 1/1.2	0, 0.5 and 1	0, 1, 3, 5, 7, 9 and 11	147

considering a critical case using the mesh adaptively option of Optum. The mesh adaptivity was earlier used by several studies to refine the mesh to obtain accurate results [30-32]. It was found that 3–4 iterations are enough to obtain consist results. Conservatively, a total of 6 adoptive iterations were considered in the analyses. In the first iteration, the number of elements was fixed to 5000. Finally, a total of 7000 elements were found to be adequate for the analysis. The same number of elements are used for all the cases in the final adoptive iteration. The six-nodded interface is idealized as an element of zero thickness between the soil and the footing. Details of the analysis can be found in Krabbenhoft et al. [29]. Sand was modelled as a drained material, and a Mohr–Coulomb model was used to represent the shear strength. The soil friction angle (φ) was assumed to be constant throughout the soil strata, i.e., the relative density of soil is not varying with the depth. The foundation was considered as a weightless rigid material. The load was applied to the footing in terms of a load multiplier, and was increased to the point of foundation failure.

4 RESULTS AND DISCUSSIONS

The effects of the setback distance on BCR were analysed for various slope inclinations, the depth of footing and the internal friction angles of the soil. The critical setback distance was estimated for various different combinations of these parameters. The effects of these parameters are discussed separately in the following four sections, i.e., the effect of setback distance, the effect of the slope gradient, the effect of the depth ratio and the effect of the friction angle of the soil. The critical setback distance is defined as a minimum distance, where the setback distance does not influence the BCR significantly. Some of the typical results are presented for soil of internal friction 35° only.

4.1 Effect of the setback distance

Though the effect of the setback distance on the BCR is determined for all the cases presented in Table 1, the results here are presented for a soil of internal friction 35°. The typical variation in BCR with the setback distance for a soil of friction angle of 35° is presented in Fig 2. The variation in BCR with the setback distance for depth ratios of 0, 0.5 and 1 are presented in Figs 2 a, b and c, respectively. In all the cases, the BCR is found to be improving with an increase in the setback distance due to an increase in the soil confinement on the slope side of the footing. The BCR increases with a relatively higher rate up to a setback ratio (B'/B) of 3, and this rate of increase in the BCR reduces for the higher value of the setback distance. It is evident from Fig 2 (a, b and c) that for a particular slope gradient and setback distance, the BCR is reducing with an increase in the foundation depth. The BCR is higher in the case of a gentle slope and the BCR is becoming constant for a small setback distance. The rate of increase in the BCR is higher in the case of a slope with a steep gradient. Increasing the B'/B value more than 5 does not improve the BCR significantly. The curves are relatively steeper in the case of the footing with a higher depth ratio, and it indicates that the rate of increase in the BCR is higher in the case of a footing with a higher depth ratio. The increase in the setback distance reduces the instability caused by the slope. Thus, the improvement in BCR and the confinement of the

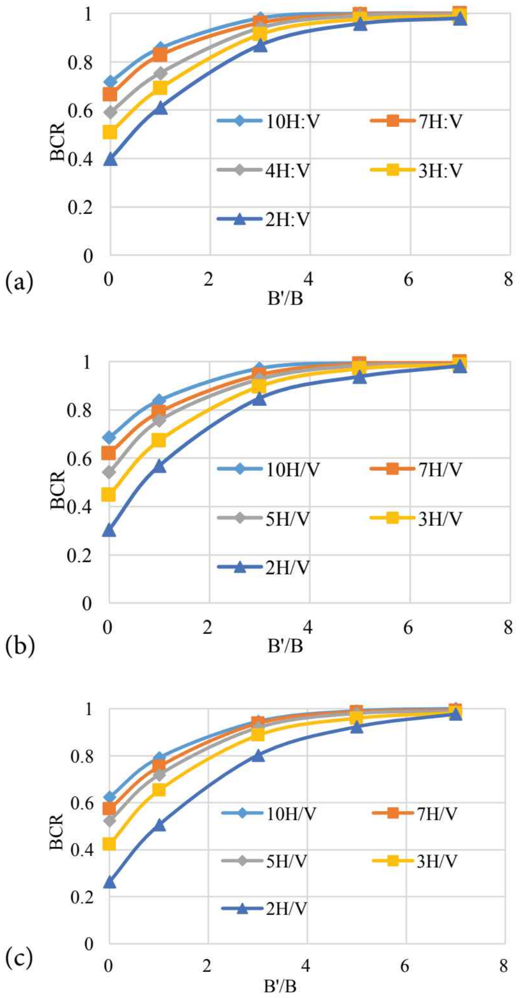

Figure 2. Effect of setback distance on BCR for a footing resting on soil of internal friction 35° for different depth of embedment: (a) D/B=0.0, (b) D/B=0.5 and (c)D/B=1.

soil is observed with larger setback distances for a given slope gradient and an embedment depth of footing.

The BCR improves with the increase in the setback distance due to the lesser effect of the instability caused by the slope. Passive resistance also increases with an increase in the setback distance due to an increase in the amount of surcharge loading and the effective soil weight contributing to the bearing capacity. Mobilization of the soil strength on the level side of the footing is also increasing with an increase in the setback distance, which is the main reason for the higher rate of improvement in the BCR at lower setback distances. The stiffness of the foundation increases with the setback. The increase in the stiffness of the soil foundation system also improves the bearing capacity of soil [33]. The results presented here for a depth of embedment of zero are comparable with earlier studies by Rostami and Ghazavi [20] and Keskin and Laman [26]. However, both studies were confined to surface footings. The testing was limited to a few relative densities, three slope angles and a maximum setback of 5B, which further restricted the authors to determine the true critical setback distance. A detailed comparison of the results with Keskin and Laman [26] is presented later in the section 'Validation of the equation with experimental data and analytical analysis'.

The effect of the setback distance on soil deformation is shown in Fig. 3. Though the analysis is carried out for a large range of soil, the results are presented for the soil of internal friction angle 35º, and slope gradient of 2H: V. The setback distance was varied from 0 to 7B. Fig. 3 (a and b) clearly shows that at a higher setback distance, the strength of the soil on the sloping side contributes to the strength of footing, while no or a partial mobilization of the soil strength is observed for smaller setback distance. This means that the behaviour of the footing at a low setback distance is entirely governed by the soil on the sloping side. Increasing the setback distance more than a certain value enables the contribution of the soil strength from both sides of the footing. The effect of the slope becomes insignificant at a setback distance of 5B. Ausilio [27] also observed that for soil with an internal friction of 35º, the effect of the slope diminished at the setback of 5B for the footing resting on the ground surface. Fig. 3 (f) shows that for a setback distance of more than the critical setback, the behaviour of the footing becomes independent of the slope geometry. At this stage the mobilization of soil strength on both sides of the footing becomes almost equal to each other, as depicted by the symmetrical failure surface on either side of the footing. So the effect of the slope on the footing's performance can be minimized by maintaining a proper distance between the slope edge and the footing. The setback distance at which the behaviour of the foundation becomes independent of the slope depends on the slope angle as well as the soil's internal friction.

4.2 The effect of the slope gradient

The effect of the slope inclination on the BCR is studied for a large range of slope gradients for stable soil slopes. The typical variations of the BCR with the slope gradient for different foundation depths on a soil with an internal friction of 35º are shown in Fig. 4. The graphs are plotted for different amounts of setback distance. The BCR decreases with an increase in the slope gradient, and this decrease in the BCR is depending on the depth of the foundation embedment and the relative location of the footing from the slope crest. The reduction in the BCR with an increase in the slope gradient is very significant when the footing is resting near the slope crest. The effect of the setback distance is becoming more evident with an increase in the slope gradient. Comparing Figs 4 (a, b and c), it is observed that the reduction in the bearing capacity with an increase in the slope gradient is marginally higher for a footing resting at a relatively higher depth.

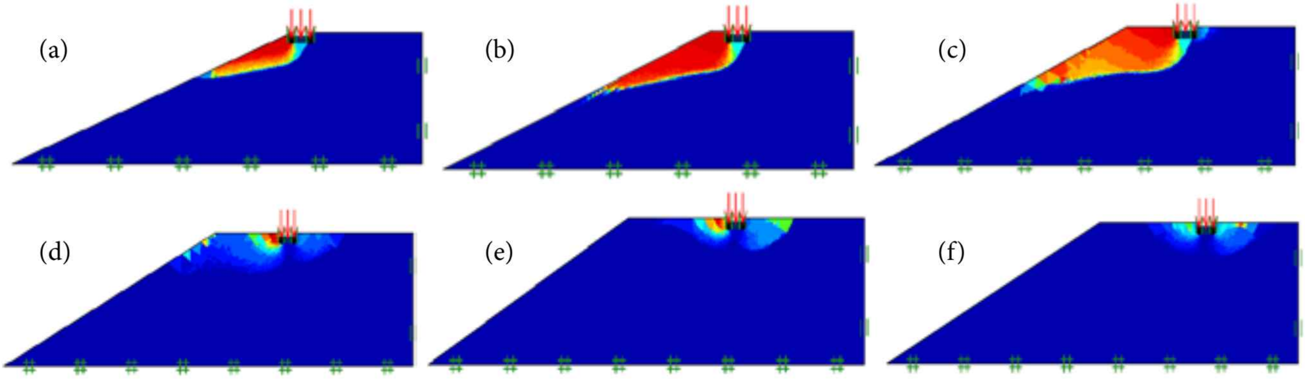

Figure 3. Effect of setback distance on the deformation profile of the soil with internal friction 35º: (a) B'/B=0, (b) B'/B=1, (c) B'/B=3, (d) B'/B=5, (e) B'/B=6, and (f) B'/B=7.

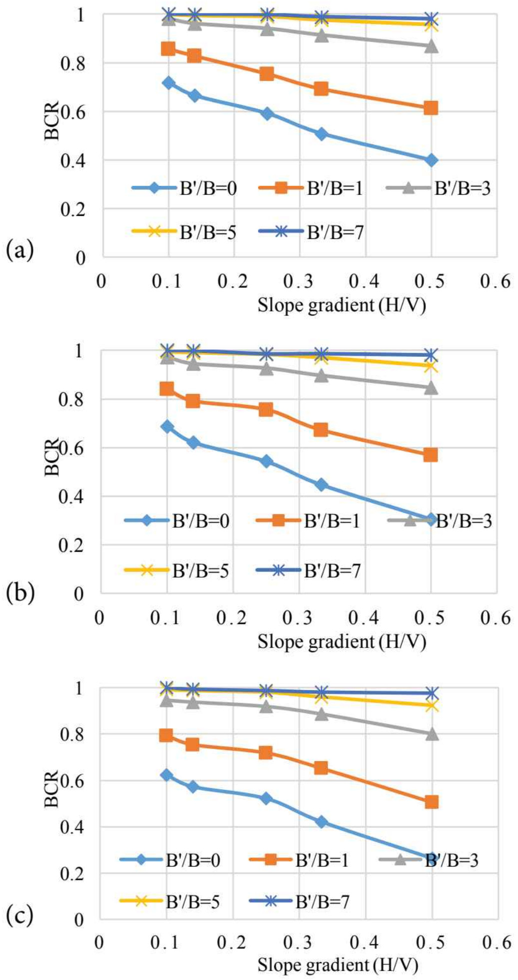

Figure 4. Effect of slope gradient on BCR for a soil of internal friction 35°. (a) D/B=0, (b) D/B=0.5 and (c) D/B=1.0.

In the case of large setback distances, the BCR remains relatively unaffected by a change in the slope gradient.

The effect of the slope gradient on the soil deformation is shown in Fig. 5. The results are presented for a soil of internal friction 35°. The setback distance and the depth ratio of the footing were maintained equal to 3B and 0.5, respectively, and only slope gradient was varied for analysis. The soil deformation further increases with an increase of the slope gradient and the maximum deformation is observed at a steep slope gradient. Figs. 5 (a-d) show that the orientation of the soil movement and failure surface is similar to a normal footing when the slope gradient is relatively very small. It also shows that the soil failure surface and the soil deformation are oriented towards the ground surface at a smaller slope gradient, and both are leaning gradually downward, i.e., towards the slopping surface with an increase in the slope gradient. Similar observations were made in the experimental studies conducted by Chang et al. [34].

4.3 The effect of embedment depth of footing

Fig. 6 shows the effect of the footing embedment depth on the BCR for various slope gradients. The BCR decreases with an increase in the embedment depth of footing, in spite of the increase in bearing capacity. The effect of the footing embedment depth is significant when the footing is resting near the slope crest, and gradually becomes negligible with an increase in the setback distance. This is due to the fact that for a setback distance, more than or equal to the critical setback, the BCR

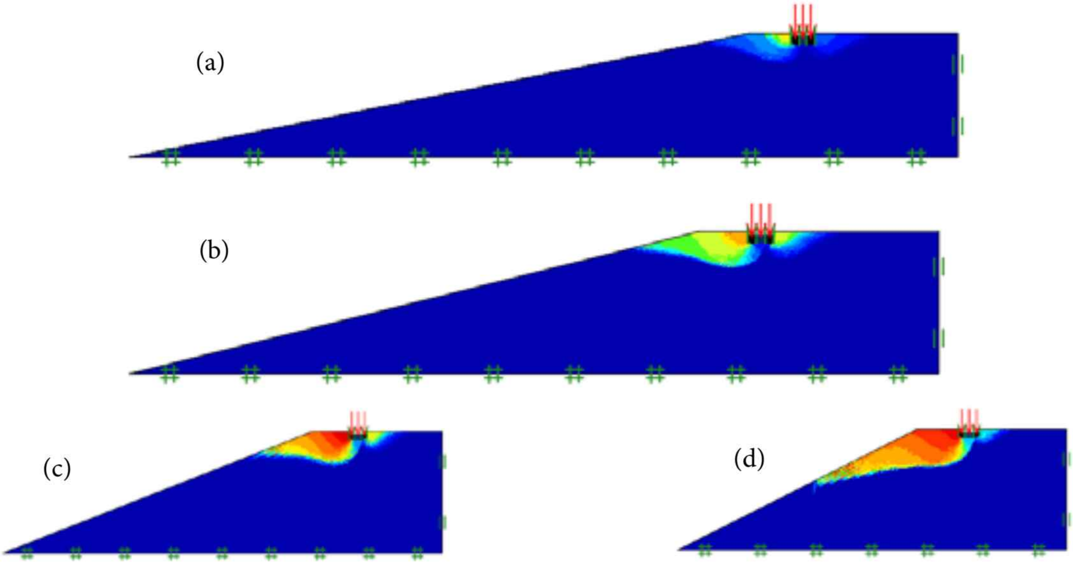

Figure 5. The deformation profile of soil slope for various slope gradients for soil of internal friction 35°: (a) 5H: V (b) 4H: 1V, (c) 3H: V and (d) 2H: V.

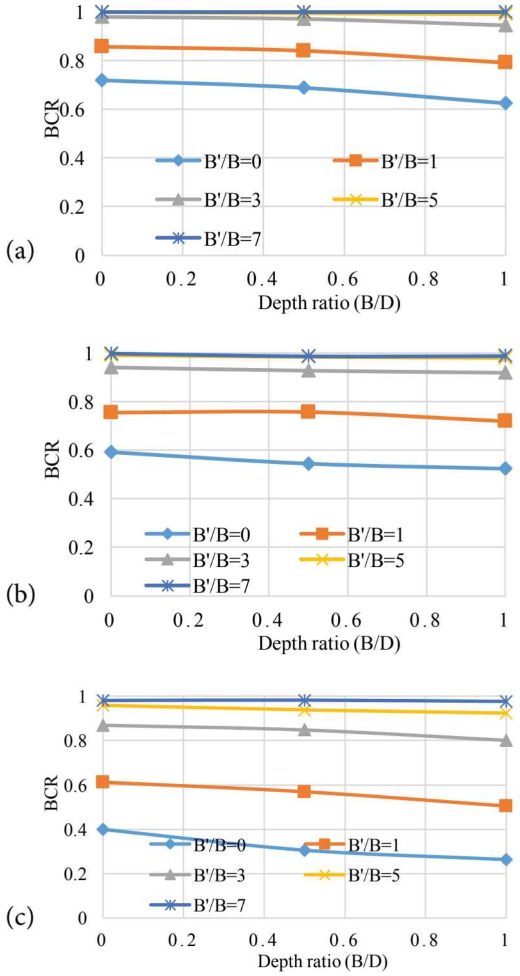

Figure 6. Effect of depth ratio of the footing on the BCR of soil with angle of internal friction 35°. (a) 10H: V, (b) 4H: V, and (c) 2H:1.

remains almost constant, irrespective of the slope inclination. Similar to the present study, Narita and Yamaguchi [11] also found that the effect of the embedment depth of the footing is significant at a low setback distance.

Two observations can be made from Figs. 6 (a, b and c). First, the BCR decreases with an increase in the depth ratio of the footing, especially in the case of a steep slope, and second, for a particular setback distance, the difference in the BCR is becoming more evident with an increase in the depth ratio of the footing. In the case of level ground, the effect of the depth ratio of the footing is relatively more significant for a soil with a low friction angle or loose soil, and a similar observation is also made in the present study for a footing resting over the slope. Castelli and Motta [15] also found that the effect of the depth of the embedment on BCR is not significant; however, the critical setback distance increases with the embedment depth.

Garnier et al. [22] found the coefficient of reduction for a surface footing is always greater than 0.2 in soil with an angle of internal friction 40.5°, even when the slope is steep (3V:2H). A similar observation is also made in the present study for the footings resting over the ground surface. In addition to the surface footing, studies are also extended to a depth ratio of 0.5 and 1. For a soil with an angle of internal friction 40.5°, the coefficient of reduction (BCR) is found to be 0.15 and 0.1, respectively, for depth ratios of 0.5 and 1.0.

4.4 Effect of the angle of internal friction of soil

The effect of the angle of internal friction of soil on the BCR of a footing resting on a different slope gradient is presented in Fig. 7. The results are presented for the surface footing only. For a particular setback distance, the angle of the slope, and the depth of footing, the BCR is decreasing with an increase in the friction of the soil (or relative density). Furthermore, the reduction in the BCR is varying with the angles of shearing resistance of soil, and this variation is depending significantly on the magnitude of the setback distance and slope gradient. The reduction in the BCR with an increase in the friction angle of soil is higher for a small setback distance and a steep slope gradient. The relationship between the BCR and the friction angle of soil is linear for gentle slopes, and it is becoming non-linear with an increase in the slope gradient. In comparison to the soil with a low internal friction angle, the pressure is distributed over a relatively large area in the case of soils with higher friction angle. To mobilize the strength of the soil completely, the footing resting on the dense sand requires a relatively large setback distance. In the loose sands, the failure is either a local shear failure or a punching shear failure, and in both cases the footing sinks without affecting the surrounding area, so these soils need a relatively small setback distance to compensate for the effect of the slope inclination. This reduction in the BCR with an increase in the internal friction angle of soil is increasing with an increase in the slope angle and a decrease in the setback distance. Rostami and Ghazavi [20] observed a similar behaviour in the case of a footing resting over the ground surface.

Based on the numerical results, the critical setback distance is identified for different slope angles, depth of foundation and soil friction angles. The normalised setback distance is represented in a tabular form in Table 2. A detailed table is included in the annexure (Table 3). Though Meyerhof [2] considered only a limited range of setback distances (0 to 6B) and depth of footing, the presented critical setback distances are compared with the Meyerhof [2].

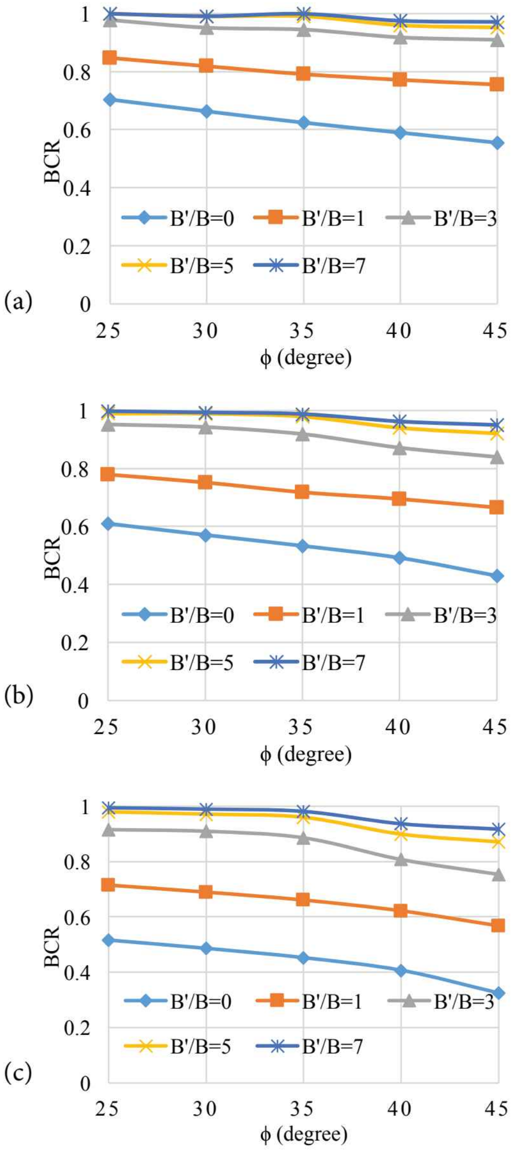

Figure 7. Effect of friction angle on BCR for a footing of zero embedment resting over soil of internal friction 35°. (a) 10H: V, (b) 4H: 1V and (c) 3H: 1V.

Table 2. Normalised critical setback distance for cohesionless soils.

Friction angle (φ^0)	Slope gradient, G (V/H)	Critical Setback distance (B'/B) from present study	Meyerhof [6]
25	1/10–1/3	2–3	-
30	1/10–1/4	3	-
	1/3–1/2	4–5	3
35	1/10–1/4	4–5	-
	1/2 –1/1.5	6–7	5
40	1/10–1/5	5–6	>6
	1/4 –1/3	6–7	>6
	1/2–1/1.3	8–9	-
45	1/10–1/4	8–9	-
	1/3–1/2	9–10	-
	1/1.5–1/1.2	>10	-

A steep slope of low relative density soil (low angle of internal friction) loses its stability with the application of a small magnitude load. In this condition, the slope sometimes fails itself and sometimes the foundation soil fails by means of local or punching shear failure (small area of shear zone). In both conditions a very small volume of soil is involved in the strength mobilization, without affecting the large mass of soil. In contrast, in the dense sand, failure is normally a general shear failure (a large area of shear zone). The larger area of soil contributes to the resistance against failure, and a large setback distance requires to mobilize the full strength of the soil. Chang et al. [34] and Raftari et al. [35] also found that the depth and the area of the shear zones increase with an increase in the setback distance in the reinforced slope. Similar to the present study, almost all previous studies also found that the critical distance increases with the increase in the angle of shearing resistance or the relative density of the soil.

5 STATISTICAL ANALYSES

Statistical analyses were also performed to determine the factors affecting the BCR using the results of numerical analyses. A simple multiple regression and correlation analysis along with other statistical tests were performed to derive an equation to determine the BCR of a footing resting over cohesionless soil.

As it can be seen from the numerical analysis, a total of four independent parameters (i.e., setback distance, slope gradient, soil friction angle and depth ratio of footing.) are influencing the bearing capacity of a footing resting near the slope. The results of the numerical study show that the relationship between the independent parameters and the bearing capacity ratio is not linear, and hence it is necessary to consider the nonlinearity in order to develop an equation for the BCR calculation. As an exact nonlinearity in the relationship is not known initially, it was assumed that the BCR is not only depending on these four parameters, but also upon various derivatives as well.

Initially, a total of 96 parameters, which are the function of these 4 independent variables, are considered in the regression analysis. T-Tests were performed to determine the dependency of the BCR on these parameters. Along with the probability level, the R^2 value was used to determine the critical factor affecting the BCR. The degree of multicollinearity was used to remove the insignificant parameters. It was found from these studies that only 12 parameters, including the four basic parameters, critically affect the bearing-capacity ratio. Later these 12 variables were used to develop the equation for the bearing capacity ratio.

Figs. 8 (a) and (b) respectively show the residues of the BCR (observed BCR-predicted BCR) versus the percentage of the value for 96 and 12 variables. The equation was developed as a consequence of a comparative study carried out to develop an equation that can predict the effect of the slope inclination and the foundation geometry very effectively. Based on a regression analysis and a comparative analysis, an equation is proposed to estimate the BCR. For this, various type of functions, such as logarithmic, linear, polynomial and exponential functions, were assumed and the best relationship is used to develop the equation. It was found that R^2 is reduced from 0.9947 to 0.987, when the number of insignificant variable were removed from the analysis. It ensures that the other assumed dependents parameters are not affecting the bearing capacity, as assumed in the initial phase of the regression analysis. Based on the T Test, the probability level and the degree of multicollinearity, the following order can be assigned to the factors, critically affecting the bearing capacity: Slope > Setback distance

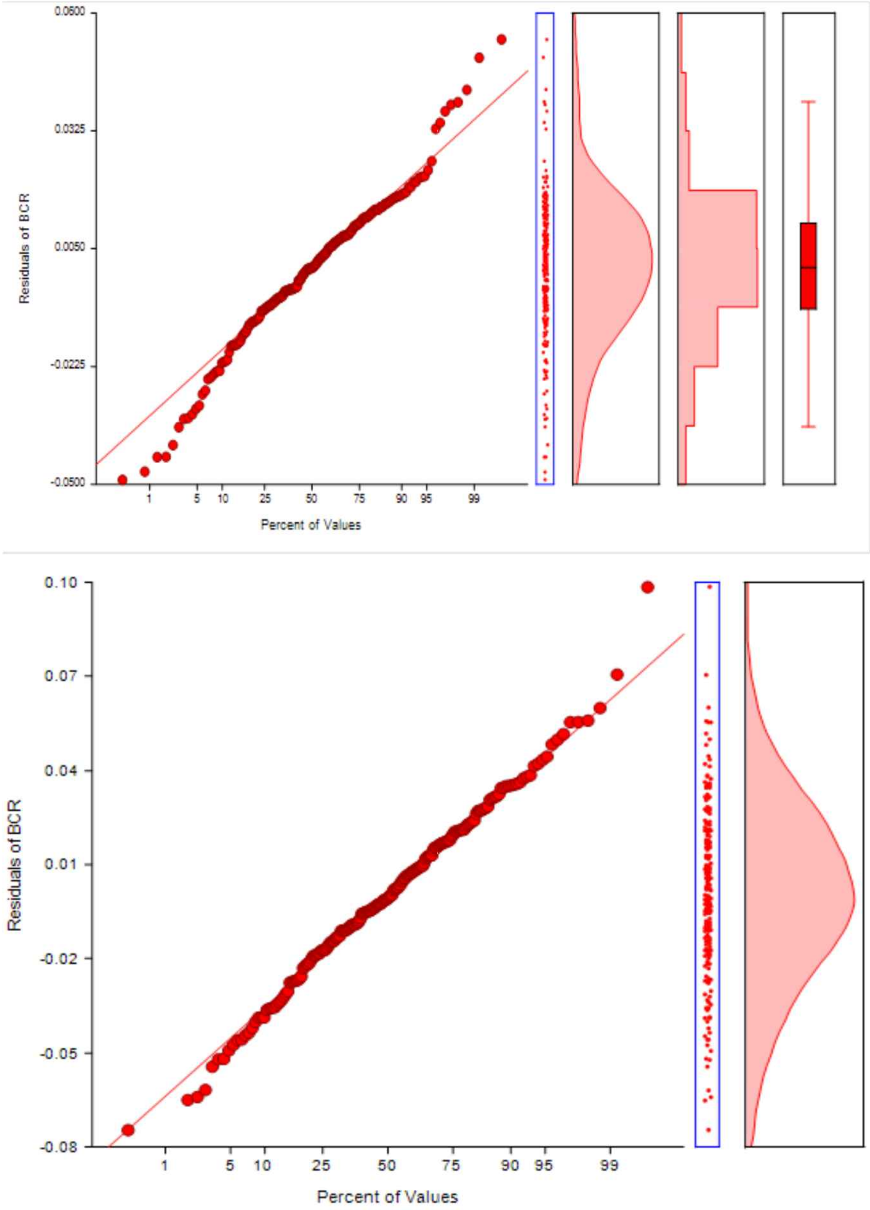

Figure 8. Residuals versus percentage of values (a) for 156 independent variables (b) for 12 independent variables.

> Friction angle > Depth ratio of footing. The effect of the depth ratio of the footing on the bearing capacity is very nominal, as compared to the other three factors. Equation 1 shows the BCR equation developed to determine the influence of the slope geometry and the angle of internal friction of the soil. Annexure shows an equation that is relatively complex, but it can predict a change in the bearing capacity with a higher accuracy.

$$\mathrm{BCR} = 1 + 0.044B'/B(1 - 0.14B'/B + 0.09D/B + 3.4\beta) + 0.06D/B(D/B - 1) - 0.4\beta(1 + 0.35\beta + 0.8\,D/B + 2.1\tan\varphi) + \tan\varphi(1 - 1.2\tan\varphi - 0.15D/B + 0.15B'/B) \quad (1)$$

where BCR = Bearing capacity ratio, B' = setback distance, B = width of footing, D = depth of footing, β = soil slope in radian and φ = angle of internal friction of the soil.

5.1 Validation of the equation with experimental and analytical analysis

The proposed Eq. 1 is validated with the experimental results of Keskin and Laman [26]. Fig. 9 shows a reasonably good agreement between the BCR predicted from the proposed equation and the experimentally measured BCR values of Keskin and Laman [26]. The predicted BCR values up to the setback distance of 4B are a little higher than Keskin and Laman [26], but these differences are within the acceptable ranges (0–15%). This variation might be attributed to the scaling effect as the numerical modelling was carried out on a prototype model, while Keskin and Laman [16] performed small-scale model testing in the laboratory. Keskin and Laman [26] used the relative density of the sand in the analysis, and it has been converted to the friction angle of the soil using a relationship given by Schmertmann [36] for comparing the results. This might be another reason responsible for the minor differences observed between the experimental values and the values predicted from the developed regression equation.

The results are also compared with the analytical analysis results of Huang and Kang [14]. To make this comparison, the results were reproduced in a different form. Here, BCR represents the ratio of the bearing capacity of the footing resting some distance from the slope crest to the bearing capacity of the footing resting precisely on the slope crest. Fig. 10 shows the comparison of the results with Huang and Kang [14]. Graphs with dotted lines show the results of Huang and Kang [14], and the solid lines show the results of the present study. The results of the former study show that the BCR become constant precisely after a certain value of the setback distance. Whereas in the present case, though BCR is not becoming constant, but the rate of increase in the BCR becomes insignificant after a certain value of setback distance. In comparison to the results of Huang and Kang [14], the BCR measured in the present study is higher for the small slope. Whereas

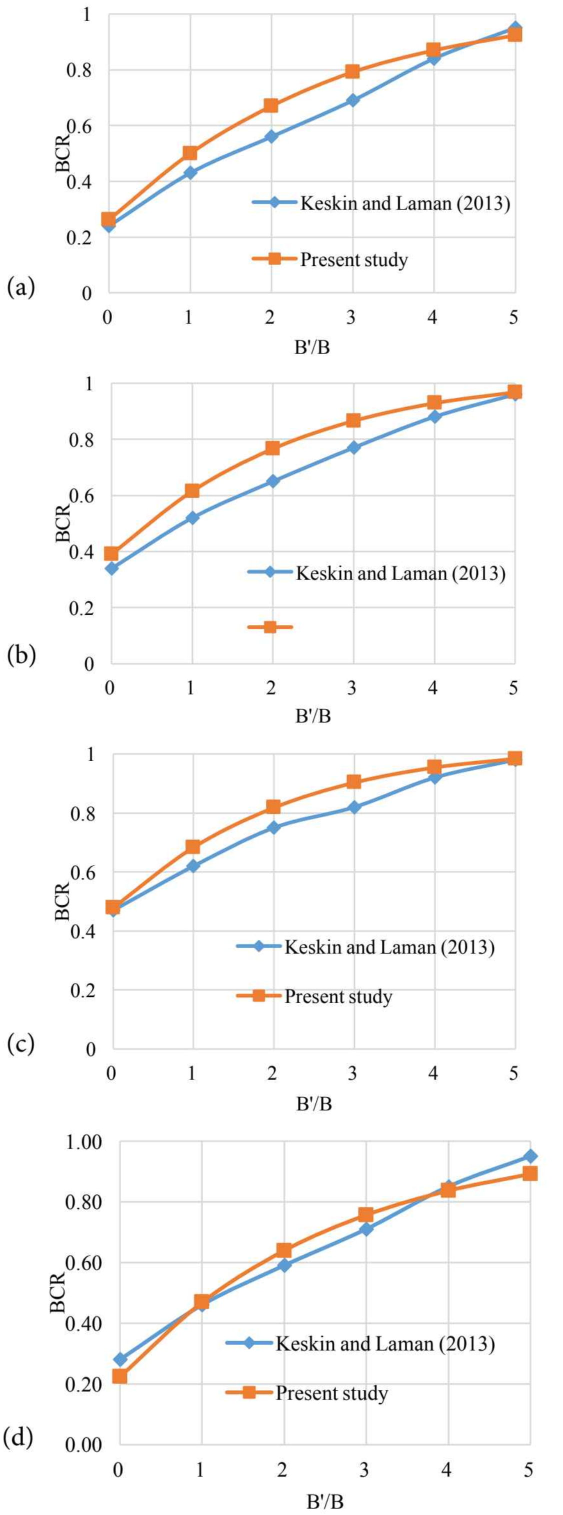

Figure 9. Variation of BCR with setback distance. (a) for soil slope 30°, φ=32°, (b) for soil slope 25°, φ=32°, (c) for soil slope 20°, φ=32° and (d) for soil slope 30°, φ=40°.

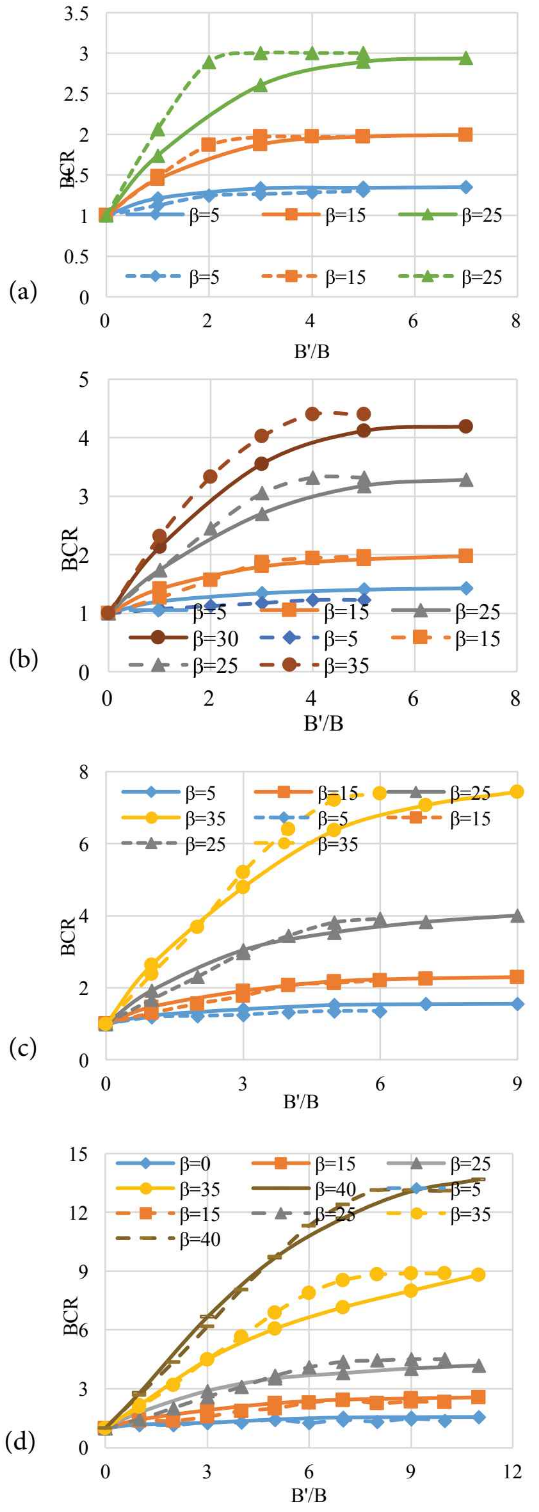

Figure 10. Comparison of results with analytical results of Huang and Kang [14] shown by dashed lines for surface footing resting on slope. (a) φ=30°, (b) φ=35°, (c) φ=40° and (d) φ=45°.

in the case of a higher slope angle, the BCR evaluated from the present study is smaller than the BCR of the former studies.

6 CONCLUSION

The slopes have an adverse effect on the bearing capacity of a footing. The slope gradient, setback distance, angle of internal friction of the soil and the depth ratio of footing affects the bearing capacity of a footing resting over the slope. The bearing capacity decreases with an increase in the slope gradient. The reduction in the bearing capacity with the slope gradient is relatively higher for a footing of large embedment depth and when the footing is resting near the slope crest. Particularly for dense sand, the effect of the slope gradient on the reduction in the bearing capacity is observed, even up to very large setback distances of 11B. Soil deformation also increases with an increase in the slope gradient. At a low slope gradient, the orientation of the failure surface and the soil deformation are very much similar to the footing resting on the level ground. Both the failure surface and the direction of propagation of soil deformation oriented downwards and towards the slope surface with an increase in the slope gradient.

The soil confinement and strength mobilization on the level side of the footing increase with an increase in the setback distance; therefore, the bearing capacity increases. The critical setback distance is increasing with an increase in the friction angle of the soil, the slope gradient and the depth of footing. The reduction in the bearing capacity with slope inclination increases with an increase in the internal friction of the soil and the depth of footing. The effect of the depth of foundation on the reduction in the BCR is relatively higher when the footing is resting near the slope crest. The predicted BCR is well matching with the BCR determined in the previous analytical and experimental studies.

REFERENCES

[1] Sarma, S. K., Chen, Y. C. 1995. Seismic bearing capacity of shallow strip footings near sloping ground. The 5th SECED conference on European seismic design practice, Balkema, Rotterdam, 505-512.
[2] Meyerhof, G. G. 1957. The ultimate bearing capacity of foundation on slopes. 4^{th} Int. Conf. on Soil Mech. and Foundation Eng., 3, 384-386.
[3] Hansen, J.B. 1970. A revised and extended formula for bearing capacity. Dan. Geotech. Ins., Bulletin 28.
[4] Shields, D., Chandler, N., Garnier, J. 1990. Bearing capacity of foundations in slopes. Journal of geotechnical engineering 116, 3, 528-537.

[5] Kusakabe, O., Kimura, T., Yamaguchi, H. 1981. Bearing capacity of slopes under strip loads on the top surfaces. Soils and Foundation, JGS 21, 4, 29-40. DOI: http://doi.org/10.3208/sandf1972.21.4_29.
[6] Graham, J., Andrews, M., Shields, D. H. 1988. Stress characteristics for shallow footings in cohesionless slopes. Canadian Geotechnical Journal 25, 2, 238-249. DOI: http://dx.doi.org/10.1139/t88-028
[7] Tatsuoka, F., Huang, C.C., Morimoto, T., Okahara, M. 1989. Stress characteristics for shallow footings in cohesionless slopes. Discussion. Canadian Geotechnical Journal 26, 4, 748-755. DOI: http://dx.doi.org/10.1139/t89-088
[8] Bowles, J.E. 1988. Foundation engineering and design. 5th Edition, McGraw-Hill, Inc.
[9] Saran, S., Sud, V., Handa, S. 1989. Bearing capacity of footings adjacent to slopes. Journal of geotechnical engineering 115, 4, 553 – 573. DOI: http://dx.doi.org/10.1061/(ASCE)0733-9410(1989)115:4(553)
[10] Michalowski, R. L. 1991. Discussion of bearing capacity of footings adjacent to slopes by Swami Saran, VK Sud and SC Handa. Journal of Geotechnical Engineering 117, 7, 1125-1127. DOI: http://dx.doi.org/10.1061/(ASCE)0733-9410(1991)117:7(1125.2)
[11] Narita, K., Yamaguchi, H. 1990. Bearing capacity analysis of foundations on slopes by use of log-spiral sliding surfaces. Soils and Foundation, JGS 30, 3, 144-152. DOI: http://doi.org/10.3208/sandf1972.30.3_144
[12] De Buhan, P., Garnier, D. 1998. Three dimensional bearing capacity analysis of a foundation near a slope. Soils and Foundations, JGS 38, 3, 153-163. DOI: http://doi.org/10.3208/sandf.38.3_153.
[13] Lee, K. M., Manjunath, V. R. 2000. Experimental and numerical studies of geosynthetic-reinforced sand slopes loaded with a footing. Canadian Geotechnical Journal 37, 828–842. DOI: http://doi.org/10.1139/t00-016
[14] Huang, C.C., Kang, W.W. 2008. The effects of a setback on the bearing capacity of A surface footing near a slope. Journal of GeoEngineering 3, 1, 25-32. DOI: http://doi.org/10.6310/jog.2008.3(1).3
[15] Castelli, F., Motta, E. 2010. Bearing capacity of strip footings near slopes. Geotechnical and Geological Engineering 28, 2, 187-198. DOI: http://doi.org/10.1007/s10706-009-9277-9
[16] El Sawwaf, M. 2010. Experimental and numerical study of strip footing supported on stabilized sand slope. Geotechnical and Geological Engineering 28, 4, 311-323. DOI: http://doi.org/10.1007/s10706-009-9293-9
[17] Naeini, S. A., Rabe, B. K., Mahmoodi, E. 2012. Bearing capacity and settlement of strip footing on geosynthetic reinforced clayey slopes. Journal of Central South University 19, 4, 1116-1124. DOI: http://doi.org/10.1007/s11771-012-1117-z
[18] Gill, K. S., Choudhary, A. K., Jha, J.N., Shukla, S. K. 2013. Large model footing load test on reinforced coal ash slope. International Journal of Geotechnical Engineering 7, 3, 257-265. DOI: http://doi.org/10.1179/1938636213Z.00000000040
[19] Nouri, M. 2014. Interaction domain of shallow foundations on the top of a slope. Master Dissertation, Department of Civil, Environmental and Land Management Engineering, Polytechnic University of Milan. Itly.
[20] Rostami, V., Ghazavi, M. 2015. Analytical solution for calculation of bearing capacity of shallow foundations on geogrid-reinforced sand slope. IJST, Transactions of Civil Engineering 39, C1, 167-182.
[21] Andrew, M. 1986. Computation of bearing capacity coefficients for shallow footing on cohesionless slopes using stress characteristics. M.Sc. thesis, University of Manitoba, Winnipeg, Manitoba.
[22] Gamier, J., Canepa, Y., Corte, J.F., Bakir, N.E. 1994. Etude delaPortance de Foundations enBorddeTalus. 13th Int. Conf. on Soil Mechanics and Foundation Engineering 2, 705-708.
[23] Georgiadis, K. 2010. Undrained bearing capacity of strip footings on slopes. Journal of Geotechnical and Geoenvironmental Eng. 136, 5, 677-685. DOI: http://doi.org/10.1061/(ASCE)GT.1943-5606.0000269
[24] Altalhea, E. B., Taha, M.R., Abdrabbob Fathi, M. 2015. Behavior of strip footing on reinforced sand slope. Journal of Civil Engineering and Management 21, 3, 376-383. DOI: http://doi.org/10.3846/13923730.2014.890646
[25] Jao, M., Ahmed, F., Muninarayana, G., Wang, M. C. 2008. Stability of eccentrically loaded footings on slopes. Geomechanics and Geoengineering 3, 2, 107-111. DOI: http://doi.org/10.1080/17486020802010772
[26] Keskin, M.S., Laman, M. 2013. Model studies of bearing capacity of strip footing on sand slope. KSCE Journal of Civil Engineering 17, 4, 699-711. DOI: http://doi.org/10.1007/s12205-013-0406-x
[27] Ausilio, E. 2014. Seismic bearing capacity of strip footings located close to the crest of geosynthetic reinforced soil structures. Geotechnical and Geological Engineering 32, 4, 885-899. DOI: http://doi.org/10.1007/s10706-014-9765-4
[28] Peck, R. B., Hanson, W. E., Thornburn, T. H. 1974. Foundation engineering. (Second edition), Wiley, New York.

[29] Krabbenhoft, K., Lyamin, A., Krabbenhoft, J. 2015. Optum computational engineering, (www.optumce.com).

[30] Keawsawasvong, S., Ukritchon, B. 2016. Finite element limit analysis of pullout capacity of planar caissons in clay. Computers and Geotechnics 75, 12-17. DOI: http://dx.doi.org/10.1016/j.compgeo.2016.01.015

[31] Lyamin, A. V., Sloan, S. W., Krabbenhøft, K., Hjiaj, M. 2005. Lower bound limit analysis with adaptive remeshing. International Journal for Numerical Methods in Engineering 63, 14, 1961-1974. DOI: http://doi.org/10.1002/nme.1352

[32] Martin, C. M. 2011. The use of adaptive finite-element limit analysis to reveal slip-line fields. Géotechnique Letters 1, 2, 23-29. DOI: http://dx.doi.org/10.1680/geolett.11.00018

[33] Varzaghani, I. M., Ghanbari, A. 2014. A new analytical model for determination of seismic settlement of foundations adjacent to slope. Geomechanics and Engineering 6, 561-575. DOI: http://dx.doi.org/10.12989/gae.2014.6.6.561

[34] Chang, J. C., Liao, J. J., Pan, Y.W. 2008. Bearing behavior and failure mechanism of a shallow foundation located on/behind the crest of a poorly cemented artificial sandstone. International Journal of Rock Mechanics and Mining Sciences 45, 8, 1508-1518. DOI: http://doi.org/10.1016/j.ijrmms.2008.01.013

[35] Raftari, M., Kassim, K.A., Rashid, A.S.A., Moayedi, H. 2013. Settlement of shallow foundations near reinforced slopes. EJGE 18, Bund. D, 797-808.

[36] Schmertmann, J. H. 1978. Guidelines for cone penetration test: Performance and Design, FHWA-TS-78-209 (report), U.S. Dept. of Transportation.

Annexures:

The equation to calculate the bearing-capacity ratio more accurately

$$
\begin{gathered}
BCR = 0.047B'/B + 0.32D/B + 4.46\tan\varphi - \\
0.02(B'/B)^2(1 - 0.34D/B - 0.75\tan\varphi + 0.15\beta) - \\
\beta^2(1 + 0.2\beta - 1.9\tan\varphi - 0.36D/B + 0.19b/B) - \\
6.45\tan\varphi^2(1 + 0.45\tan\varphi + 0.16\beta - 0.04D/B + 0.01b/B) - \\
D/B^2(1 - 0.7D/B + 0.017b/B - 0.22\beta - 0.04\tan\varphi) + \\
0.034(b/B)D/B(1 - 2.35\tan\varphi) + 0.42(b/B)\beta(1 - 0.07D/B) + \\
0.1(b/B)\tan\varphi(1 - 1.23\beta) - 0.2(D/B)\tan\varphi(1 + 0.5\beta) - \\
\beta(1 - 0.24\tan\varphi + 0.55D/B)
\end{gathered}
$$

Table 3. Normalised critical setback distance for cohesionless soil.

Friction angle (φ^0)	Slope gradient, G (V/H)	Depth of Embedment (B/D)	Critical Set-back distance (S/B)	Meyerhof et al. [5]
25	1/10–1/5	0.5	2	-
	1/5–1/3	1	3	-
30	1/10–1/4	0	2	2
		0.5	3	
		1	3–4	
	1/4–1/2	0	3	3
		0.5	3–4	
		1	4–5	
35	1/10–1/5	0	4–5	
		0.5	5	
		1	5–6	
	1/4–1/2	0	5–6	
		0.5	6	
		1	6–7	
	1/2–1/1.5	0	5–6	
		0.5	6–7	
		1	7–8	
40	1/10–1/5	0	5–6	
		1	6–7	
	1/5 –1/2	0	6–7	>6
		1	7–8	
	1/2–1/1.3	0	7–8	>5
		1	8–9	>7
45	1/10–1/4	0	7–8	
		1	8–9	
	1/4–1/2	0	8–9	
		1	10–11	
	1/2–1/1.2	0	>12	
		1	>12	