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Critical setback distance for a footing resting on slopes under seismic loading

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Abstract. A footing located on slopes possess relatively lower bearing capacity as compared to the footing located on the level ground. The bearing capacity further reduces under seismic loading. The adverse effect of slope inclination and seismic loading on bearing capacity can be minimized by proving sufficient setback distance. Though few earlier studies considered setback distance in their analysis, the range of considered setback distance was very narrow. No study has explored the critical setback distance. An attempt has been made in the present study to comprehensively investigate the effect of setback distance on footing under seismic loading conditions. The pseudo-static method has been incorporated to study the influence of seismic loading. The rate of decrease in seismic bearing capacity with slope inclination become more evident with the increase in embedment depth of footing and angle of shearing resistance of soil. The increase in bearing capacity with setback distance relative to level ground reduces with slope inclination, soil density, embedment depth of footing and seismic acceleration. The critical value of setback distance is found to increase with slope inclination, embedment depth of footing and density of soil. The critical setback distance in seismic case is found to be more than those observed in the static case. The failure mechanisms of footing under seismic loading is presented in detail. The statistical analysis was also performed to develop three equations to predict the critical setback distance, seismic bearing capacity factor ($N_{\gamma qs}$) and change in seismic bearing capacity (BCR) with slope geometry, footing depth and seismic loading.

Keywords: slope; footing; bearing capacity; pseudo-static; critical setback distance

1. Introduction

Structures are frequently built on the slope under various circumstances. Foundations resting over or near a slope lack in soil support from the slope side, which makes its behavior very different from foundations resting over the level ground. The strength of slope side soil mobilizes completely before optimum mobilization of soil strength on the level side of footing. Consequently, the footing does not reach to its ultimate capacity. Therefore, the foundations located near to slope possess relatively lesser load carrying capacity as compared to the same footing resting on the level ground under similar loading condition (Sarma and Chen 1995). The bearing capacity can be reduced further due to the occurrence of earthquake.

A number of studies have analyzed footings on a slope under static loading. However, there is no agreement in reported critical value of setback distance, at which bearing capacity becomes independents of slope inclination. A few studies reported the critical setback distance to be 2-3 times of footing width (B) in static cases (Graham 1988, Bowles 1988, El Sawwaf 2010, Georgiadis 2010, Altalhea 2015, Acharyya and Dey 2017). However, some other studies found same value to be varying up to 6B (Meyerhof 1957, Shields *et al*. 1990, Saran *et al*. 1989, Lee and Manjunath 2000, Chang *et al*. 2008, Keskin and Laman 2012). Apart from these studies, there are a few other studies, which found the critical setback distance even up to 9-12B (Mizuno *et al*. 1960, Giroud 1971, Huang and Kang 2008, Naeini 2012, Nouri 2014, Shukla and Jakka 2017).

A good number of studies are reported in the literature on the seismic bearing capacity of a footing on slopes. However, most of the studies considered a footing resting precisely on slope crest with zero setback distance (Sarma and Chen 1995, Kumar and Mohan Rao 2003, Jahanandish and Keshavarz 2005, Choudhury and Subba Rao 2006, Kumar and Ghosh 2006, Varzaghani and Ghanbari 2014, Huang and Kang 2008, Huang 2009, Arvin *et al*. 2012, Kumar and Chakraborty 2013, Chakraborty and Kumar 2014, Casablanca *et al*. 2016). A few studies have considered the influence of setback distance on seismic bearing capacity. Sawada *et al*. (1994) restricted the maximum setback distance up to 5B. However, presented plots clearly show that the seismic bearing capacity has not attained stable value even at a setback distance of 5B. Askari and Farzaneh (2003) presented dimensionless seismic limit pressure charts for setback distance of 0 and 0.5B only. Castelli and Motta (2010) found that the bearing capacity factors decrease significantly with seismic acceleration. The threshold distance was not determined in the case of steep slopes. Yamamoto (2010) found that the bearing capacity increases significantly even after a setback distance of 5B for a soil of friction angle of 30°. This critical setback distance may further increases with the increase in angle of internal friction of soil. Ausilio (2014) used upper bound of the plasticity and found the critical setback distance to be 5B

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Table 1 Description of parameters considered in the study

Angle of internal friction ($\varphi°$)	Setback distance (B'/B)	Slope angle ($\beta°$)	Depth of embedment (D/B)	Horizontal seismic coefficient (α_h)	No. of analysis
25	0, 1, 3, 5	0, 5, 10, 15, 20	0, 0.5,1.0, 1.5	0, 0.05, 0.1, 0.15,0.20,0.25	480
30	0, 1, 3 5, 7, 9	0, 5, 10, 15, 20, 25	0, 0.5,1.0, 1.5	0, 0.05,0.1, 0.15, 0.20, 0.25	864
35	0, 1, 3, 5, 7, 9,11	0, 5, 10, 15, 20, 25, 30	0, 0.5,1.0, 1.5	0, 0.05, 0.1, 0.15,0.20,0.25,0.3	1372
40	0, 1, 3, 5, 7, 9, 11, 13, 15	0, 5, 10, 15, 20, 25, 30, 35	0, 0.5,1.0, 1.5	0, 0.05, 0.1, 0.15,0.20,0.25,0.3	2016
45	0, 1, 3, 5, 7, 9, 11, 13, 15, 17	0, 5, 10, 15, 20, 25, 30, 35, 40	0, 0.5,1.0, 1.5	0, 0.05, 0.1, 0.15,0.20,0.25,0.3	2520
Total number of analysis					7252

for a soil of internal friction 35°. Ghazavi and Mahali (2013) found that the bearing capacity achieved the stable value at a setback distance of 4B in soil having internal friction 30° and a slope inclination of 10°. Chakraborty and Mahesh (2015) found that the value of threshold setback distance for a footing resting on an embankment made of a soil of internal friction of 40° to be approximately 13B, 15B, and 5B for the bearing capacity factors N_c, N_q, and N_γ, respectively. These values can confuse a practicing engineering to what value of critical setback distance should be considered in planning and design of a structure on slope. However, the critical setback for other cases have not been provided in the study.

Literature study shows that only a few studies have considered the influence of setback distance on seismic bearing capacity of a footing. However, the considered range of setback distance is very narrow and, the effect of various other parameters on setback is not studied in detail even for considered setback distances. There is no consensus over the critical value of setback distance even for the static case, though qualitative observations are similar in various previous studies. It means that the true critical value of setback distance is still not investigated for seismic cases. Therefore, in the present study, an attempt has been made to study the influence of setback distance and other parameters on seismic bearing capacity of footing. A series of finite element analyses have been carried out to determine the effect of various factors on the seismic bearing capacity of a footing resting near or on the slope crest. The change in the seismic bearing capacity is determined in term of bearing capacity ratio (BCR). The factor, BCR is a ratio of seismic bearing capacity factor ($N_{\gamma qs}$) for a footing resting near the slope to the identical footing resting over the level ground under same loading and soil condition. The effect of various factors on seismic bearing capacity has been demonstrated using failure mechanism. The statistical analysis is also carried out to develop regression equations to determine the critical setback distance, seismic bearing capacity factor ($N_{\gamma qs}$) and change in seismic bearing capacity (BCR) for a particular values of slope inclination, soil strength, horizontal seismic acceleration and footing depth.

2. Parameters studies in analysis

Various parameters influencing the bearing capacity of a strip footing resting near the slope crest under seismic loading has been considered in the analysis. These parameters include the slope gradient, setback distances, seismic acceleration, the angle of shearing resistance of soil and footing properties. The details of parameters range used in the study is presented in Table 1. To consider the seismic loading, pseudo-static method has been implemented. Earlier studies found that the range of angle of shearing resistance varies between 27° and 42° (Peck *et al*. 1974). However, to maintain the uniformity in results, the range of angle of internal friction of soil is varied from 25° to 45°. To maintain the stability of the soil slopes, slope inclination is set to be smaller than the angle of shearing resistance of the soil. Furthermore, the stability analyses were also performed to check the stability of slopes. The density of soil is varied on the basis of the angle of shearing resistance of the soil. Three unit weights, used in the study are 16, 17 and 19 kN/m^3. Poison ratios considered against the assumed unit weights are 0.25, 0.30 and 0.35 respectively. The stiffness of soil is assumed to be 10000 kN/m^2, 12500 kN/m^2, and 14000 kN/m^2 respectively for assumed soil weights and Poisson ratios. These values were selected based on the rigorous review of previous studies. The setback distance and embedment depth of footing are normalized with respect to the width of footing and stated as setback ratio and depth ratio, respectively.

3. Numerical modelling

A 2D limit state finite element analysis was used to model the problem. The OptumG2, a FEM program was used in the analysis. It can be used to perform the limit, elastoplastic and seepage analysis. However, present study uses the limit analysis to analyze the problem. Both lower bound elements and upper bound were used in the analysis to determine the bearing capacity. The converged value, which is close to exact collapse load is used for further analysis. The lower bound element of three nodes uses the linear change in the stresses between junction nodes.

Lower bound elements linked by two elements with zero-thickness in order to produce the statically admissible stress discontinuity between junction nodes. For maximum lower bound limit, load is determined by finding a collapse load which satisfies a statically admissible stress field defined by the stress equilibrium equations at triangular elements. Similar to the lower bound element, the upper bound element uses the linear interpolation of stresses, while unknown displacements were determined using

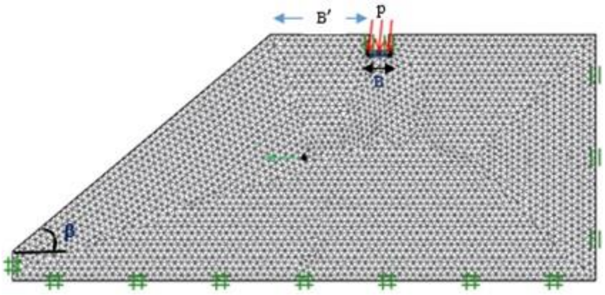


Fig. 1 A typical finite element model used in the study

quadratic interpolation. The displacements are continuous between the elements. The six nodded zero thickness element was used to model the interface of soil and footing. To determine the effect of interface properties, the interface value changed from 0.5 to 1. It was observed that the bearing capacity changing with the interface value. However, the change in BCR is very marginal. To model the rough strip footing, the interface value is assumed to be 1, which does not allow any relative movement between the footing and the soil.

A typical model used in the analysis is shown in Fig. 1. The gradient of the slope, assumed to be uniform throughout the soil slope. Based on the slope geometry and setback distance, the area of the domain was selected large enough to minimize the boundary effect. The width and height of domain were usually maintained 15B and 10B, respectively. However, in few cases (gentle slope and higher value of seismic acceleration coefficient), the width of domain was even increased to 30B. A total of 5000 elements were used in the first iteration. A number of iterations were performed to achieve the stable results (i.e., convergence of collapse load). Mostly, 3-4 iterations were found enough to achieve a stable result. After every iteration, the fineness of mesh is increased. Similar to the present study, a number of other studies have used adaptive iterations to refine the mesh (Lyamin *et al*. 2005, Keawsawasvong and Ukritchon 2016). This permits to achieve accurate results with a lesser time and reasonable computational effort. The cohesionless soil was modeled as a drained material. The shear strength of soil is represented using Mohr-Coulomb model. The angle of shearing resistance of soil (φ) is assumed to be uniform throughout the depth of soil strata. The foundation was modeled as a rigid material of weight equal to concrete weight. The loading was applied in terms of load multiplier directly over the footing, and it is increased continuously till the failure of foundation. The detail of finite element program is provided in Krabbenhoft *et al*. (2015). As mentioned earlier, the load carrying capacity of a footing is estimated based on the ultimate failure. The settlement criterion has not been used in the present study due to the inability of limit analysis

4. Validation of model used in the present study

For validation of model used in the present study, the bearing capacity factors determined in the present study are

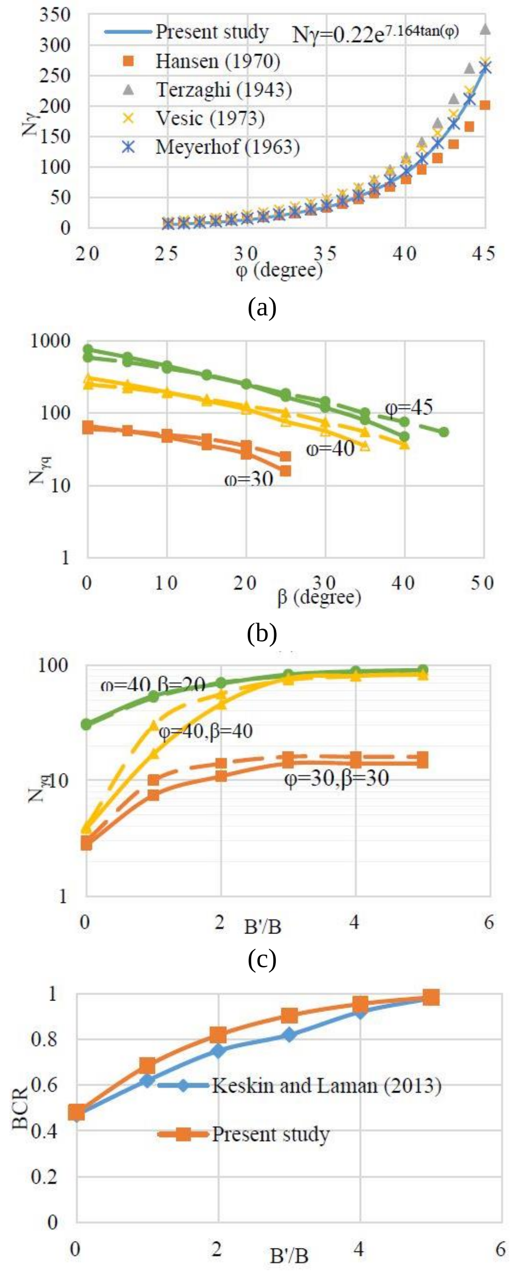


Fig. 2 Comparison of results with published studies: (a) On level ground, (b) On slope (slope inclination effect), (c) On slope (setback effect), (d) On slope (through experiment)

compared with the bearing capacity factors determined in the previous studies, and presented in Fig. 2. In Fig. 2 (a), the bearing capacity factor, $N_{\gamma q}$ for level ground is compared with the conventional theories of Hansen (1970), Terzaghi (1943), Meyerhof (1965), Vesic (1973). In level ground surcharge loading is not present, and therefore, $N_{\gamma q}$ becomes N_{γ}. It is observed that the values of bearing capacity factor from the model are well below of those presented by Terzaghi (1943) and greater than the Hansen (1970) values. However, the values are found very close to Meyerhof (1951), Vesic (1973).

Fig. 2 (b, c), show the comparison of bearing capacity factor, $N_{\gamma q}$ on slopes determined by Meyerhof (1957).

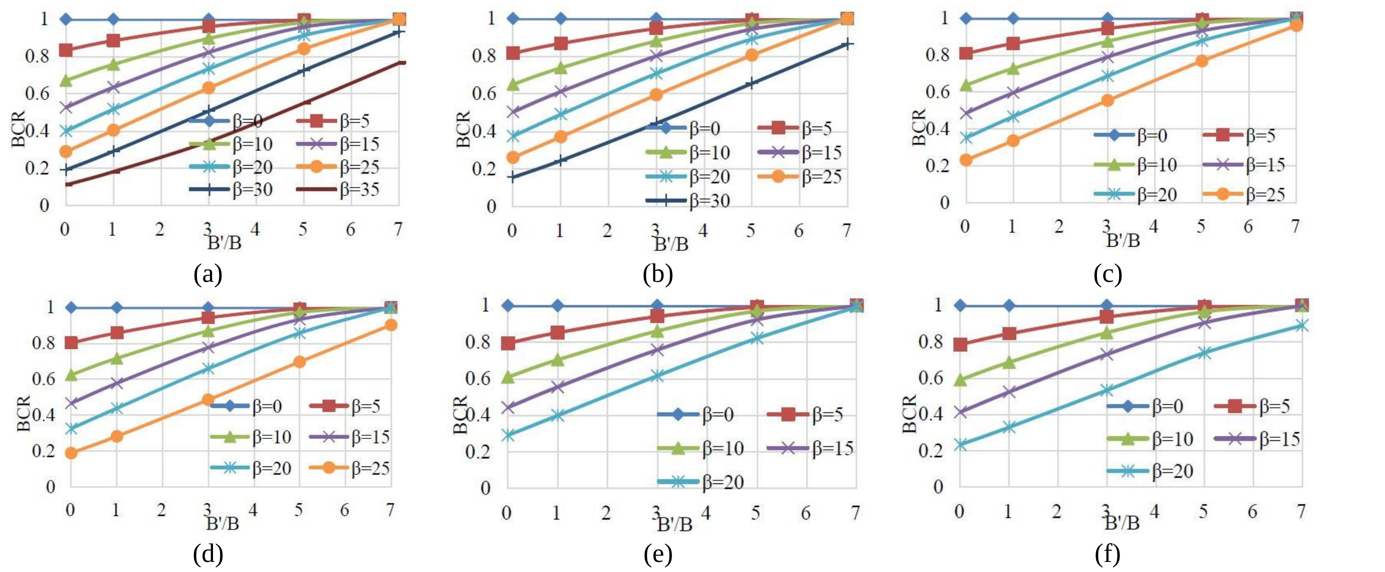


Fig. 3 Effect of setback distance on bearing capacity enhancement for a footing of depth ratio 1: (a) α_h=0, (b) α_h=0.05, (c) α_h=0.10, (d) α_h=0.15, (e) α_h=0.20, (f) α_h=0.25

Bearing capacity factor, $N_{\gamma q}$ considers the combined effect of soil weight and surcharge loading acting above the base of footing. The effect of slope inclination is relatively more noticeable in the present study compared to Meyerhof (1957). The model is also validated with experimental results of Keskin and Laman (2012) for static case on sloping ground, and is shown in Fig. 2(d). The BCR values evaluated from present study up to setback distance of 3B are little higher than the values determined by Keskin and Laman (2012), but these differences are within the acceptable ranges (0-10%). The validation shows that the numerical model used in the present study can predict the bearing capacity of a footing on slopes as well as level ground considering the soil weight and surcharge effect together.

5. Results and discussions

The effect of setback distance on the seismic bearing capacity of strip footing was investigated for a wide range of selected parameters. In addition to the effect of setback distance, the effects of other parameters are also discussed in the sections namely; Effect of slope, Effect of angle of shearing resistance of soil and Effect of embedment depth of footing. The bearing capacity factor ($N_{\gamma qs}$) was also determined for all cases. However, the results are presented for BCR only. The critical setback distance was assessed for a combination of parameters. The threshold setback distance is defined as the lowest distance at which the bearing capacity become independent of slope gradient. The study was carried out for a wide range of parameters, however, typical plots are presented for the soil of internal friction 35°. The method of superposition gives the unconservative results for a footing under seismic loading, and it further increases with the increase in seismic loading (Castelli and Motta 2010). Therefore, to avoid this drawback, the method of superposition has been used, and the bearing capacity factor ($N_{\gamma qs}$) was evaluated by considering the effect of surcharge and soil weight together.

5.1 Effect of setback distance

The variation in BCR with setback distance for a footing with depth ratio 1.0 resting on soil slopes having soil friction angle 35° is shown in Fig. 3. The typical variations are presented for different value of horizontal seismic coefficient (α_h=0, 0.5, 0.1, 0.15, 0.20, 0.25). It shows that the bearing capacity ratio improves with the increase in setback distance. The improvement in bearing capacity with setback distance depends upon slope angle, depth of footing and horizontal acceleration. Though the absolute bearing capacity decreases with the increase in slope inclination and seismic acceleration, the rate of increase in BCR increases with these factors. The relationship between BCR and setback becomes linear with the increase in slope inclination and seismic acceleration.

Similar to static case, higher setback distance is required to achieve a stable BCR in steep slopes i.e., to mobilize the soil strength optimally. This value further increases with increase in horizontal acceleration. The confining pressure and soil intactness increase with the increase in setback distance, which increase the passive resistance from both the slope side (El Sawwaf 2007). The area contributing to bearing capacity also increase with the increase in setback distance. Varzaghani and Ali (2014) observed that the increase in setback distance increases the stiffness of foundation and which increases the bearing capacity of soil. The results of static cases are very much similar to those achieved in static studies of Rostami and Ghazavi (2015) and Keskin and Laman (2012).

The typical variation in failure pattern with setback distances is presented in Fig. 4. It shows the soil deformation for a footing of embedment ratio 1 resting over the slope inclination of 20^0 under a horizontal acceleration of 0.15 g. The Fig. 4 (a-f) shows the change in failure mode

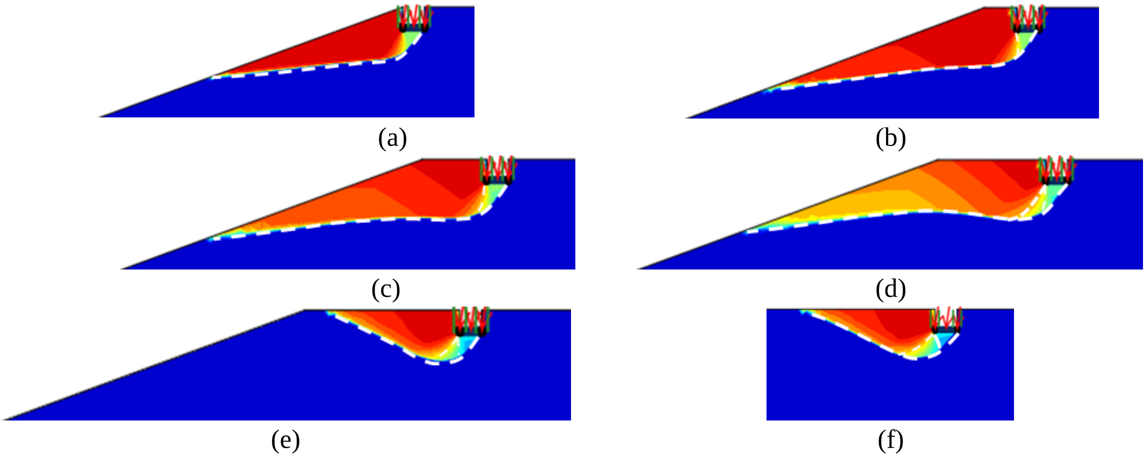


Fig. 4 Effect of setback distance on failure pattern under seismic loading: (a) *B'/B*=0, (b) *B'/B*=1, (c) *B'/B*=3, (d) *B'/B*=5, (e) *B'/B*=7, (f) level ground

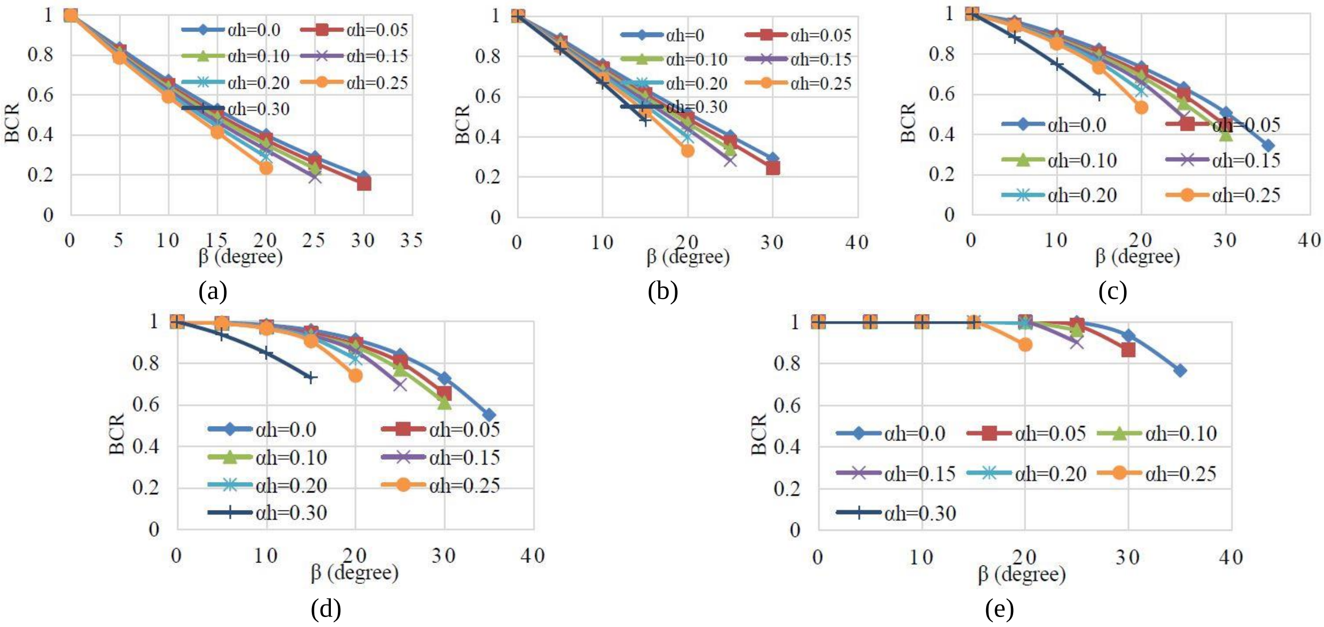


Fig. 5 Effect of slope on enhancement of bearing capacity for a footing of embedment ratio 1.0: (a) *B'/B*=0, (b) *B'/B*=1, (c) *B'/B*=3, (d) *B'/B*=5, (e) *B'/B*=7

with the increase in edge distance. The deformation is large and significant for the footing resting precisely on the slope crest. The interaction between footing and slope decreases with increase in the setback distance, and it decreases with soil deformation below as well as near the footing. The area of large soil deformation within the fracture surface also decreases with the increase in setback distance. The slip lines also change the direction of propagation with the increase in setback distance. The downward movement of slip line changes to upward direction with the increase in setback distance, and become independent of slope inclination at setback of 7B in this particular case. This causes the change in failure mechanism. At the smaller setback distance the footing fails due to sliding and local shear failure, however, at large setback distance, the footing fails under general shear failure.

5.2 The effect of slope gradient

The typical variation in bearing capacity ratio with slope inclination for a footing of depth ratio 1 resting on the soil of angle of internal friction 35° for different setback distance is presented in Fig. 5. The BCR decreases with the increase in slope gradient. Comparing Fig. 5(a-f), it is observed that the rate of reduction in bearing capacity with slope gradient is relatively large in the case of footing resting near or precisely on the slope crest. The rate of reduction further enhances with the increase in seismic loading. The similar observations are made for footings of other embedment depth (*D/B*=0 and 0.5). With the increase in setback distance, the plots between slope inclination and BCR become concave from convex. It indicates the reduction in adverse effect of slope inclination in bearing capacity.

The typical variations in failure mechanism for various slope inclination for seismic acceleration coefficient of 0.20 and setback of 5B are presented in Fig. 6. It shows that not

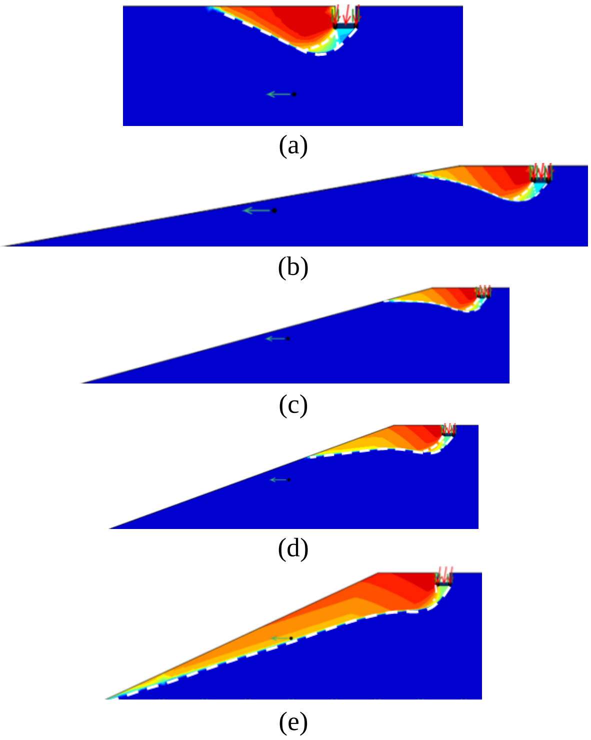


Fig. 6 Effect of slope inclination on failure pattern: (a) without slope, (b) 10°, (c) 15°, (d) 20°, (e) 25°

only area but also shape varies with the slope inclination. For level ground and small inclination, the slip line originated from footing edge and moving toward the upward side indicating general shear failure. This observation is similar to level ground and it indicates the absence of interaction between slope and footing. However, the slip line moves downward and touches to slope surface at large slope inclination, which resulted to failure of foundation at lower load. This indicates the large interaction between slope and footing, at this stage foundation fail due to the instability of slope induced from footing loading rather than bearing capacity failure alone. Furthermore, the cases where foundation fails due to slope failure have not been considered in the regression analysis. Chang *et al*. (2008) and Cure *et al*. (2014) have made observation similar to present study in statics cases. This downward direction of slip line indicates the increased interaction between footing and slope. The interaction further enhances with the increase in seismic acceleration. Therefore, BCR decreases with the increase in slope inclination, and more setback distance is required to mobilize the soil strength.

5.3 The effect of embedment depth of footing

The typical effect of embedment depth of footing on BCR for the soil of friction angle 35^0 for various horizontal seismic coefficient is presented in Fig. 7. Though the bearing capacity increases with the increases in depth ratio of footing, the plotted graphs illustrate that for a particularly considered condition, BCR decreases with the increase in depth of footing. The reduction in BCR with depth of footing becomes more visible with decrease in the edge distance and increase in steepness of slopes. The results of static cases are contrary to Giroud and Tran-Vo-Nhiem (1972) but matching with number of previous studies, such as Meyerhof (1957), Saran *et al*. (1989), Castelli and Motta (2010). Similar to the present study, Narita and Yamaguchi (1990) also found that the effect of embedment depth of footing is significant for steep slopes and footing resting at low setback distance.

At steep slope slopes, the soil on the slope side of the footing contributes to bearing capacity and the soil on the

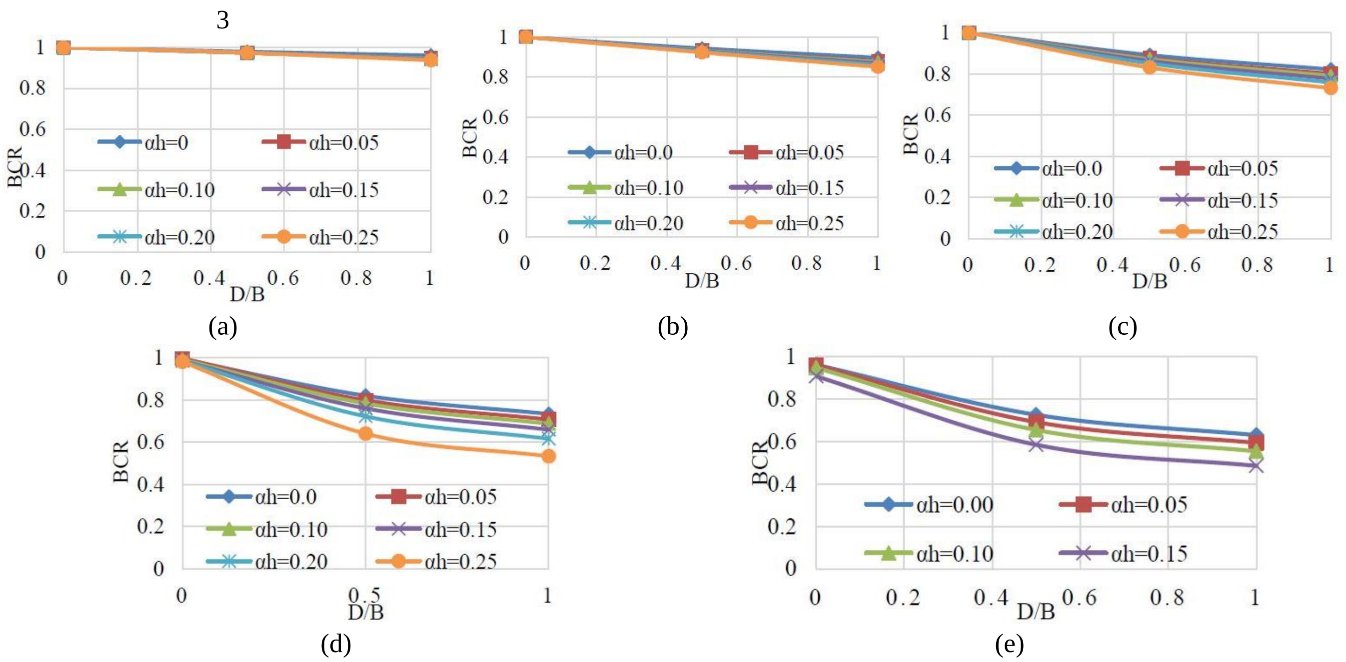


Fig. 7 Effect of friction angle on BCR for a footing resting at a setback distance of 3B: (a) β=5°, (b) β=10° (c), β=15°, (d) β=20°, (e) β=25°

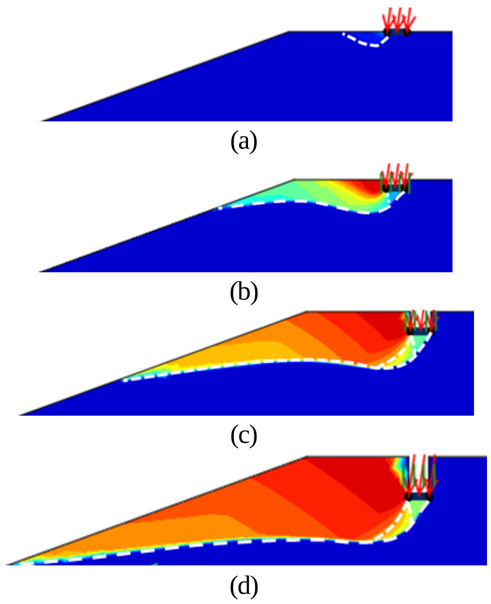


Fig. 8 Effect of footing embedment depth on failure pattern under seismic loading (a) D/B=0, (b) D/B=0.5, (c) D/B=1.0, (d) D/B=1.5

level side does not contribute to bearing capacity. At this stage, a very small percentage of soil surcharge (less than 50%) contribute to bearing capacity. The interaction between slope and slope and soil foundation system enhances with the increase in seismic acceleration. Therefore, the contribution of soil surcharge further reduces with the increase in seismic acceleration (Fig. 7). It reduces BCR, which represent the relative bearing capacity with respect to level ground. The footings of large embedment depth possess the relatively higher bearing capacity and a large area is required to transfer the large load. The required large area can be achieved through an increase in setback distance.

The typical effect of embedment depth of footing on failure mechanism under horizontal acceleration is presented in Fig. 8. At small embedment depth, very small amount of soil interacts with footing and slope. Therefore, a small value of setback distance is enough to achieve a stable state, independent of slope inclination (Fig. 8a). It shows that the magnitude of soil deformation under within slip line increases with the increase in embedment depth of footing. The footing resting on ground surfaces fails due to local shear failure. The inertia forces reducing the bearing capacity, also increases with the increase in embedment depth. The interaction between slope and footing increases with the increase in footing depth. Therefore, BCR reduces with the increase in embedment depth of footing as shown in Fig. 7.

5.4 Effect of friction angle of soil

Fig. 9 shows the typical variation in BCR with the angle of shearing resistance of soil under different seismic acceleration. Results are presented for a footings embedment ratio of 1 resting over the slope of 20° at a setback distance of 3B. The bearing capacity increases

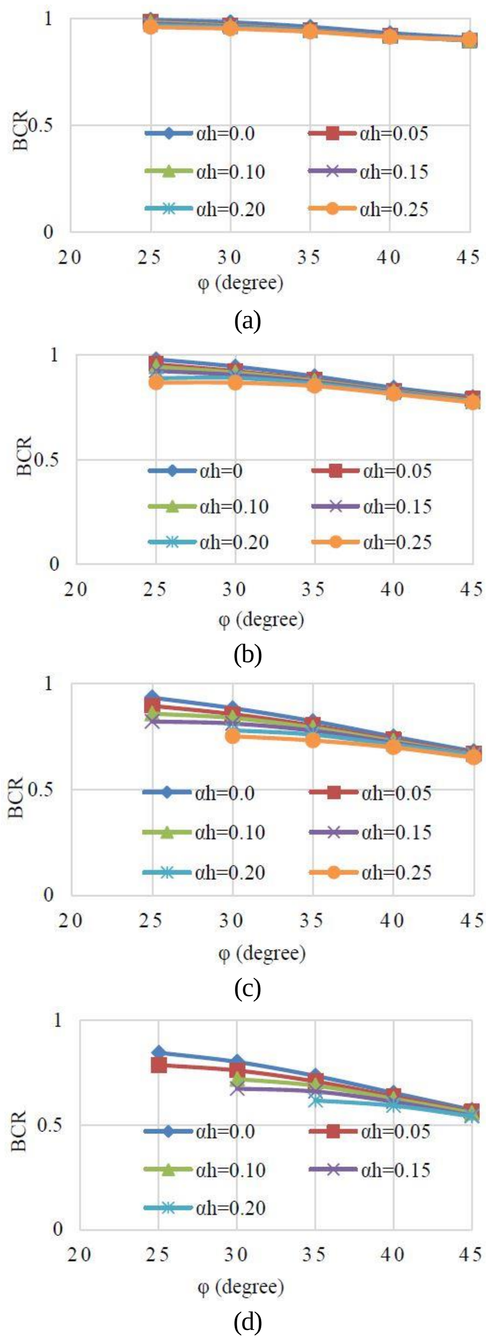


Fig. 9 Effect of friction angle on BCR for a footing resting at a setback distance of 3B: (a) β=5°, (b) β=10°, (c) β=15°, (d) β=20°

significantly with the increase in angle of shearing resistance of soil. However, plots show that the BCR decreases with increase in the angle of shearing resistance of soil. This behavior is observed due to two reasons; first, the increase in bearing capacity with the angle of shearing resistance is relatively large in level ground. The second, the soils of the large angle of shearing resistance possess the large bearing capacity and which needs a large area to distribute the load to the soil. Therefore, for a given slope inclination, embedment depth, and setback distance, the BCR reduces with the increase in angle of shearing resistance of soil. The reduction in the BCR with an

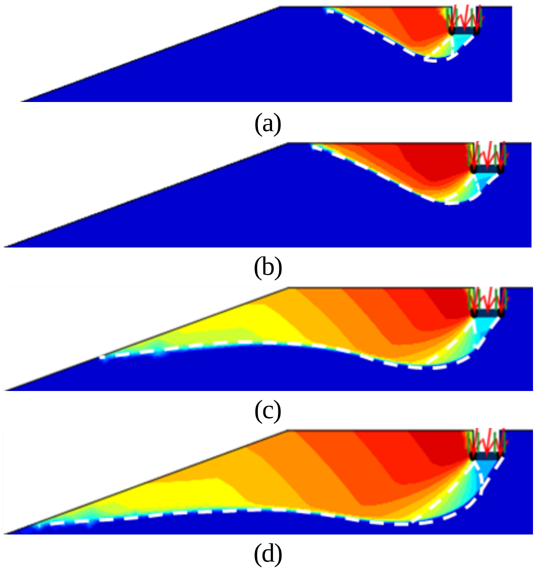


Fig. 10 Effect of friction angle on failure pattern: (a) φ=30°, (b) φ=35°, (c) φ=40°, (d) φ=45°

increase in the friction angle enhances with the increase in slope angle and decrease in the setback distance. The similar observation was made for case of static analysis in the previous studies (Rostami and Ghazavi 2015, Shukla and Jakka). The reduction in BCR with the increase in angle of shearing resistance of soil becomes more evident with the increase in seismic acceleration.

The reduction in BCR with soil internal friction angle can be easily explained through the Fig. 10. The Fig. 10 (a, b, c, d) are presented for a footing of depth ratio 1 resting on a slope of inclination 20° at a setback distance of 7B. The area of shear zone increases with the increase in angle of internal friction of soils. Footing of higher embedment depth resting over dense soil possess higher load carrying capacity, and the large load needs to distributed over a large area, therefore, a large setback distance is required to mobilize the optimum strength of soil.

Hence the critical setback distance increases with the increase in relative density of soil and embedment depth of footing. The area of shear zone remains independent of slope inclination in footings resting over the soils of friction angle 30^0 and 35^0 (Fig. 10 a, b). However, for the soils of internal friction of 40^0 and 45^0, there is an interaction between slope and foundations, and the shear zone does not develop completely (Fig. 10 c, d). Therefore, the BCR is relatively less in dense cohesionless soils. This behavior is very much to those observed due to increase in depth of footing.

5.5 Effect of horizontal seismic coefficient

The effect of the increase of horizontal seismic coefficient in BCR is presented in Fig. 11. The increase in horizontal seismic coefficient reduces the bearing capacity factor as well as BCR of footing. The reduction in BCR is observed due to decrease in area of shear zone and increases interaction between slope and footing, which further reduces the bearing capacity of footing. It is observed that

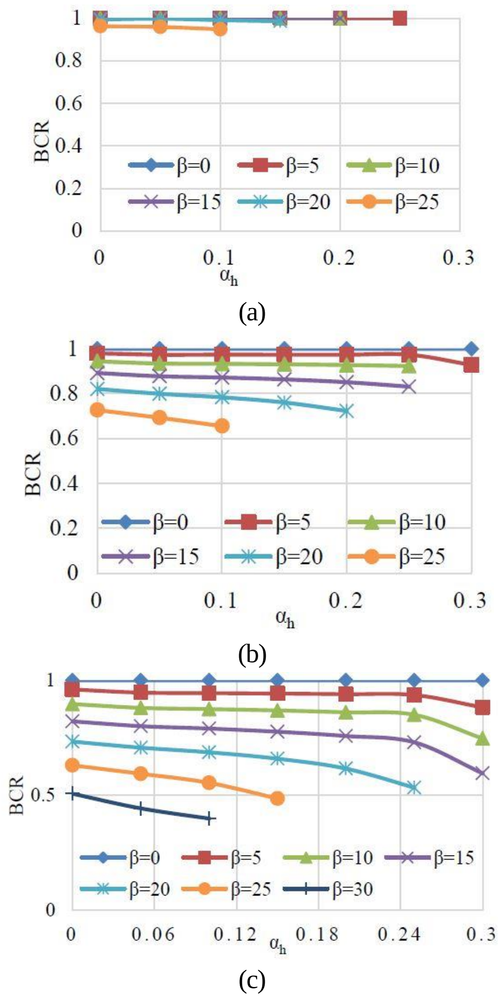


Fig. 11 Effect of seismic acceleration on BCR: (a) D/B=0, (b) D/B=0.5, (c) D/B=1.0

the effect of seismic acceleration is severe in the case of steep slopes than level ground. The interaction between slope and footing escalates with the increase in seismic acceleration. This induces a negative impact on bearing capacity improvement and a higher setback distance required to achieve the stable state.

The effect of seismic acceleration on footing bearing capacity increases with increase in the depth of footing. The capacity of footing of large depth possess higher bearing capacity, and therefore, higher shear force at the base of footing due to seismic loading. The inertial force and kinematic interaction increase also with increase in the depth of footing. Therefore, bearing capacity factor reduces with significantly in case of footings with small depth of embedment. The footing resting on surface of ground level fails either by sliding or overturning without much interaction with foundation soil (Fig. 8a).

On the basis of results of numerical analyses, the critical setback distance is identified for a combination of parameters and presented in Table 2. The critical setback distance increases with the increase in pseudo-static acceleration, footing depth and internal friction of soil. The strength of soil and area of shear zone below footing under seismic loading decreases with the increase in seismic

Table 2 The critical setback distance for strip footing on cohesionless soil slope

Friction angle (φ°)	Slope angle (β°)	Horizontal seismic coefficient (α_h)	Critical setback distance (B'/B)	Critical setback distance, static case (B'/B)
25	0-20	0-0.20	2-5	2-3
30	0-25	0-0.25	5-8	5-6
35	0-30	0-0.30	7-11	7-8
40	0-35	0-0.30	9-14	9-10
45	0-40	0-0.30	>15	>12

acceleration in level ground, and similar observation is also made in case of slope. However, the increase in the seismic loading increases the interaction between slope and foundation. This increases in the interaction, pushes the slip lines downward and toward slope setback significantly, consequently the critical setback at which foundation becomes independent to slope increases greatly. The difference in optimum setback distance in static and seismic cases becomes more evident with an increase in the strength of soil.

6. Statistical analysis

A nonlinear multiple regression and correlation analysis along with other statistical tests were performed to derive equations to determine the critical setback distance, bearing capacity factor ($N_{\gamma qs}$) and BCR of a footing resting over cohesionless soil. It is observed from the numerical analyses that a total of five independent variables (i.e., setback distance, slope inclination, soil friction angle, depth ratio of footing and seismic acceleration) influences the seismic bearing capacity of a footing resting near the slope. Similarly, critical setback distance depending on four independent variables, namely, angle of internal friction of soil, slope inclination, seismic acceleration and depth ratio of footing. It is observed that the relationship between independent variables and dependent variable (bearing capacity ratio, seismic bearing capacity and critical setback distance) is not linear, and therefore, it is obligatory to consider the nonlinearity in development of regression equations for seismic bearing capacity factor and BCR. The precise nonlinearity in the relationship is not known initially, therefore it was supposed that BCR is not only depending on these 5 variables but also upon various other derivatives as well. Approximately, 7000 data have been used to carry out statistical analysis.

Initially, a total of 55 variables, which are the function of 5 independent variables are considered in the regression analysis to develop equations to compute bearing capacity ratio and seismic bearing capacity factor. *T*-Tests were performed to determine the dependency of BCR and bearing capacity factor on these variables. The degree of multi-collinearity was used to remove the insignificant variables. It was found from these studies that only 20 variables, including five basic variables critically affect the bearing capacity ratio. Latter these 20 variables were used to develop the equation for bearing capacity ratio as well as seismic bearing capacity factor. It is found that R^2 reduces from 0.991 to 0.953, when number of insignificant variable were reduced from 55 to 20. It ensures that the all assumed dependents variables are not affecting bearing capacity significantly as assumed in the initial phase of regression analysis. In development of regression equation for critical seismic bearing capacity factor, 20 variables were used, which reduces the R^2 from 0.986 to 0.943. Similarly, in development of regression equation for critical setback distance, 10 variables in addition to four basic variables were used. This reduces the final R^2 to 0.981 from 993.

Based on statistical testing, the following factors are found to be affecting the bearing capacity critically in the order of their influence: Slope inclination>angle of internal friction angle of soil > Seismic acceleration > Depth ratio of footing > Setback distance. This order provides the relative importance of various factors, which helps the practicing engineer in planning and design of foundations and suitable remedial measures. The internal friction of soil is an important factor, indicates the soil resisting against driving force indicated by slope inclination and seismic force. The influence of depth of footing and setback distance is relatively less as compared to angle of internal friction of soil. The embedment depth of footing contributes to stability and bearing capacity of footing, has relatively larger influence than setback distance. Increasing the depth of footing not only increases the resisting force due to surcharge loading but also increases the effective setback distance. Whereas, increase in the setback increase the distance between slope edge and footing, which provides additional stability to footing as it increases soil strength mobilization.

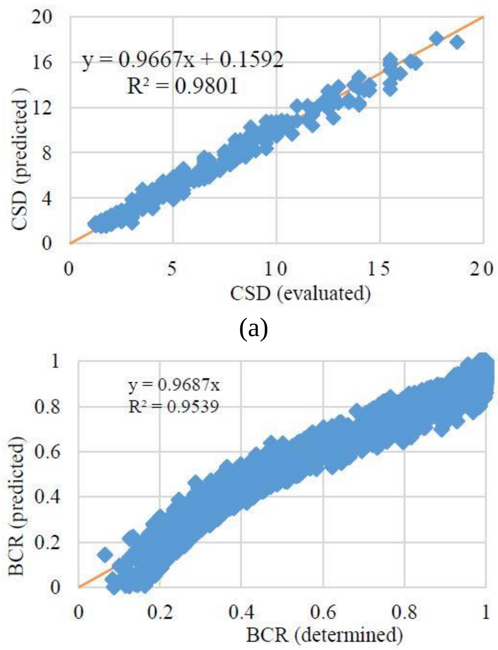
Eq. (1) has been developed to determine the critical setback distance (CSD) for a footing resting on the slope crest on near to slope. The comparison of evaluated critical setback distance and evaluated BCR values with predicted values are presented in Fig. 12. It shows that the Eq. (1) and Eq. (3) predict the critical setback distance and BCR, respectively, very precisely considering the effect of slope geometry, seismic acceleration and embedment depth of footing. Eqs. (2) and (3) respectively shows the bearing capacity factor ($N_{\gamma qs}$) and BCR equation developed to determine the influence of slope geometry, seismic acceleration and angle of internal friction of soil.

$$\begin{aligned}\mathrm{CSD} &= 4.5 - 2\mathrm{D/B}(1 - 0.4\mathrm{D/B} - 1.65\alpha_h) - 13.4\beta(1 - 0.45\beta - 0.4\mathrm{D/B} - 2\tan\varphi) \\ &\quad - 18.5\alpha_h(1 - \alpha_h - 3\beta) - 8.5\tan\varphi(1 - 0.67\tan\varphi - 2.4\alpha_h - 0.2\mathrm{D/B}\end{aligned} \tag{1}$$

$$\begin{aligned}N_{\gamma qs} &= 200 + \beta(630 + 5.5\beta - 1038.4\tan\varphi + 732.4\alpha_h) + \tan\varphi(1080\tan\varphi \\ &\quad - 1006.6 + 384D/B + 43B'/B) + D/B(9.2B'/B - 15.3D/B \\ &\quad - 96.3 - 301.5\beta) + B'/B(35.6\beta - 0.54B'/B - 28.5 - 42\alpha_h) \\ &\quad + \alpha_h(940\alpha_h + 1282 - 2268\tan\varphi - 371.4D/B)\end{aligned} \tag{2}$$

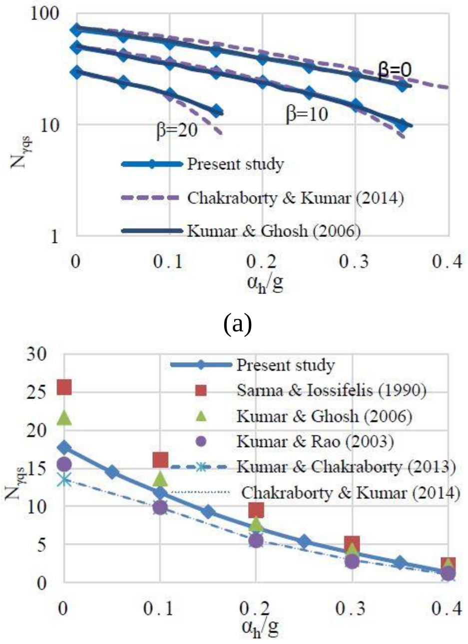
$$\begin{aligned}BCR &= 1 - 0.9\beta(1 + 0.35D/B + 0.7\tan\varphi + 1.4\alpha_h - 0.03\beta) \\ &\quad - 0.025\tan\varphi(1 + 2.5\tan\varphi - 20\alpha_h + 1.75B'/B) \\ &\quad - 0.15D/B(1 + 0.25B'B - 0.75D/B - 0.75\tan\varphi) - 0.4\alpha_h(1 + 0.4\alpha_h \\ &\quad + 0.25D/B) + 0.1B'/B(1 - 0.05B'/B + 0.5\alpha_h + \beta)\end{aligned} \tag{3}$$

$$\text{Seismic Bearing capacity} = \frac{1}{2}B\gamma N_{\gamma qs} \tag{4}$$



(b)

Fig. 12 Comparison of values determined with predicted values: (a) CSD, (b) BCR



(b)

Fig. 13 Validation of proposed equation: (a) For D/B=1.0 and different slope inclination, (b) For D/B=0.0 and β=0°

$$\text{Seismic bearing capacity on slope} = BCR(\text{seismic bearing capacity on level ground}) \quad (5)$$

where, CSD=critical setback distance, $N_{\gamma qs}$=seismic bearing capacity factor considering the combined effect of soil weight and surcharge loading, BCR=Bearing capacity ratio, B'=setback distance, B=width of footing, α_h=horizontal acceleration coefficient, β=slope inclination in radian, D=depth of footing and φ=angle of internal friction of soil in degree.

Various type of functions, such as, linear, exponential, polynomial and logarithmic, functions were initially assumed and finally the best relationship was used to develop these equations. These equations (Eqs. (1), (2) and (3)) can be used further for static case as well by keeping α_h value to be 0. Seismic bearing capacity of footing on slope can be evaluated by using Eq. (4). The value of $N_{\gamma qs}$ is to be obtained from Eq. (2). The form of Eq. (4) is similar to the one proposed by Meyerhof (1957) for static case on slopes. Alternatively, the seismic bearing capacity of footing on cohesionless soil slope can be directly determined by using Eq. (5), if the seismic bearing capacity of same footing on level ground is already known. The seismic bearing capacity of footing on level can be determined directly using earlier presented method.

7. Comparison of results with previous studies

For validation of equation presented in the study, the bearing capacity factor determined in the present study is compared with the bearing capacity factor determined in the previous studies, and presented in Fig. 13. In Fig. 13(a), the bearing capacity factor, $N_{\gamma qs}$ is compared for the footing of depth ratio one resting over the soil of angle of internal friction of 30° with Kumar and Ghosh (2006), Chakraborty and Kumar (2014), where setback distance was not considered. The setback distance was not considered in both these studies and footing was considered to be resting on the slope and which is completely different from present study. Therefore, the geometry of slope and footing location was made similar to the previous studies in order to make results of present comparable with the both studies. The footing is assumed to be resting on the level ground, the slope of 10° and 20°. The values of $N_{\gamma qs}$ decreases with seismic acceleration and is found very close to those achieved in previous studies.

The results are also compared for the footing resting on the surface of the level ground (D/B=0, β=0°) and presented in Fig. 2(b) with a number of previous studies. The variation of bearing capacity factor, $N_{\gamma qs}$ obtained from the present analysis for φ=30°, D/B=0 for different values of seismic accelerations are compared with the limit analysis solution of Sarma and Iossifelis (1996), method of the stress-characteristics solution presented by Kumar and Rao (2003), the upper-bound limit analysis solution of Kumar and Ghosh (2006), the lower-bound theorem analysis of Kumar and Chakraborty (2013) and Chakraborty and Kumar (2014). Fig. 13(b) shows that the results are the lower side of those achieved through upper bound solutions. The results are the higher side of those achieved through the lower bound analysis and method of the stress-characteristics. The Fig. 12(b) also shows that the equation proposed in this study gives the value of seismic bearing capacity factor close to the average of previous studies. Therefore, it can be stated confidently that the bearing capacity determined using Eq. (1) can be neither uneconomical nor on unsafe side for both static as well as seismic bearing capacity determination.

Kumar and Rao (2003) presented equations for bearing capacity factors (N_γ and N_c). Later, Yamamoto (2010) also provided an equation to determine the seismic bearing capacity. However, these presented equations are infeasible for practical use due to highly complicated nature and longer length. Contrary to present study, these previous equations do not consider the all possible factors affecting the seismic bearing capacity together in one equation, such as edge distance, slope inclination, soil strength, depth of footing and seismic forces.

Critical setback distance estimated for different cases in the present study, has also been compared with various codal provisions given standard codes. Uniform building code (1997) and International Residential Code (2015) suggest the maximum setback to be H/3 or 12 m, whichever is minimum. However, when slope inclination is greater than 45°, the setback distance needs to be measured from an imaginary intersection point on ground surface, obtained by drawing a line originating from slope toe and making an angle of 45° with horizontal surface. Indian standard IS: 1904-1986 suggested that a footing should be placed at a distance of 0.9 m from the slope surface. However, IS code does not specify anything about a footing resting near to slope crest. In the present study, the critical setback is varying approximately from 2 to 36 m or 0.15H to 1.3H depending on a number of parameter, which is significantly different and higher than the values suggested in codes. The study further highlights the fact that a constant value of setback distance suggested in codes irrespective of slope geometry, foundation and soil properties, is not appropriate.

8. Conclusions

The presence of slope near to footing increases the soil deformation and decreases the bearing capacity of the footing. The earthquake further reduces the stability of slope and bearing capacity of footing. Seismic bearing capacity is minimum when footing is resting precisely on the slope crest and it improves with an increase in setback distance. The critical value of setback distance is identified in this study and found to be varying from 2B to 17B depending upon a number of factors. However, currently, standards suggest setback distance mainly based on slope height and slope inclination. The current study clearly highlights the need for setting the setback distances based on soil properties, seismic acceleration, foundation and slope geometry. The critical setback distance required for optimum mobilization of soil strength increases with the increase in the depth of footing, the density of soil, seismic acceleration and slope inclination.

The rate of increase in BCR with setback distance is found to be higher in the case of a steep slope though the BCR is always less in a steep slope. The influence of slope inclination becomes substantial with the increase in seismic coefficient. The BCR decreases with the embedment depth of footing. The effect of embedment is relatively large when footing depth ratio increases from 0 to 0.5 and BCR decreases with a relatively smaller rate with further increase in the depth of footing. The effect of footing depth is relatively significant in steep slope as compared to level ground. Though, the bearing capacity increase with soil friction angle, the BCR is decreasing with soil friction angle. The rate of decrease in the BCR with soil friction angle is large in steep slopes under low seismic acceleration.

The area of shear zone increases with the increase in depth of footing, setback distance, and soil friction angle. However, it decreases with seismic acceleration and slope inclination. The failure surface is turning upward with an increase in relative density and setback distance, whereas it turns downward with an increase in the slope inclination and seismic acceleration due to an increase in the interaction between slope and footing. The large interaction leads to failure of foundation due to the instability of slope rather than bearing capacity failure alone. Two separate equations were proposed to determine the seismic baring capacity factor ($N_{\gamma qs}$) for slopes and change in seismic bearing capacity (BCR) with respect to level ground. The proposed equation gives the value of seismic bearing capacity factor. The critical value of setback can also be determined very precisely with proposed equation.

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Notations

The following are symbols and notations used in present paper:

B	= width of footing
B'	= setback distance
D	= depth of footing
p	=loading (kN/m)
CSD	=critical setback distance
D/B	= footing depth to footing width ratio
B'/B	=setback to footing width ratio
BCR	= bearing capacity ratio
CSD	= critical setback distance
N_{γ}	=bearing capacity factor considering soil weight only
$N_{\gamma q}$	=bearing capacity factor considering soil weight and surcharge together
$N_{\gamma qs}$	=seismic bearing capacity factor considering soil weight and surcharge together
α_h	= horizontal seismic coefficient
β	= slope inclination
φ	= angle of internal friction of soil