Stability Analysis of Soil Slopes Subjected to Foundation Loads during Earthquakes

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Abstract. The stability of slopes subjected to foundations loads near the top of the slope has been investigated in the present study. The c-ϕ soil slope with different width and embedment depth of foundation has been considered here. In the present study, the building load is considered as a surcharge load on the slopes. Strength reduction method has been adopted to investigate the variation of Factor of safety (FOS) of slope against the different parameters of the imposed load and slope angle. The earthquake force has been considered as fixed body force within the soil mass. From this study, the FS decreases with the increase of building or foundation loads and at a certain distance from the edge of the slope, the FOS remained constant. The improvement of FOS has been observed with the increase of embedment depth of footing for all surcharge loads. The rapid reduction of FOS has been noted when foundation load is increased on slopes in both static and seismic case.

Keywords: Slope Stability, Foundation loads, Strength reduction method, Setback distance, Earthquakes.

1 Introduction

The design of shallow foundations in hill slopes is a challenging task for geotechnical engineers since ancient days. Recently due to lack of land or increase in population, the construction of building in hilly areas are increasing. Several researchers have reported that the bearing capacity decreases with the increase of slope angle for both static and seismic conditions. The slopes get more unstable which are marginally stable before earthquake and the existing or newly constructed building loads may create a vulnerable situation. Last few earthquakes for example 2005 Kashmir earthquake and 2011 Sikkim earthquake have shown the vulnerability of commercial buildings in slopes and hilly areas. Therefore, stability of the existing slopes should be checked before designing any structure on slopes.

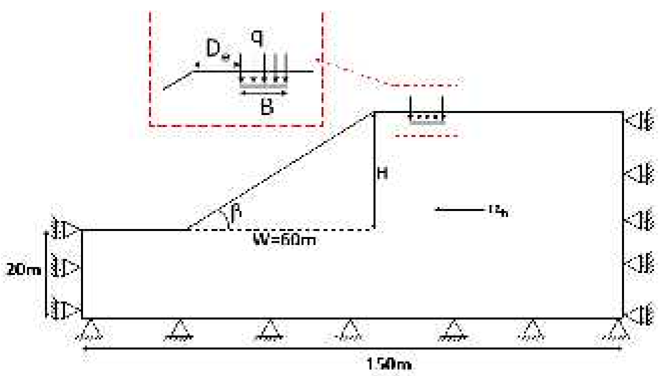
It is expected that when a footing placed at the crest of the slope the stability of the slope should be reduced. Although it depends on edge distance of footing, embedment depth and imposed loads on footing. Meyerhof [1] proposed an analytical formula for estimation of bearing capacity of footing on the face and near the top of the slope. Several researchers performed experimental and theoretical investigation to determine bearing capacity of footing on slopes [2-8]. In most of the study, it has been observed that the bearing capacity decrease with the increase in the slope angle. However, with the increase of edge distance (3-5times of footing width) of footing from crest of the slope the bearing capacity is not dependent on slope angle. Keskin and Laman [8] performed small scale experimental test and numerical analysis to determine the bearing capacity of footing on slopes. They also checked stability of that slope after applying ultimate load on the footing. Numerical model study has been also carried by many researchers for the evolution of bearing capacity factors of footing on slopes [9-13]. Archaryya and Dey [13] studied bearing capacity of footing near the top of the soil using Finite Element Method and compared with past experimental results. Raj et al. [14-15] investigated the stability of the slope under the building loads. They reported that stability of slopes increases with the increase of footing width and its distance from the slope. Although, they considered footing on the face of the slope. Baah Frempong and Shukla [16] studied the stability of cohesionless soil slope supporting an embedded strip footing. This study is limited on static and sandy type of soil.

In the present study, the stability of the c-ϕ soil slope subjected to strip footing loads has been studied for both static and seismic conditions. Different influence factor on stability of slopes has been studied such as loading factor [*q/¥H*, where, *q* = Load intensity (kN/m^2), γ = Unit weight (kN/m^3) and H= Height of slope (m)], Embedment depth ratio [D_f/B, where, D_f = Depth of footing from ground level, *B* = Footing width] and setback distance [D_e/B, where, D_e = Distance of footing edge from crest of slope, *B* = Footing width]. Duncan [17] reported, the shear strength of soil must be divided by factor of safety (FOS) to bring the slopes on the verge of failure point. Which is commonly known as strength reduction method (SRM). A finite element limit analysis (FELA) uses optimization techniques to directly compute the upper or lower bound plastic collapse load (or limit load) for a mechanical system rather than time stepping to a collapse load, as might be undertaken with conventional non-linear finite element techniques [18].

2 Numerical Modeling

In the present study, two homogeneous soil slopes (slope angle, β 20^0 and 30^0) under the foundations loads have been studied. The soil properties have been taken from Panigrahi et al. [19] where the site is located at hilly terrain within the Mizoram state as shown in Table. 1. The strip footing width (*B*=1, 3 and 5m) at an edge distance (D_e=0, 3, 6, 9, 12, 15, 18 and 21m) from the crest of the slope has been considered. The footing embedment depth (D_f =0.5, 1 and 2m) effect on stability of slopes also studied. A schematic diagram of slope subjected to footing loads is presented in Fig. 1.

The 2D finite element limit analysis (FELA) based on strength reduction method (SRM) has been adopted to check the stability of slopes under the footing loads. In



SRM methods, the soil strength reduced by a factor and at verge of failure factors are represented by strength reduction factor or factor of safety of the slope [20-22]. An elastoplastic constitutive model based on Mohr-Coulomb failure criterion and following associated flow rule has been used for soil modeling in FELA. The strip footing modeled as a steel plate with Young's modulus (*E*) compare to soil. A uniformly distributed load (UDL)has been applied to represent the super structure loads. The boundary conditions are considered in such a way that the bottom is fixed against both (horizontal and vertical) directions. While vertical edge is fixed laterally (horizontal) and free to move vertically. The model dimensions have been chosen by several trial, where the effect of boundary condition is insignificant. The sensitivity analysis has been performed for optimum (number of element at which FOS are not changing much) meshing and approximately at 8000 elements are sufficient for the present study. The 15noded triangular plane strain elements has been considered. Loukidis and Salgado [23-24] reported that the 15-node elements have the fastest convergence with adaptive free meshing where it yields particular location of failure slip surface in Optum G2. In this meshing additivity system needs lesser number of elements to produced accurate results. A fixed body force within the soil mass has been considered in the present study.

Fig. 1. Schematic diagram of slope subjected to footing loads.

Table 1: Basic Soil Properties (after Panigrahi et al. [20])

Descriptions	**Values**
Unit weight, ¥ (kN/m^3)	20
Poisson's ratio, «	0.3
Cohesions, *c* (kPa)	15
Angle of internal friction, ¤:(Degree)	30
Young's modulus, *E* (MPa)	250

3 Results and Discussions

In the present study, using FELA method the stability of slopes in terms of factor of safety (FOS) with different condition of footing has been studied. Keskin and Laman [8] performed experimental test for bearing capacity of footing on slopes and checked FOS by limit equilibrium method. For the FELA and keeping same parameters, a comparison has been shown in Table 2. It can be observed that there is a good agreement between the test results and the present study. The maximum value of q considered in the analysis is 800kPa.

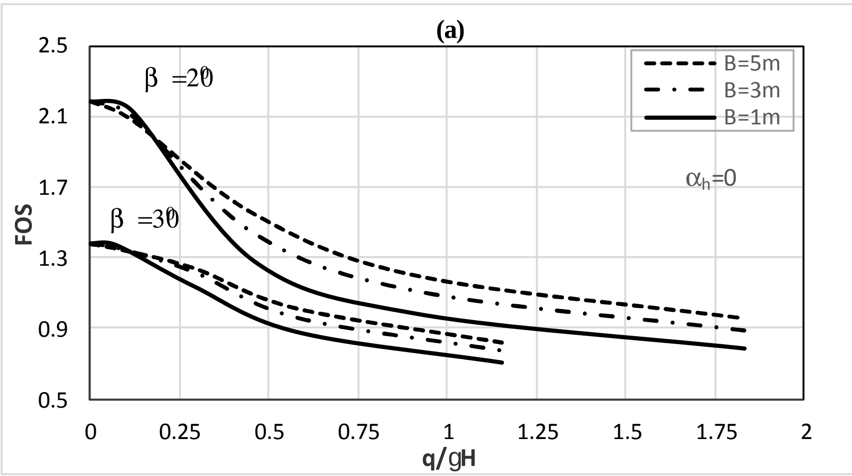


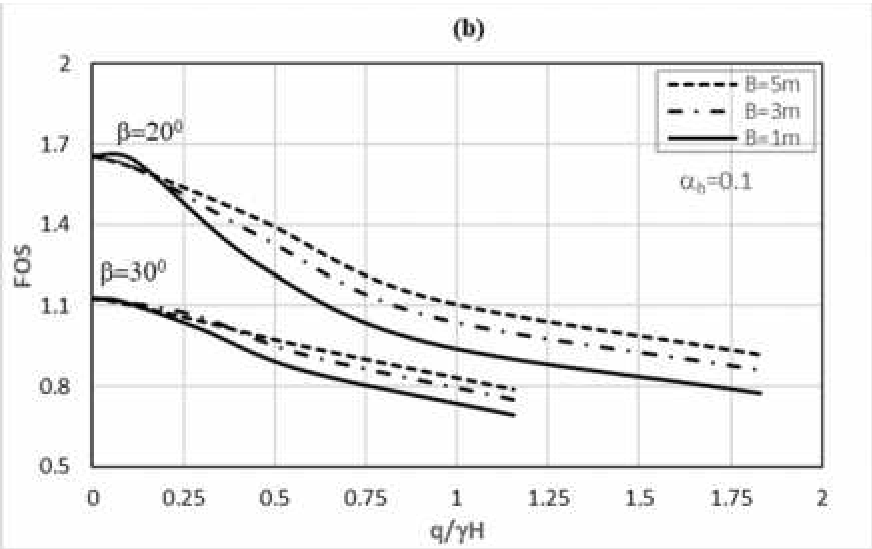
Fig. 2. Variation of FOS vs. Loading Factor for different slope angle for D_e=3m, D_f= 0.5m: (a) Static case (b) Seismic case.

Table 2: Comparison of bearing capacity, q_u (kPa) and FOS

	Qu (kPa)		FOS at 60kPa load	
D_f/B	(K&L)	Present Study	K&L	Present Study
0	31.50	33.61	1	1.03
1	56.70	57.33	1.86	1.84

Note: Results of Footing Located at Different Locations from the Slope Crest (β=30°, D_r=65%, B=70 mm), K&L means Keskin and Laman [8].

A strip footing located at the top of the slope (20^0 and 30^0) for different footing width and load factor has been analyzed. It is clear from the Fig. 2 (a, b) that with the increase of footing load, factor of safety (FOS) of the slope reduced for both static and seismic cases. At 30^0 slope the load carrying capacity quite less compare to 20^0 slope. It can be observed that for small surcharge i.e. upto load factor 0.12 there is not much effect of footing width on FOS. This phenomenon is known as global (overall stabil-



ity of slope) and local failure (bearing capacity of footing) problem as explained by Paul and Kumar [25]. In local failure problem, when footing width increases the bearing FOS increase. Therefore, the FOS of the slope also increases with the footing width. A total displacement of slopes for loading factor 1 for 20^0 Slopes has been presented in Fig. 3 *(i-iii*). In Fig. 3 (*iii*) for footing width 5m the deformation is more. As footing width increases the contact pressure is also increase and deformation increases as loading intensity is fixed (q in kN/m^2).

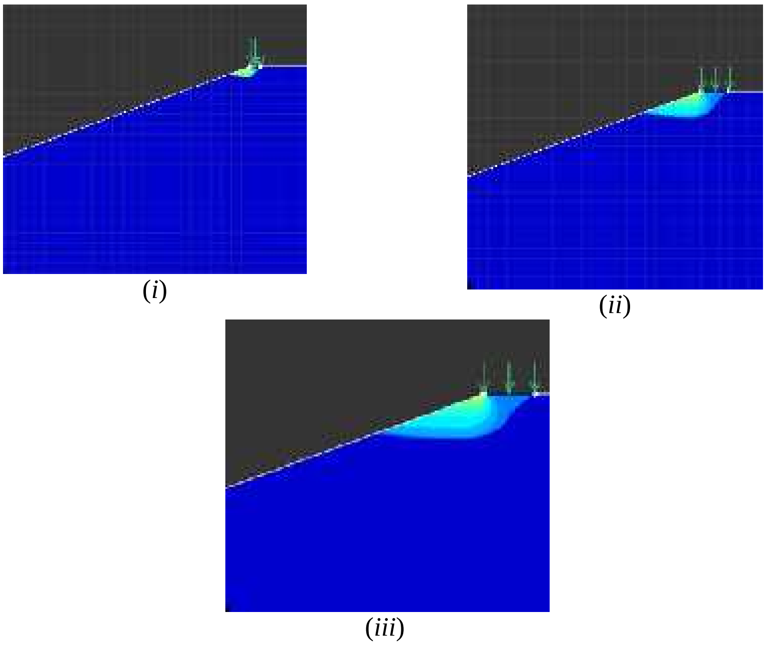
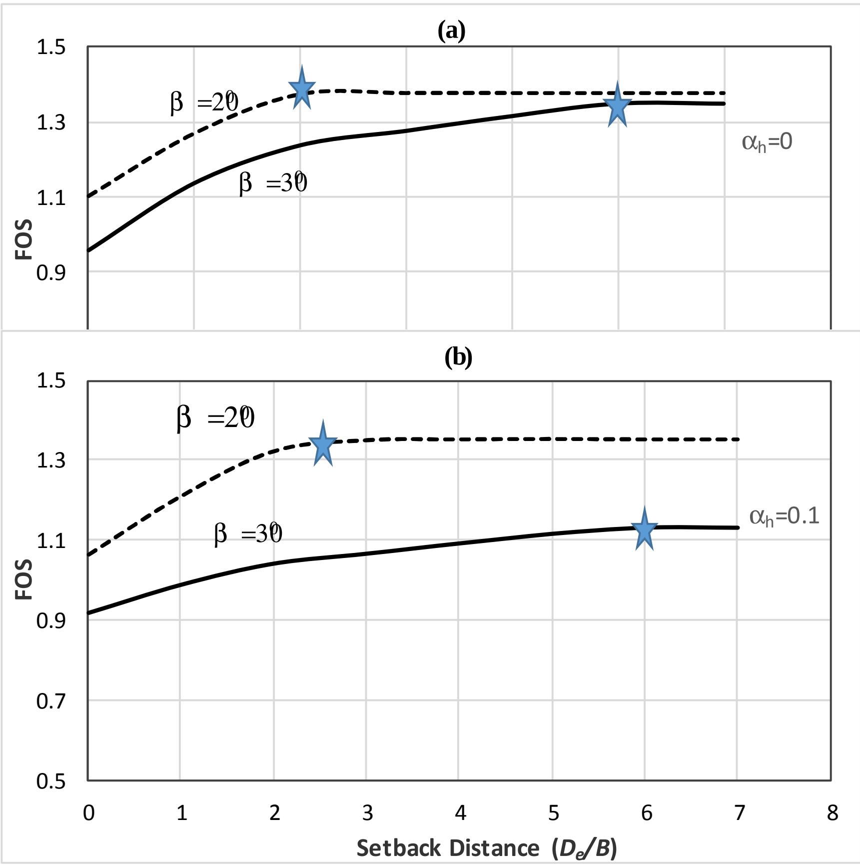


Fig. 3. Slope failure pattern for different footing with for β=20°, q=300kPa, α_h=0 and D_f=0m: (i) B=1m (ii) B=3m and (iii) B=5m.

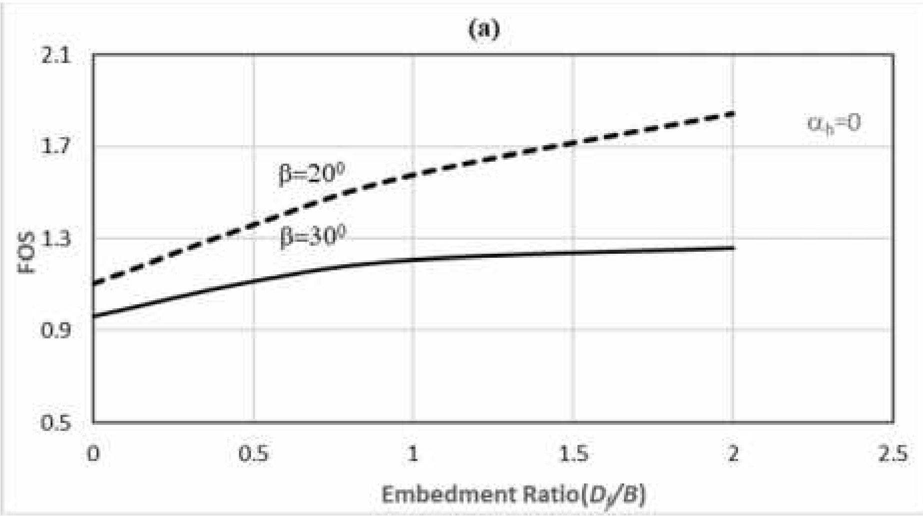
With the increase of setback distance the effect of slope angle on bearing capacity of footing and FOS of slopes gets decreases. At a certain setback distance of the bearing capacity of footing is constant or not influenced by slope angle and this distance is called as critical setback distance. For bearing capacity problem, the critical setback distance 2-5 times of footing width for static case and 3-9 times of footing width for seismic case [13, 26]. The same trend has been found in this study but different criti-



cal setback distance.

Fig. 4. Variation of FOS vs. Setback Distance (D_e/B) for different slope angle for q=300kPa, D_f=0m and B=3m: (a) Static case (b) Seismic case.

From the Fig. 4 (a, b), the critical setback distance is found 2 times of footing width for static case and 2.5 times of footing width for seismic case for 20^0 slopes. For 30^0 slopes, 5 and 5.5 times of the footing width respectively. An overall critical setback distance can be identified from this study and past research based on bearing capacity problems. For seismic cases the critical distance may vary for different seismic coefficient. Therefore, at 20^0 slope after setback distance 2-2.5 times of footing width goes into a local failure problem. Similarly, 30^0 slope after 5-5.5 times of the footings width the failure get transfer from global failure to local failure.



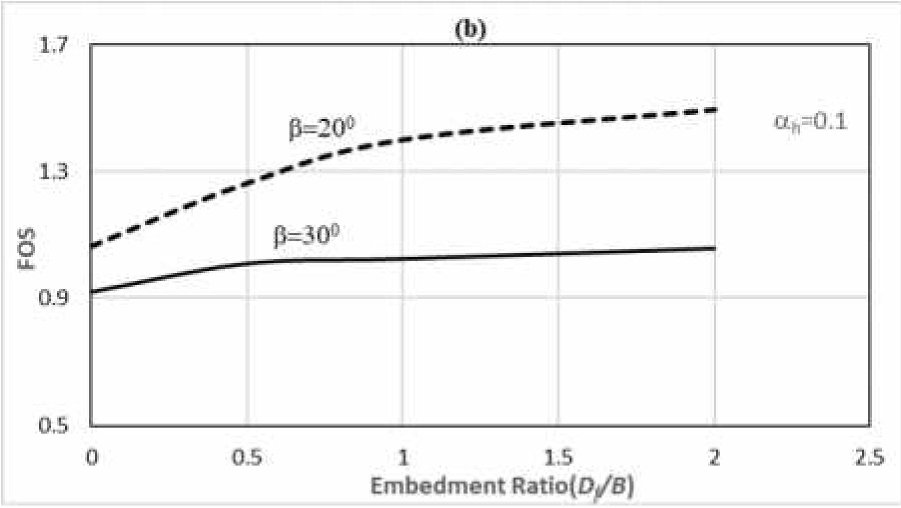
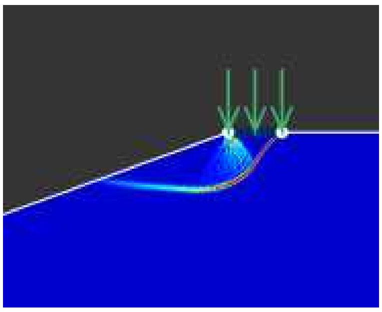


Fig. 5. Variation of FOS vs. Embedment Ratio (D_f/B) for different slope angle for q=300kPa, De=0m and B=3m: (a) Static case (b) Seismic case.

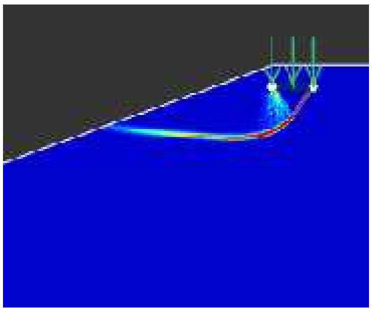
Table 3: Critical setback distance (m)

	Slope angle 20^0	Slope angle 30^0
Static	2	5
Seismic	2.5	6

The effect embedment depth (D_f) on stability of slopes has been presented in Fig. 5 (a, b). The FOS or stability of the slope increase with the increase of embedment ratio for all cases as shown in Fig. 5. The shear zones increase with the increase of embedment ratio and the failure shape get modified as presented in Fig. 6.



(i)



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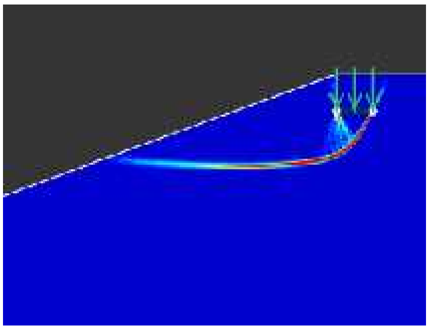
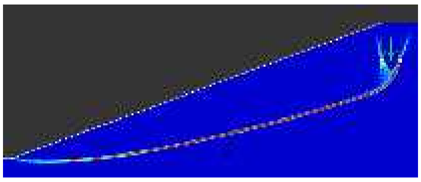


(iii)



(iv)

Fig. 6. Failure pattern with different embedment ratio for $\beta=20^o$, q=300kPa, $\alpha_h=0$ and B=3m, i) $D_f=0m$, ii) $D_f=0.5m$, iii) $D_f=1m$ and iv) $D_f=2m$

4 Conclusions

A series of numerical analyses has been performed to check the stability of the slope subjected to foundation loading for static and seismic condition. The primary focus of the present study is to identify global and local failure problem when footing placed near the top of slope. And influence of other effects that are footing loads, Embedment ratio, Footing width. From the above study the following conclusions can be drawn:

1. For a given slope angle, after a certain footing load the FOS gets reduced drastically. This threshold load indicates the change of global to local failure problem. However, with the increase of slope angle the threshold load decreases.
2. Within the local failure problem, the FOS increases with the increase in footing width but within global failure problem the effect of footing width on FOS is insignificant.
3. At a particular embedment and slope angle, the FOS of the slope is remained constant after certain setback distance. Moreover, at 20^0 slope, The FOS of the slope is remained constant after setback distance 2 and 2.5 times of footing width in static and seismic cases. Similarly, for 30^0 slope after 5 and 6 times of the footings width the FOS of the slope is remain constant in static and seismic cases.
4. The FOS increases with the increase in embedment depth of footing but initially the rate of increase of FOS is higher for a constant slope angle, footing width and Load. In both static and seismic cases, with the increases of slope angle the FOS decreases and the trend remained same.
5. The influence zone increased with the increases of Footing width as well as embedment depth in conditions. Therefore, irrespective of slope angle

and seismic conditions the FOS is directly proportional to the footing width and embedment depth of footing.

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