EFFECT OF TOE CUTTING ON HILLSLOPE STABILITY

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ABSTRACT: This paper reports about the numerical analyses conducted to investigate the instability induced due to toe cutting of simple homogeneous slopes during possible construction and widening of roads. A simple homogeneous hill slope made up of *c-φ* soil and overlying a rigid bedrock foundation material has been analyzed using Morgenstren-Price limit equilibrium method with the aid of Geostudio SLOPE/W 2007. Toe cutting analyses have been conducted for a wide variation of geotechnical, hydraulic and seismic parameters. The stability of the slope is assessed by the evaluated factor of safety which defines the mobilization of the shear strength along a particular slip line. Analyses are done in three stages. In the first stage, simplified hill slopes are analyzed solely under self-weight of the slope. In the second stage, pseudo-static analysis has been conducted. In third stage, water table variation is incorporated in the toe cutting analysis. Results are presented in graphical form and based on present study discussions are made regarding the critical horizontal extent of vertical toe cutting of hill slopes depending upon the slope type and different geotechnical parameters.

Keywords: Toe cutting, Hillslope stability, Morgenstern-Price method, Pseudo-static analysis, SLOPE/W 2007

1 INTRODUCTION

Major slope excavations are routinely carried out to facilitate construction and widening of roads. The objectives of routine road cuts are to create space for the road template and driving surface, to remain stable over time, to not be a source of sediment and minimize long term costs. A major cause of cut slope failure is related to the reduced confining stress within the soil upon excavation. Undermining the toe of the slope or increasing the slope angle results in slope failure. The major cut slope design parameters are slope geometry, soil shear strength and predicted or measured ground water levels. For cohesionless soil, stability of a cut slope is independent of height and therefore slope angle becomes the key parameter of concern. For cohesive soils, the height of the cut becomes the critical design parameter. For *c-φ* and saturated soils, slope stability is dependent on both slope angle and height of cut.

Preliminary slope stability analysis can be performed using simple stability charts. These charts can be used to determine if a proposed slope might be subjected to failure. If slope instability appears possible, or if complex condition exits beyond the scope of the charts, more rigorous methods can be employed. Ling *et al.* (1997) had given a simple closed form solution of slope stability by limit equilibrium (LE) method considering both the horizontal as well as vertical seismic accelerations using pseudo-static approach. Choudhury *et al.* (2007) used a simplified method of vertical slices by limit equilibrium approach for the determination of dynamic factor of safety of any generalized slope under seismic condition considering pseudo-static seismic forces both in horizontal and vertical directions. Recently nonlinear programming based on minimization of factor of safety approach has been used frequently for locating the critical slip surface. Effective use of these programs requires accurate determination of site geometry including surface profiles, soil unit boundaries and location of the water table, as well as unit weight and strength parameters. Presently, stability of slope can be analyzed using several available geotechnical software which use the LE or FE methodologies. GEOSTUDIO is developed specifically for the analysis of deformation and stability of geotechnical structures based on limit equilibrium principles and finite element modules. Saikia *et al*. (2014) investigated numerically the failure of virgin slopes characterized by different strength parameters, slope heights and slope angles using LE method with the aid of SLOPE/W module of Geostudio and also suggested the different types of stabilization measures. Chakraborty and Dey (2016) has investigated numerically the stability of slopes for a wide range of geotechnical, seismic and hydraulic parameters under different circumstances using the SLOPE/W. This paper mainly reports the SLOPE/W analyses conducted to investigate the slope instability induced due to toe cutting of simple homogeneous hill slopes during possible construction or widening of roads.

2 Numerical Model

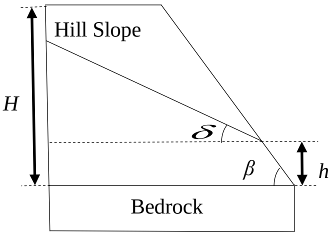


Fig. 1 Schematic diagram of the problem statement

A 40 m high slope made up of *c*- *φ* soil and overlying a rigid bedrock foundation material has been analyzed for instability due to toe cutting for a wide range of cohesion (*c*) and angle of internal friction (*φ*) using Geostudio *SLOPE/W 2007* utilizing Morgenstren-Price limit equilibrium method.

Determining the position of the critical slip surface with the lowest FoS remains one of the key issues in a stability analysis. There are many different ways for defining the positions of trial slip surfaces in *SLOPE/W 2007*, namely Grid and Radius method, Entry and Exit method, Fully specified slip surfaces. In the present analysis, *Entry and Exit method* has been used.

The most realistic position of the critical slip surface is obtained when effective strength parameters are used in the analysis. Effective strength parameters, however, are only meaningful when they are used in conjunction with pore-water pressures. There are different ways to specify the pore pressure conditions in *SLOPE/W 2007*, namely Single piezometric line, Multiple piezometric line, Pore water pressure head with spatial function. In the present analysis, *single piezometric line* method has been used. The variation of water table has been considered by specifying height and inclination of the piezometric line. Pseudo-static analysis has been conducted by adopting horizontal and vertical pseudo-static coefficients as 0.18 and 0.09 respectively, corresponding to the Seismic Zone V in which the regions of the North-East India are located.

3 RESULTS AND DISCUSSIONS

3.1 Effect of Toe Cutting on Dry Slopes

Results obtained are shown in Figures 2 to 4 below. Analyses conducted shows that flatter slopes (slope inclination varying from 30^0 to 40^0) having low *c* and *φ* values are failing under self-weight of the slopes only [e.g., for (a) β=30^0, c=10kPa, φ=20^0 the FoS value is 0.893 and (b) β=40^0, c=10kPa, φ=20^0 FoS value is 0.681 respectively under self-weight of the slope]. Therefore, vertical toe cutting for road construction or widening is not possible for such slopes without adequate safety measures. Higher *c* and *φ* values may lead to safe toe cutting even up to a horizontal extent (b_t) of more than 15m [e.g., for (a) β=30^0, c=50kPa, φ=20^0 toe cutting of more than 25m and (b) β=40^0, c=30kPa, φ=35^0 more than 15m]. On the other hand, for comparatively steeper slopes (slope inclination varying from 50^0 to 60^0) having higher *c* and *φ* values also fail under self-weight [e.g., for β=60^0, c =30kPa, φ=30^0 the FoS value is 0.842]. A reasonably high value of *c* and *φ* (e.g. for β=60^0, c =70kPa, φ=35^0) allows a horizontal extent (b_t) of toe cutting of around 10m, but such combination of *c* and *φ* values may not be practically feasible.

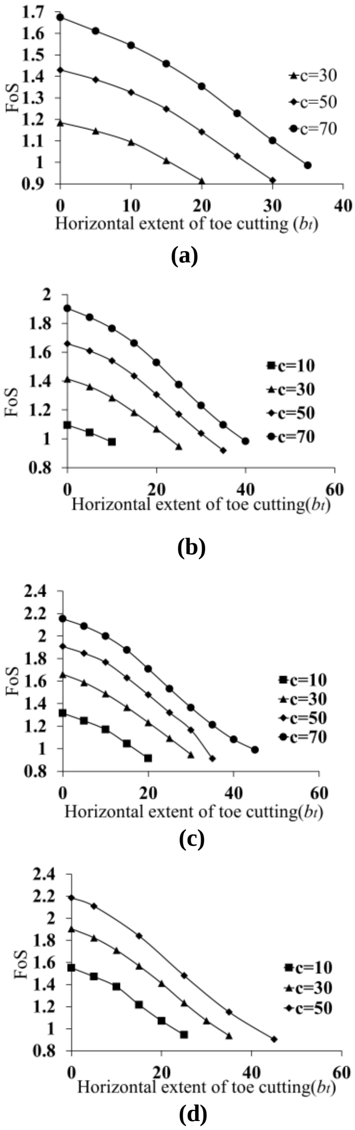
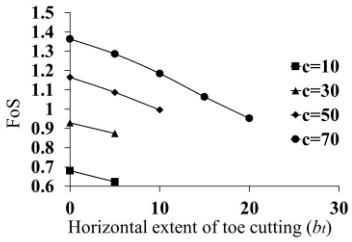
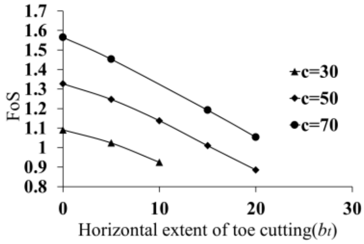


Fig. 2 Effect of toe cutting on dry hill slopes for β=30^0, (a) φ=20^0 (b) φ=25^0 (c) φ=30^0 (d) φ=35^0



(a)



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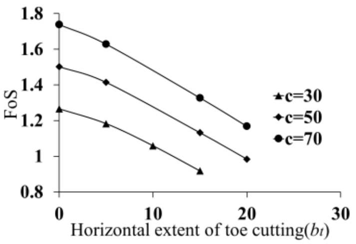

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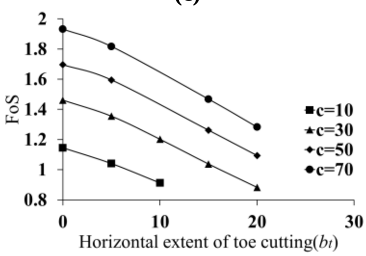
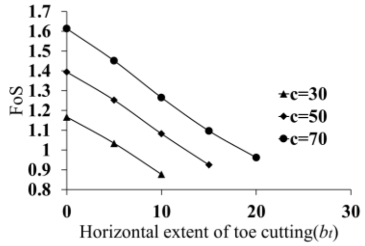


(d)

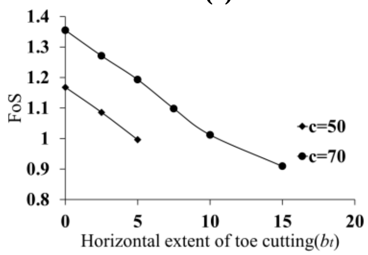
Fig. 3 Effect of toe cutting on dry hill slopes for β=40^0, (a) φ=20^0 (b) φ=25^0 (c) φ=30^0 (d) φ=35^0

3.2 Effect of Toe Cutting on Dry Slopes with Pseudo-static Earthquake

Results obtained are shown in Figure 5. Analyses conducted shows that flatter slopes (slope inclination varying from 30^0 to 40^0) having low *c* and φ values are failing under the action of pseudo-static earthquake [e.g., for (a) β=30^0, *c*=10kPa, φ=25^0 the FoS value is 0.775 and (b) β=40^0, *c*=30kPa, φ=25^0 FoS value is 0.819 respectively]. Therefore, vertical toe cutting for road construction or widening is not possible for such slopes without adequate safety measures. Higher *c* and φ values lead to safe toe cutting even up to a horizontal extent (b_t) of more than 15m [e.g., for (a) β=30^0, *c*=30kPa, φ=35^0 and (b) β=40^0, *c*=50kPa, φ=30^0] . On the other hand, for comparatively steeper slopes (slope inclination varying from 50^0 to 60^0), having higher *c* and φ values, also fail under the action of pseudo-static earthquake only [e.g., for (a) β=50^0, *c* =30kPa, φ=35^0 the FoS value is 0.896 and (b) β=60^0, *c* =50kPa, φ=35^0 the FoS value is 0.912]. A reasonably high value of *c* and φ [e.g., for (a) β=50^0, *c* =70kPa, φ=30^0 and (b) β=60^0, *c* =70kPa, φ=35^0] allows a horizontal extent of toe cutting of around 2m, but such combination of *c* and φ values may not be practically feasible.

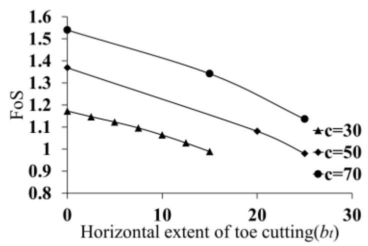


(a)

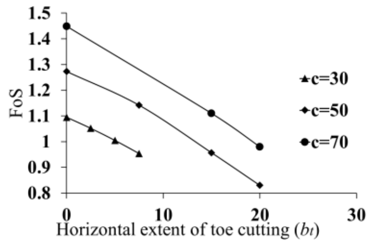


(b)

Fig. 4 Effect of toe cutting on dry hill slopes for (a) β=50^0, φ=35^0 (b) β=60^0, φ=35^0



(a)

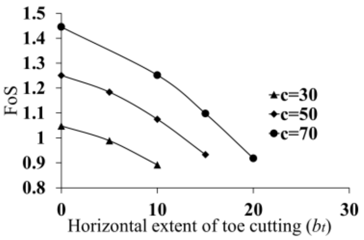


(b)

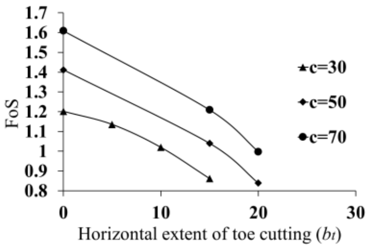
Fig. 5 Effect of toe cutting on dry hill slopes with pseudo-static earthquake for (a) β=30^0, φ=30^0 (b) β=40^0, φ=35^0

3.3 Effect of Toe Cutting on Partially Saturated Slopes

The height of piezometric line from toe (h) is considered to be $2H/3$ and at an inclination of $\delta=\beta/3$. Results obtained are shown in Figure 6. Analyses conducted shows that flatter slopes (slope inclination 30^0) having low c and φ values are failing due to presence of water table [e.g., for (a) $\beta=30^0$, c=10kPa, $\varphi=20^0$ the FoS value is 0.776 and (b) $\beta=40^0$, c=10kPa, $\varphi=20^0$ FoS value is 0.562 respectively]. Toe cutting for such slopes without adequate safety measures may cause failure of the slope. Higher c and φ values lead to safe toe cutting even up to a horizontal extent (b_t) of more than 15m [e.g., for (a) $\beta=30^0$, c=30kPa, $\varphi=30^0$ and (b) $\beta=40^0$, c=70kPa, $\varphi=30^0$] On the other hand, FoS values of comparatively steeper slopes (slope inclination varying from 50^0 to 60^0) having higher c and φ values also fall below unity [e.g., for $\beta=50^0$, c =30kPa, $\varphi=35^0$ the FoS value is 0.917]. A reasonably high value of c and φ [e.g., for $\beta=50^0$, c =70kPa, $\varphi=35^0$] allows a horizontal extent of toe cutting of around 5m, but such combination of c and φ values may not be practically feasible.



(a)



(b)

Fig. 6 Effect of toe cutting on partially saturated slopes for (a) $\beta=40^0$, $\varphi=30^0$ (b) $\beta=40^0$, $\varphi=35^0$

CONCLUSION

In this paper, simple homogeneous hill slopes are analyzed for vertical toe cutting for construction or widening of roads. Study shows that slopes with very low c and φ values fail under self-weight of the slope only, therefore vertical toe cutting without adequate stabilization measures are not recommended in such cases. Higher c and φ values may lead to a safe toe cutting up to a certain extent depending on the geometrical, seismic and hydraulic conditions. Moreover, steeper slopes having comparatively high c and φ values also fail under self-weight. A reasonably high c and φ values may allow safe vertical toe cutting, but such combination of c and φ values may not be practically feasible.

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