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Geo-Mechanical Behaviorof Toe Excavated Land Slope

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Abstract

The toe cutting of the hill slope is commonly practiced in India by local residents in the temptation to occupy free land to build a residence or for the use of farming activities on the hill slope without being scared of landslide and their consequences. This study reports the effect of the toe cutting on various scales on the stability status of the land slope. A homogeneous soil slope made up of cohesive frictional soil is analyzed to understand the instability status of hill slope under varying degrees of toe cutting. The finite element slope stability module of geo-studio SLOPE/W is used to analyze the stability status. Effects of toe cutting on stability have been conducted for the wide variation of the geometric and geotechnical parameters. The instability of slope has been assessed in terms of the factor of the safety (FoS), which defines the ratio of the resisting forces to the driving forces and represents themobilization of the strength of earth masses on a particular slip surface. Theeffects of toe cutting on various combinations of the cohesion and angle of internal friction were analyzed,along with varying the angle of the hill slope in a wide range of variations. Results of the study represent in the graphical layouts, and based on the current study, comments were made on thecritical extent of toe cutting.

Key Words: Toe Cutting, Slope Stability, Hill Slope

INTRODUCTION

Landslide is defined as a downward and outward movement of the land's mass under gravity due to human-made or environment-caused events. Man-made triggering includes the cutting of the toe of the hill slope, illegal farming activities on the hill slope, excavation on the hill slope, etceterawhich reduces the stability of the slope(Ering et al., 2015; Sarvade et al., 2017; C. R. Shah et al., 2021; Singh et al., 2016). A landslide is a disastrous event that can profoundly make socio-economical losses(Petley, 2012; Schuster & Fleming, 1986). In the past 20 years, the rate of landslide incidence rounds the year, growing at rapid rates. Besides, in the construction of the road and rail route need is arisen to cut the toe of the hill to build a rail or road base. In these circumstances, we must have knowledge of the critical extent of the toe cutting of the hill so it could not bring the landmass movement. Major parameters that governthe cut geometry and stability of the slope are shear strength parameters(M. v. Shah & Sudani, 2020; P. Sudani & Shah, 2019),i.e., cohesion and angle of internal friction, slope geometry, and groundwater hydrology(P. G. Sudani et al., 2022; P. Sudani & Patel N. A., 2021). In cohesionless soil, slope angle is the critical parameter to analyze, and in cohesive soil height of the cut is a vital and crucial parameter to understand and analyze(Chakraborty & Dey, 2016). While on another hand, for cohesive frictional soil, the instability status of the hill slope depends on both angle of slope as well as the extent of the cut, and we need to care for them during stability analysis.

Besides the vulnerability of landslides due to toe cutting, competent authorities should impose strict restrictions. However, we still seea lack of action on such an illegal excavation of the toe of the hill slope. In our previous visit in April 2022, at Barman-mota village of Amreli district of Gujarat, India, we observed such activities on the downhill slope, presented here in Fig-1, for reader's reference. People of the village have excavated the toe of the hill and built the residence in that place which is dangerous as it might trigger a landslide duringthe rainy season.Also, besides that, they started farming in the excavated area of the toe.

Fig-1. Toe excavation of hill slope at Barman Mota Village of Gujarat

Slope stability analysis can be performed by calculating the hill slope's resisting forces and driving forces. Still, ifthe slope condition seems complex, more precise methods need to be employed for stability analysis. For complex slope requirements like seismic effect simulation, Ling etal. (1997) provide the closed-form resolution of stability investigation by the limit equilibrium method(Ling et al., 1997). For another complex condition where we need a dynamic factor of safety, Choudhury et al. (2007) provide the simplified limit equilibrium solution(Choudhury et al., 2007).Nowadays,programming-based software which uses limit equilibrium and finite element methodologies is used widely in research for stability analysis of any complex condition of the land slope accurately and at a very fast speed (Thiebes et al., 2014). Some examples of software that provides the solution for stability analysis of landmasses are, Slope/W, Plaxis, Geo5, and many more. Effective use of this software required accurate information about the hill slope, including the geometry of the slope, material properties of the slope, hydrological condition of the slope, the boundary condition of the slope, water table, and geotechnical properties of the soil consisting of the slope. Geo-studio is programmed various modules for geotechnical analyses such as seepage, stability, earthquake, soil-structure interaction, etc., based on limit equilibrium principles and finite element methodology. Slope/W is a module of Geo-studio software that provides the finite element-based rapid analysis of the stability of the slope and has been on the market since 1977. Saikia et al. (2014) successfully investigated the instability of unalter slopes of different shear strength, slope angles, and slope heights using the limit equilibrium method with the help ofthe SLOPE/W software module(Saikia et al., 2014). Also,Chakraborthy and Dey (2016) have investigated parametrical investigation using a wide range of geotechnical and hydraulic parameters under various circumstances with the aid of SLOPE/W(Chakraborty & Dey, 2016).

This study reports the effect of the toe cutting on various scales on the stability status of the land slope. A homogeneous soil slope made up of cohesive frictional soil is analyzed to understand the instability status of hill slope under varying degrees of toe cutting. The finite element slope stability module of geo-studio SLOPE/W is used to analyze the stability status. Effects of toe cutting on stability have been conducted for the wide variation of the geometric and geotechnical parameters. Instability of slope has been assessed in terms of the factor of the safety (FoS), which defines the ratio of the resisting forces to the driving forces and represents the mobilization of the strength of earth masses on a particular slip surface. The effect of toe cutting on various combinations of the cohesion and angle of internal friction is analyzed along with varying the angle of the hill slope in a wide range of variations. Results of the study represent in the graphical layouts, and based on the current research; comments were made on the critical extent of toe cutting.

Methodology

The present study investigates the effect of the toe excavation on the hill slope stability. The geometry of the slope was used to vary in terms of the inclination of the slope angle in the range of the 25˚ to 45˚; this range was investigated in three parts, i.e.,i) with 25˚ inclination, ii) with 35˚ inclination, iii) with 45˚ inclination of the slope. Further, each inclination wasanalyzed for different shear parameters,i.e., cohesion and angle of internal friction. Cohesion was used to vary in the range of 10 KPa to 70 KPa in increment of 20 KPa, while on another hand angle of internal friction was used to vary in the range of 10˚ to 35˚ with an increment of 5˚. The geometry of the slope used in the investigation is, as presented in fig-1. The height of the slope is 50 m.The stability of the slope wasanalyzed in a dry state of the slope.A groundwater table was encountered at the base for dry slope conditions. The Morgenstern-price method is employed to analyze the slope stability as this method can simulate the effect of both vertical and horizontal interaction force between the slice. The surface soil's behaviorwas modeled as linear and elastic-plastic soil material using the Mohr-coulomb material model.

Fig-1 Geometry of the slope model for 25˚ slope angle with 5 m toe excavation

Toe excavations were simulatedon the slope in 5 m horizontal excavation intervals until the slope got fails. The strength parameters called cohesion and angle of internal friction was varied to analyze the effect of these shear strength parameters on the toe excavation.

Modeling of the slope

A sample study has been carried out on assumed slope geometry. The slope was modeled with an assumed homogeneous fill of the cohesive frictional soil. The slope's current condition was determined using limit equilibrium finite element slope stability modeling through the SLOPE/W program. The influence of the stability with the cohesion, angle of internal friction, and toe excavation was examined.

The modeling sequenceincludes the path like, Geometry input – material definition – Mesh Generation – Boundary Condition – Loading condition – Construction sequence definition – Analyse Case – Check Results.

RESULT AND DISCUSSION

The effect of toe cutting on the stability of slope is examined in 3 different cases as are listed here,

Case-1, 25˚ slope angle slope,

Case-1, 35˚ slope angle slope,

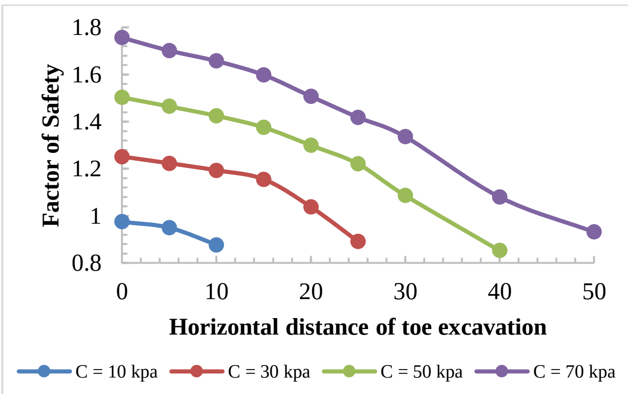
Case-1, 45˚ slope angle slope

All three listed cases were investigated for the wide variation of cohesion and angle of internal friction. Table-1 shows the wide range of shear parametric trials adopted to analyzethe effect of toe excavation on hillslope stabilitywith the aid ofthe SLOPE/W module of the geo-studio.

Table-1, Table of trial solutions adopted for SLOPE/W analysis

	Φ (°)	C (KPa)	Φ (°)	C (KPa)	Φ (°)	C (KPa)	Φ (°)	C (KPa)
Case-1, 25˚ slope angle slope	20	10	25	10	30	10	35	10
		30		30		30		30
		50		50		50		50
		70		70		70		70
Case-2, 35˚ slope angle slope	20	10	25	10	30	10	35	10
		30		30		30		30
		50		50		50		50
		70		70		70		70
Case-3, 35˚ slope angle slope	20	10	25	10	30	10	35	10
		30		30		30		30
		50		50		50		50
		70		70		70		70

Results of the investigation for all three cases are presented here in fig-2, fig-3, and fig-4 in the graphical demonstration.



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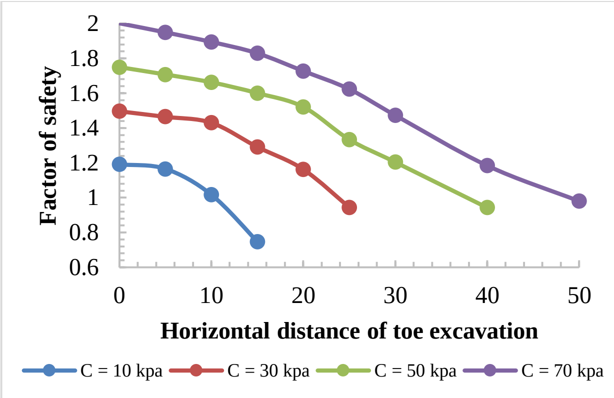

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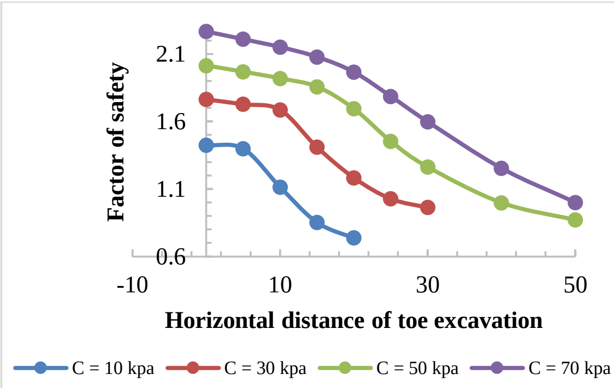

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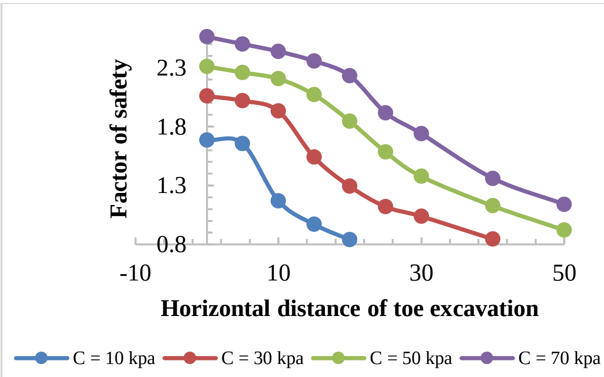
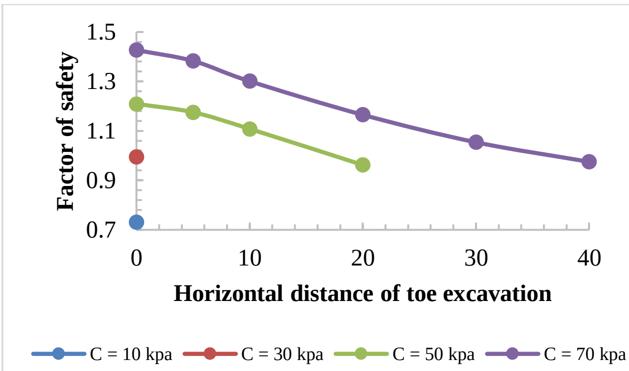
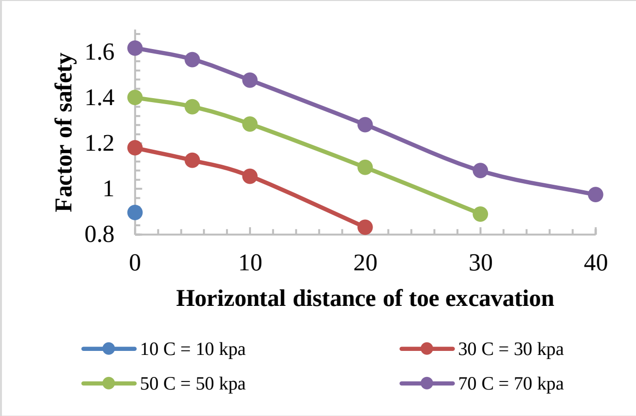


(d)

Fig-2, Effect of toe excavation on hill slope stability for 25° slope angle, a) φ = 20°, b) φ = 25°, c) φ = 30°, d) φ = 35°



(a)



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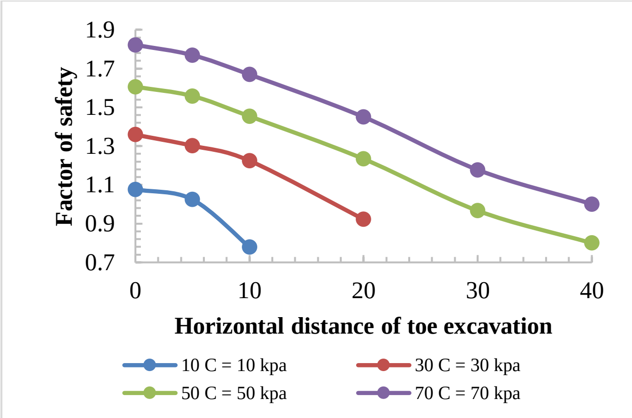
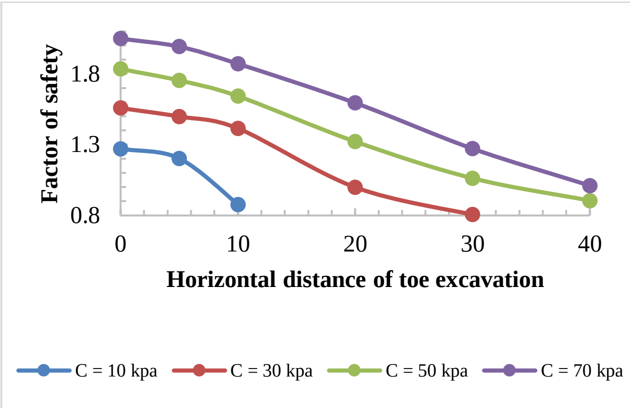
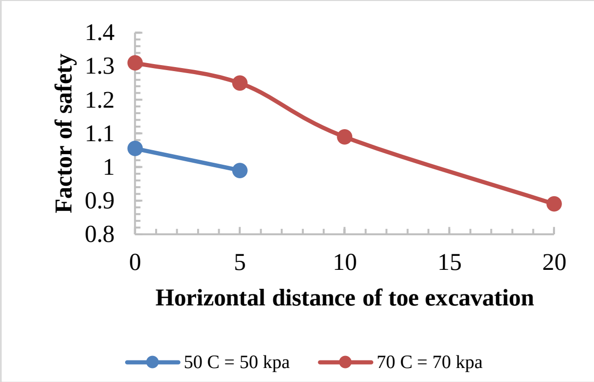


(C)

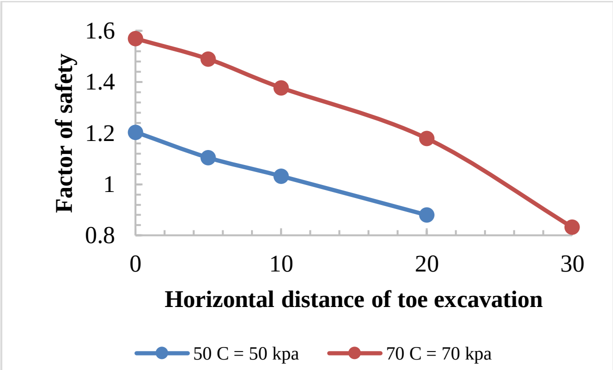


(d)

Fig-3, Effect of toe excavation on hill slope stability for 35° slope angle, a) φ = 20°, b) φ = 25°, c) φ = 30°, d) φ = 35°



(a)



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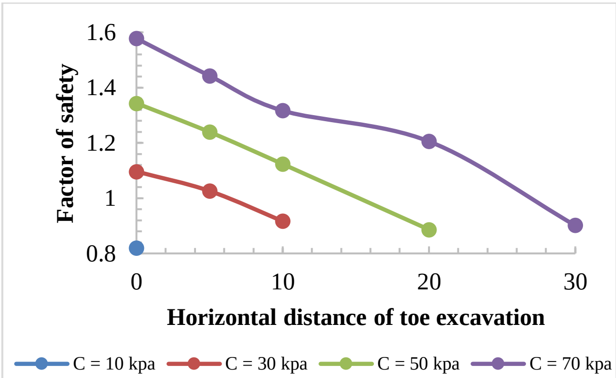
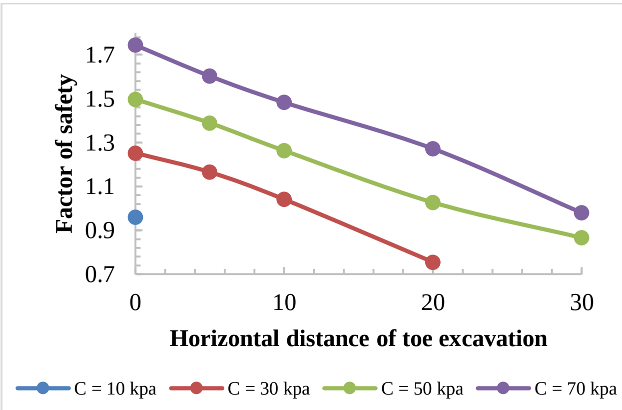


(c)



(d)

Fig-4, Effect of toe excavation on hill slope stability for 45° slope angle, a) φ = 20°, b) φ = 25°, c) φ = 30°, d) φ = 35°

Extensive stability analysis of hillslope with toe excavation reveals how the stability of the slope gets affected as the toe is excavated horizontally. From the study,it's observed that toe excavation can sustain stability in a dry state maximum of up to 50 m for 25° slope angle, up to 40 m for 35° slope angle, and up to 30 m for 35° slope angle (Fig-1, Fig-2, and Fig-3). Analysis shows that the more flatter slope i.e. 35° and 45° angle slope with lesser cohesion and angle of internal friction falling under self weight (i.e., Fig-2, (a) – φ = 20 and C = 10 & , φ = 20 and C = 30 (b) φ = 20 and C = 10 and Fig-3, (a) - φ = 20 and C = 10; C = 30, (b) - φ = 25 and C = 10; C = 30, (c) - φ = 30 and C = 10, (d) - φ = 35 and C = 10). Which represents the vertical toe excavation for such a slope for any reason it is not possible for such a kind of slope. Besides this, for higher cohesion and angel of internal friction, even for steeper slopes up to 45° of inclination,the safe toe excavation up to 30 m on dry a slope could be possible (Fig-4). A flat slope allows more extent of the toe excavation, which is up to 50 m on a 50 m high slope (Fig-2).

Analysis of the safety of the slope presented here is only of the dry hill slope. Monsoon always makes the slope saturated, which further leads to affect the safety of the slope, and it must be analyzed carefully if you worked under a slope that has the possibility of being saturated during your work. Further research in this direction could be possible to analyze the same hill slope for various saturation conditions to know the effect on the stability of the hill slope. Further illegal toe excavation by the villagers is strongly not suggested. During the rainy season, due to the groundwater effect and saturation evolution, slope safety could be dropped drastically, resulting in a disastrous landslide. It is recommended to stop such activities on the downhill slope. Forthe already excavated toe slope, proper remedies' should be adopted to protect human lives and the economy.

CONCLUSIONS

In consideration of frequent landslides due to toe excavation by the local people in the temptation of occupying free land for the use of building a residence or for the benefit of farming activities on hill slope without being scared of landslide and their consequences, this study reports the effect of the toe cutting in various scales on the stability status of the land slope. A homogeneous soil slope made up of cohesive frictional soil is analyzed to understand the instability status of hill slope under varying degrees of toe cutting. The study shows that the very low value of cohesion and angle of internal frictions do not even sustain theirself-weight. Therefore in such a case, toe excavation is not possible without adopting any stabilization measures. While on the other hand, for higher cohesion and angle of internal friction value up to some extent, safe toe excavation could be possible depending on geometrical and hydrological conditions. Higher C-φ soil allows for a reasonable extent (e.g., up to 50 % of the total base length (Fig-2)), but such a combination of C-φ is not feasible in the actual case. Further research in this direction could be possible by considering the effect of the water saturation along with toe excavation.

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