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Chapter

Performance Evaluation of Geometric Modification on the Stability of Road Cut Slope Using FE Based Plaxis Software

Fentahun Ayalneh Mekonnen

Abstract

Slope failures are among the common geo-environmental natural hazards in the hilly and mountainous terrain of the world. Specially it is the major difficulty for the development of construction as it causes considerable damage on the infrastructure, human life and property. Different causes of slope failure and stabilization methods are proposed by different scholars. In this study the performance of geometric modification in slope stability was investigated using numerical method. The study uses slope height, slope angle and slope profile i.e. single slope, multi slope and bench slope as a governing parameter in the performance evaluation of geometric modification on the slope stability. The evaluation was conducted on a newly constructed road cut slope using a finite element based plaxis software. The result from performance evaluation of slope profiles show that geometric modification provides better and economical slope stability. The stability of slope decreases with increase in slope height and slope angle leading to an uneconomical design of high slopes in a single slope profile. However, the use of benching improves the stability of cut slope (i.e. the use of 2 m and 3 m bench improves the factor of safety by 7.5% and 12% from single slope profile). The method is more effective in steep slopes. Similarly, the use of a multi slope profile improves the stability of slope in stratified soil with varied strength. The performance is more significant when it is used in combination with benches. The study also provides comparison of slope profiles based on different criteria's and recommend the selection profile based on site-specific considerations.

Keywords: slope profile, bench slope, multi slope

1. Introduction

A slope is an inclined ground surface formed naturally or by excavation for different human activities. Its stability is the major consideration in civil engineering infrastructural projects such as open-pit mining operations, road cut or embankment slopes as its failure causes considerable damage on the infrastructure, human life and property.

Instability of slope can be occurred due to internal or external factors which causes failure either by reducing the shear strength of slope material or by increasing the shear stress on the slope [1]. Different processes such as increased pore pressure, cracking, swelling, decomposition of clayey rock fills, creep under sustained loads, leaching, weathering, and cyclic loading are responsible to a reduction in shear strengths [2]. In contrast to this, the shear stress in slopes may increase due to additional loads at the top of the slope, increase in water pressure, increase in soil weight due to saturation, excavation at the bottom of the slope, and seismic effects [1]. Also, it must be noted that, slope geometry, state of stress, and erosion contributes to the failure of slope. The mechanism of slope failure varies and takes place as speed or slow rate, depending on the type of material, slope geometry, and types of triggering factors. Slide, fall, earth flow, debris flow, topple, planar and wedge failure are the common methods of slope failure.

As both natural and human activities are responsible for the failure of slopes, it is difficult to avoid the problem entirely. However, the level of damage can be significantly reduced by assessing the stability condition and adopting different preventive measures on it. There are various remedial measures applied during and after construction to reduce the impact of slope failure and these can be grouped into four general classes i.e. geometric modification, drainage control, slope reinforcement, and retaining structure [3].

Now a day slope stability studies have been attracted researcher's attention as their understanding on the impact of slope failure in human life and infrastructural development increases. Numerous slope stability studies were carried around the world so far and better understandings are established about causes of failure, mechanisms of failure, methods of analysis, and possible remedial measures. However, the damages due to slope failure are increasing from year to year and still the major difficulty for the development of infrastructural constructions in Ethiopia. A review of previous slope stability assessments [4–6] indicates that slope failures are the main constraint for road and railway construction in Ethiopia. To overcome this problem and acquire better solutions a continuous effort is needed. Hence, this study was carried to evaluate the performance of geometric modification i.e. slope profiles (single slope, multi slope and multi slope) on slope stability using numerical methods.

2. Description of the study area

The study area is located at Adama city in Ethiopia on a newly constructed ring road project. The area is in the east African refit valley system which is dominated by escarpments of various landscapes and bordering. The slope is formed by excavation of volcanic ridges and its height extends up to 40 m with 3 m bench every 10 m. Reddish to brownish color residual soils formed by a physical and chemical process from parent rock and volcanic rocks of different degree of weathering are the major type of materials found in the cut slope (**Figure 1**).

3. Geometry of slope

Geometry is among the most critical factors controlling the stability of the slope [7, 8]. Generally, slope height, slope angle and slope profile are the major parameters in geometric modification. Cut and embankment slopes can be formed using one of the three profiles i.e. single slope, multi slope and bench slope. But depending on the composition of slope material, height of the slope, and hydrological conditions these profiles have different performance in the stability of slope.

Figure 1.
Location of the study area and slope section of the road.

Single slope profile is used in cut and embankments of dense soils with enough resistance against failure with a limited height [9]. Increasing height (h) and angle of slope (α) will increase the shear stress and decrease normal stress on the potential rupture plane [2]. As a result, h and α are major parameters control the performance of single slope profile.

Multi-sloped profiles are provided in cuts where the stratigraphy of soil consists of two or more layers with different strength characteristics [9]. The method allows the use of both steep and gentle slopes in stiff and weaker layer of the slope section respectively.

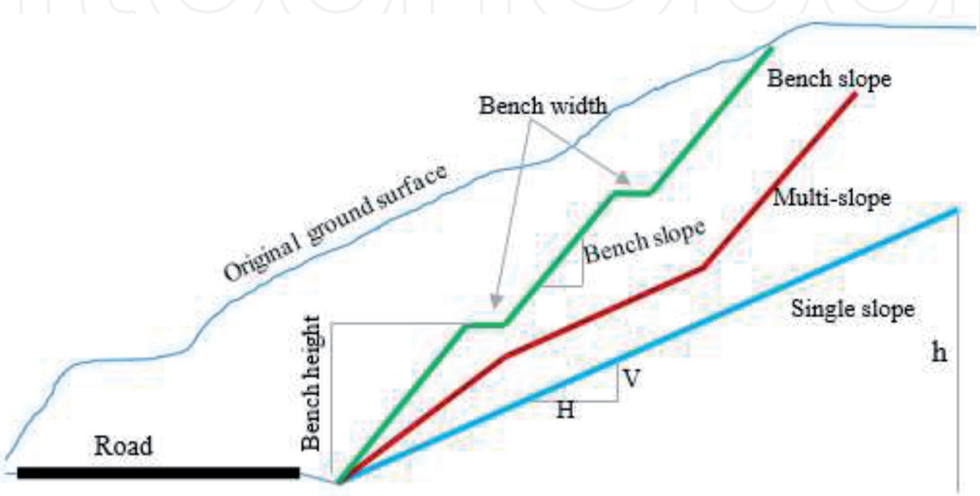

Figure 2.
Geometric profiles of cut slope.

Bench slope profile is a technique in which the overall slope is divided into multiple small slopes. It reduces the driving forces above the failure surface by reducing the weight of slope [8]. Bench slope, bench height and bench width are the major parameters control the performance of bench slopes (**Figure 2**).

4. Methodology

To investigate the performance of slope profiles a newly constructed road cut slope in Adama city was used. Under this investigation the effect of slope profiles and its parameters (slope height, slope angle, bench width, no of bench, and bench angle) on the stability of slope was evaluated interims of FS and deformation. The performance of multi-slope and bench slope profiles was evaluated with respect to single slope profiles and further comparison was made between them interims of construction difficulty, appearance or esthetic value, drainage control, and accessibility for maintenance.

4.1 Numerical modeling

The numerical modeling was carried using finite element method (FEM). The method discretizes a continuum into elements to describe the behavior or actions of individual pieces and reconnecting them to represent the behavior of the continuum [10–12].

5. Material parameters for modeling

For this FE modeling an elastic perfectly plastic Mohr-Coulomb material model was used. The model uses material stiffness (E and v) as elasticity parameter, material strength (φ, and c) as soil plasticity and ψ as angle of dilatancy [10]. The slope section used for this investigation has both soil and rock layers, hence to determine the parameters both field and laboratory tests were carried. The soil shear strength parameters were obtained from direct shear test and its stiffness parameters were correlated with SPT data. Similarly, the strength and deformation parameters of rock layers were determined by correlating field and laboratory tests with rock data software. The geometric and material data used for this investigation were summarized in **Figure 3** and **Table 1**.

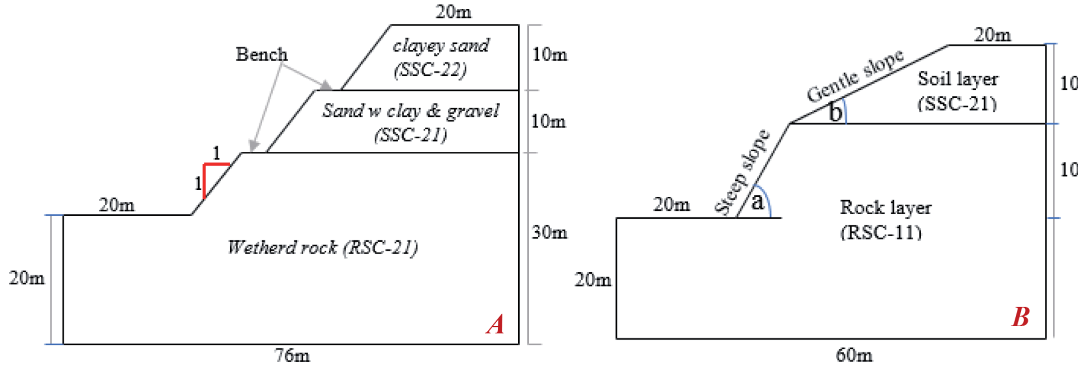

Figure 3.
Cross-section of the newly constructed road cut slope.

DOI: http://dx.doi.org/10.5772/intechopen.99633

Sample code	Description of soil and rocks	γ_{stu} (kN/m^3)	γ_{dry} (kN/m^3)	C (kN/m^2)	$\varphi°$	$\psi°$	E (MPa)	V
SSC-22	Clayey sand	20.1	16.4	14.57	27.89	0	25	0.215
SSC-21	Sand with clay and gravel	20.1	16.6	9.7	35.75	5.75	35	0.261
RSC-11	Slightly to moderately weathered rock	21.3	20.1	130	29.21	0	1962.8	0.35
RSC-12	Highly weathered rock	19.8	18.7	600	20.32	0	686.9	0.38

Table 1.
Material properties used in numerical modeling.

5.1 Stability analysis

To evaluate the stability of slope in different profiles first initial stress and pore water pressure distribution was generated using $k0$ procedure and phreatic water level respectively. Then the deformation and safety analysis were carried with plastic calculation and phi-c reduction method for the same loading conditions. Phi-c reduction is a method where the shear strength parameters (c and tan∅) are successively reduced until the failure occurs [13]. During the process the strength reduction factor ($\sum Msf$) is increased start from 1. The global safety factor is equal to the total multipliers $\sum Msf$ at the point of failure which is expressed as the ratio of initial and reduced strength parameters [10].

$$FS = \sum MSF = \frac{\tan \varnothing_{input}}{\tan \varnothing_{reduced}} = \frac{C_{input}}{C_{reduced}} \quad (1)$$

6. Numerical validation

To validate the numerical model a slope section for this study was evaluated using Fellenius method (analytical solution) and the result was compared with numerical value both in FEM (plaxis) and LEM (slide) software's (**Figure 4**).

Validation also made using slope section first introduced by Zhang [14] and later used by numerous investigators i.e. Ferdlund and Krahn [15], Chen et al. [16], Griffiths and Marquez [17], Zhang et al. [18], and Chaowei et al. [19] to validate their 2D and 3D slope stability evaluations (**Figure 5**). The section was modeled using a slide, Plaxis-2D, and Plaxis-3D software with the same material and boundary condition. The result in **Figure 6** shows a drift of ± 5% from previous investigators. Generally, from both validations the result from numerical modeling shows good agreement with the analytical solution and the previous works.

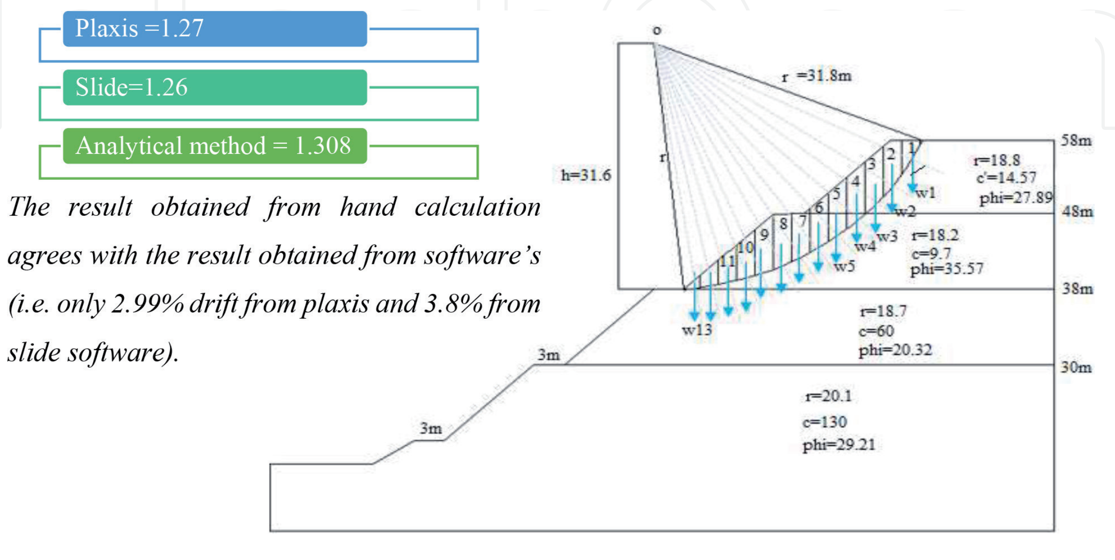

Figure 4.
FS determination using analytical solutions.

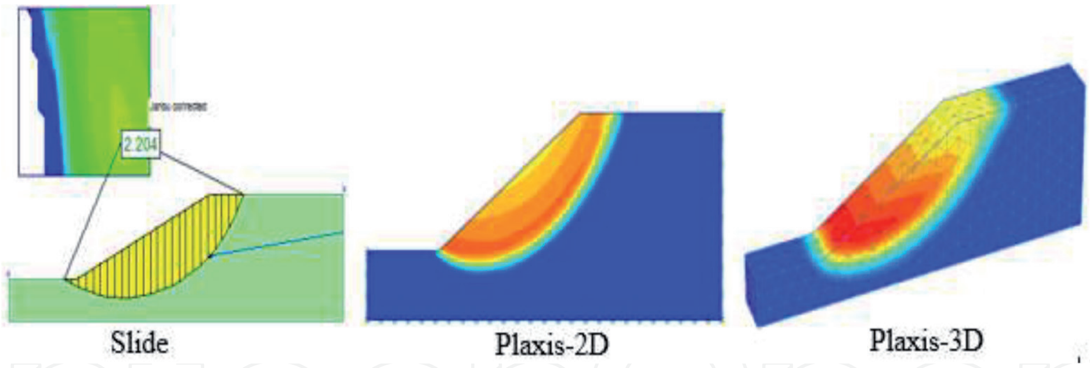

Figure 5.
Modeling of slope section used for validation in slide, Plaxis-2D, and Plaxis-3D.

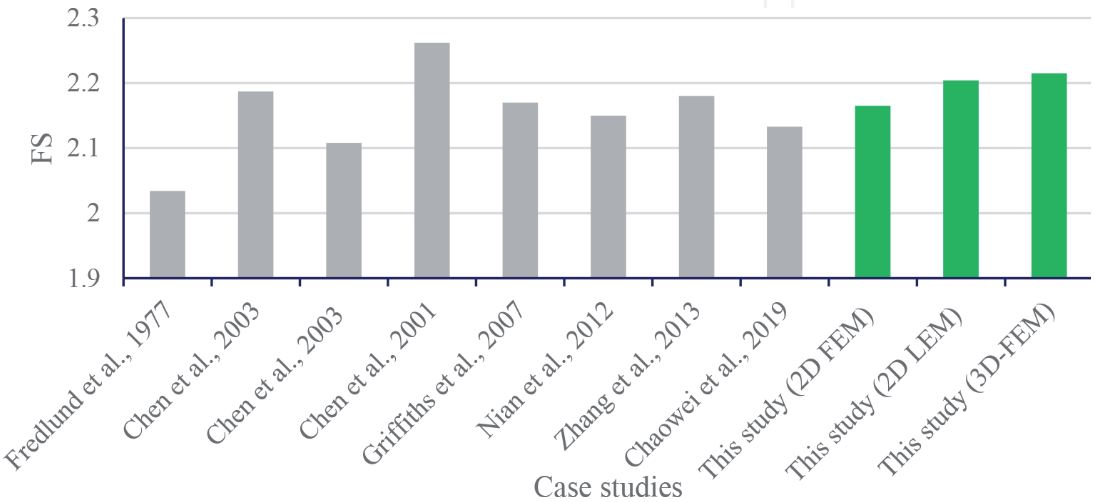

Figure 6.
FS from different researchers and this study on Zhang [14] slope section.

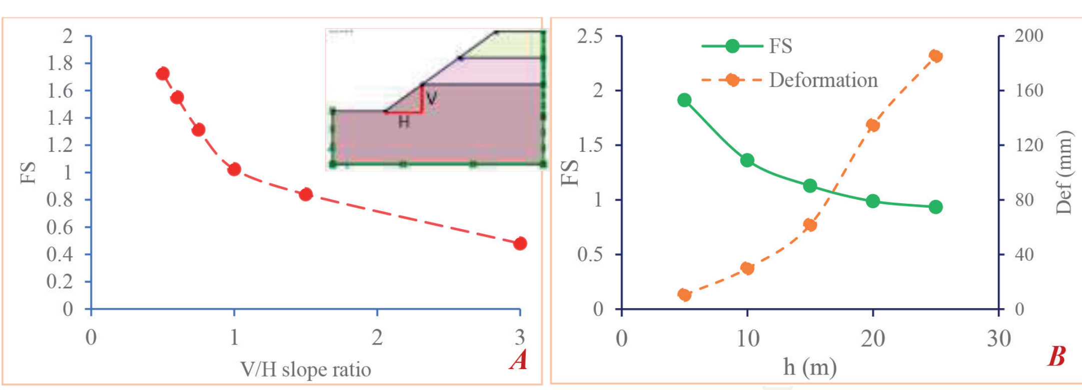

Figure 7.
Effect of slope angle and slope height on the performance of single slope profile.

7. Effect of slope height and slope angle

Increasing angle and height of slope affects the stability by increasing the shear stress and decreasing shear strength on the potential rupture plane. To examine the effect of these parameters numerical models on **Figure 3** was made for different slope height and slope angles.

Figure 7A shows FS of slope for 27°, 34°, 45°, 63°, and 73° (i.e. increasing slope angle reduces the FS). Similarly, **Figure 7B** shows the effect of slope height on FS in an ideally sandy lean clay slope for different slope heights (i.e. increasing slope height increases the deformation and decrease the FS of the slope). Hence it is recognized that both slope height and slope angle reduce the FS of slope in the same principle i.e. increasing self-weight (driving force) above the failure surface and decreasing the normal force on the failure surface.

8. Performance of bench on slope stability

Bench width, cut angle and no bench are the major parameters which control the performance of bench slope profile. To examine the performance of benching and its parameters on the stability of slopes a typical slope section given in **Figure 3** was used. **Figure 8A** shows the FS of slope for 1, 2, 3, 4, 5 and 6 m bench width with a constant 10 m bench height. As the figure indicates stability increases with increasing bench width (i.e. FS increases in 3.5%, 7.7%, and 12% from single slope profile in 1:1 slope ratio for 1 m, 2 m and 3 m bench widths respectively). The percentage change of FS from equivalent single slope profile is 1.7%, 3.6%, 7.7% and 17.4% for 27°, 34°, 45° and 63° respectively in a constant 2 m bench width as shown in **Figure 8B**. Hence the use of benching is more effective in steep slopes.

Similarly, the effect of bench height was evaluated using uniform clayey sand soil in two cases (i.e. case 1, when the overall cut varies with constant slope within bench. Case 2, when overall cut is constant with varied slope within bench as shown in **Figure 8C**). Accordingly, decreasing bench height (increasing no of bench) increases the FS of slope in case 1. However, it has no significant effect in case 2. Generally, benches improve stability of slope in the opposite principle of slope

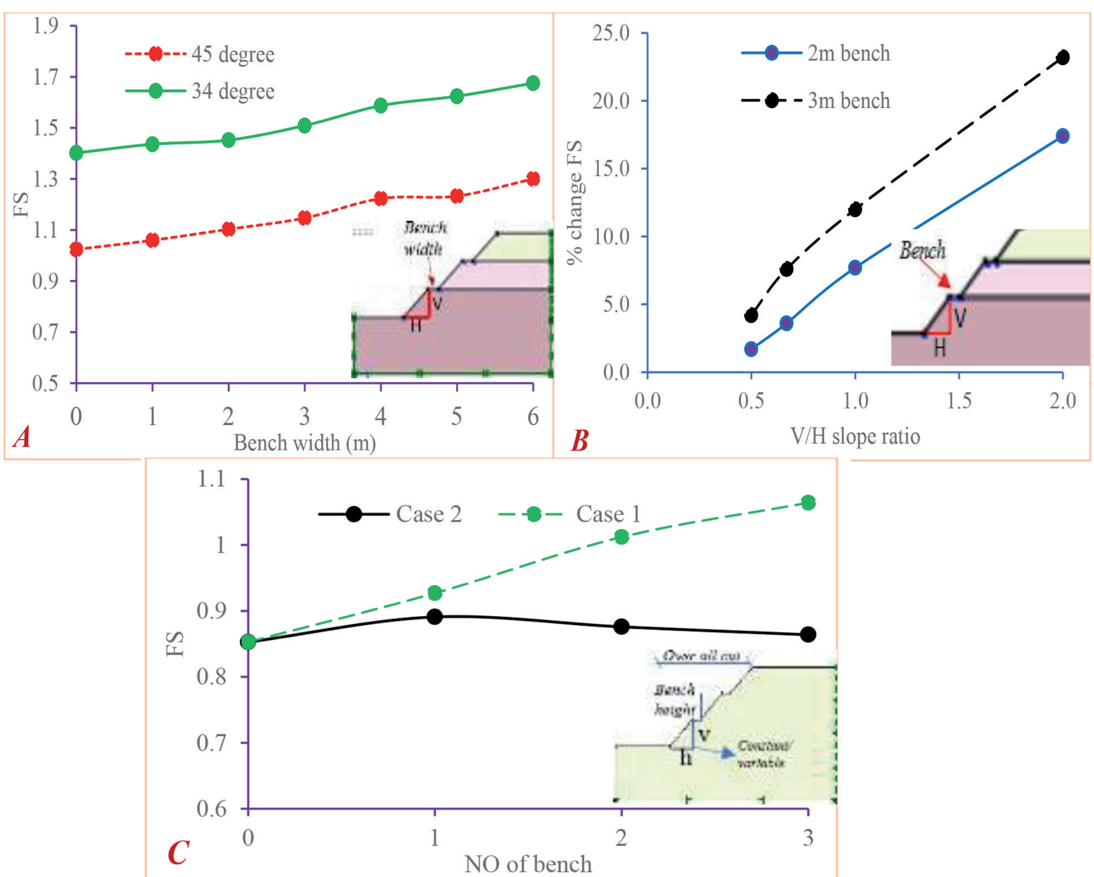

Figure 8.
Effect of bench width, bench slope and bench height on the performance of bench slope profiles.

DOI: http://dx.doi.org/10.5772/intechopen.99633

Slope	a (stronger layer)	45	48	51.3	55	59	63.4	68	78.67	90
	b (weaker layer)	45	42.3	39.8	37.5	35.5	33.69	32	29	26.5
FS		1.202	1.251	1.325	1.414	1.472	1.513	1.55	1.5	1.45

Table 2.
FS for different combination multi-slope profiles (a= stronger slope & b= weaker slope).

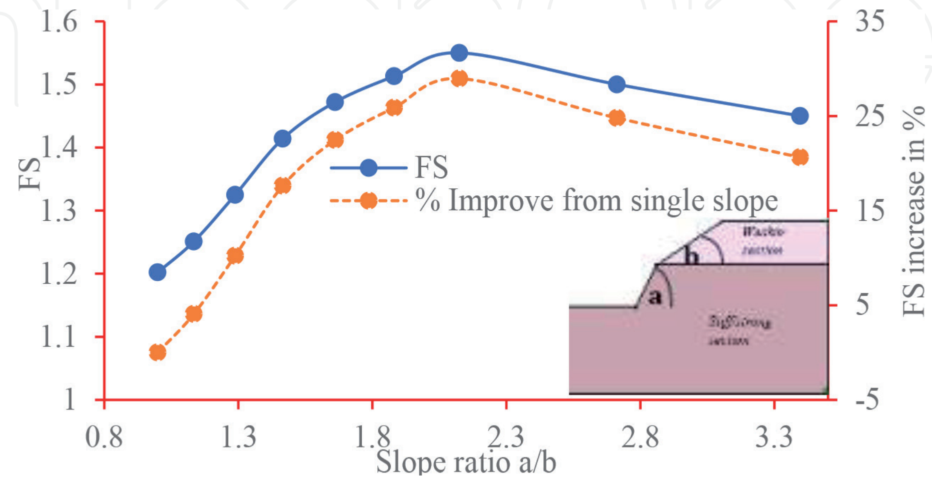

Figure 9.
FS and its change from single slope in % for d/t combination of multi-slope profiles.

height and slope angle by decreasing the driving force of the slope above the failure surface. The method is effective to avoid the use of gentle and high slopes in the design of cut slope.

9. Performance of multi slope profile

To assess the performance of multi slope profile in stratified soils a layered slope section shown in **Figure 3B** is evaluated for different combinations of slope angle (i.e. in the weaker and stronger section). **Table 2** and **Figure 9** shows FS for different combination of weaker and stiffer slope section. Accordingly, FS is improved up to 30% from a single slope profile by adjustment of cut angle (i.e. decreasing weaker section and increasing stiffer section). But it should be reminded that the amount of change in FS depends on the strength characteristics of the slope section. Generally, multi slope profile allows the use of steep and gentle slope in stiff and loses materials respectively in stratified soil.

10. Comparison of slope profiles

Further comparison was made on the performance of profiles by evaluating the slope section in **Figure 10A** for single, multi, bench slope and combination both. **Figure 10B** shows the result of the comparison i.e. FS changes in 13%, 22.7%, and 37.5% from single slope profile in bench, multi-slope, and the combinations of both methods respectively. Hence the use of bench slope, multi slope and combination them provide effective stability in high and stratified slope.

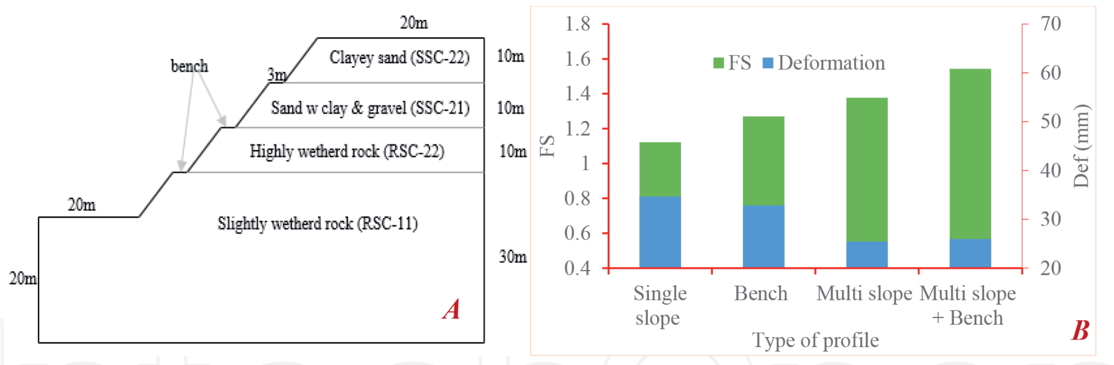

Figure 10.
FS and deformation for different slope profiles.

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From the above evaluation, it is recognized that modification of slope geometry is one and the very first economical alternative of slope stability improvement. Although this investigation is made in a specific type of slope material there is no doubt in the role of geometric modification in slope stability. However, the selection of these slope geometry should depend on site-specific parameters i.e. susceptibility of the slope to erosion and infiltration, the variability of slope material, the height of slope, and adjacent area of the slope.

According to the evaluation result, the use of a single slope profile is effective in homogenous stiff slope material when the height of the slope is low. Otherwise, the method may not be safe and economical choice as weak and high slope sections need very gentle slopes. Multi slope profiles are suitable in slopes where there is material strength variability. It provides a very economical slope design without extra excavation by making adjustments only within the slope section. Especially the method is ideal in slopes comprise both rock and soil. The use of bench is an effective geometric measure when the height of the slope is large. It increases FS by reducing the driving force above the failure surface. In addition to this the use of bench slope can provide

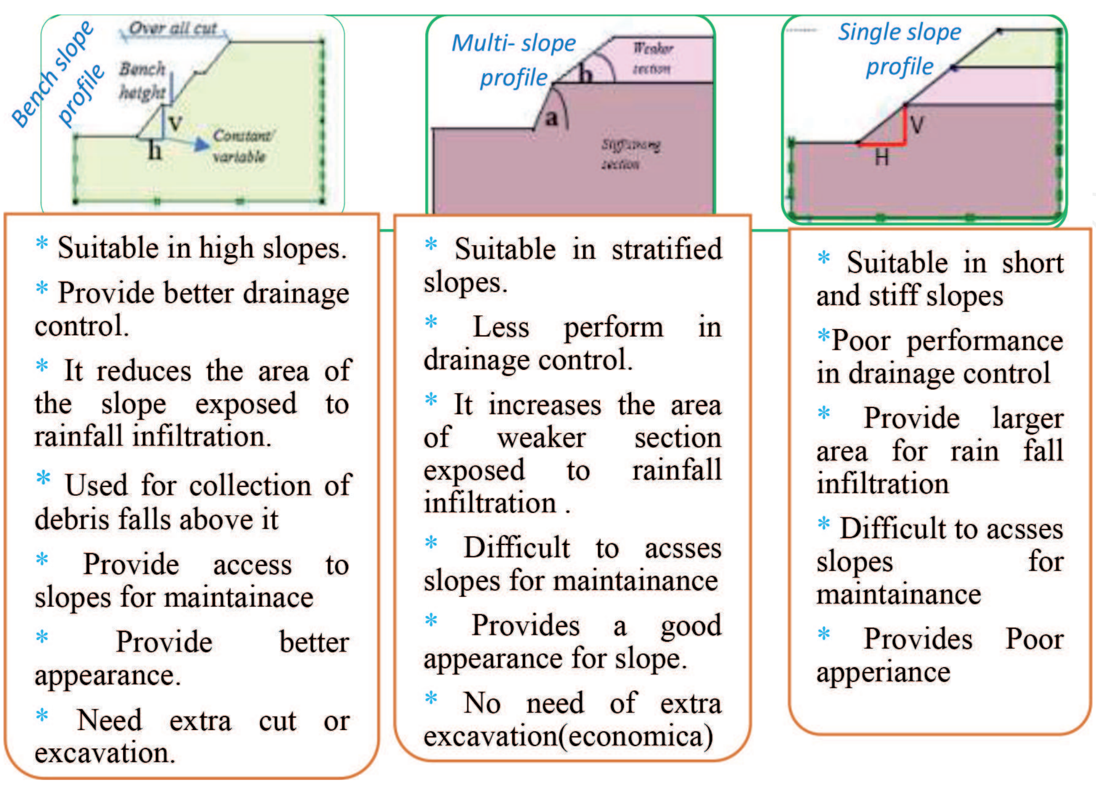

Figure 11.
Advantages and limitations of slope profiles.

the following advantages. (1) It reduces the area of the slope exposed to rainfall infiltration as it allows the use of steep slope between every benching. (2) It provides effective drainage control by collecting the rainwater from each slope profile and draining it laterally to ditches. (3) It provides access to side slopes for maintenance, plantation of vegetation, and decoration. (4) It uses for collection of debris falls above it. (5) It provides esthetic value and better appearance for slopes especially when it located around towns. In general slope profiles have advantages and limitations depending on site specific conditions as shown in **Figure 11**.

11. Conclusion

The performance evaluation of slope profiles in this study was made for the objective of creating awareness on the effect and its suitable condition of different geometric profiles on slope stability. The effect of geometric parameters like slope height, slope angle, bench width, no of bench and bench angle on slope stability were evaluated interims of FS and deformation on selected critical slope sections from the newly constructed road cut slope. From the result, it has been seen that geometric modification will provide better and economical slope stability compared to other structural remedies.

Accordingly, the stability of slope decreases with an increase in slope height and slope angle in single slope profile leading to an uneconomical design of high slopes in a single slope profile. Benching provides an important stability for cut slope especially for slopes having larger height and its performance is more effective in steep slopes. Bench width and bench height also parameters which affect the performance of benching. Multi-slope profile provides an effective slope stability in a stratified soil of varied strength. It allows economical slope design without extra excavation by making adjustments only within the slope section. In addition to its direct effect on the FS, slope profiles have different performance on drainage control, access to maintenance, and its esthetic value. Therefore, the selection of slope profiles during design should be based on site-specific considerations.

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