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# Geometrical profile of cohesive-frictional soil slopes for optimal stability

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## ABSTRACT

**:** In this study, finite element method with strength reduction technique is employed to study the stability of slopes with non-straight line profiles comprises three segments. According to this method, the strength parameters are reduced until the slope becomes on the verge of failure. A software called (Optum G2) is used to analyze the geometrical and mechanical parameters. The effect of the geometrical shape of the slope with specific limitations on the factor of safety (FOS) has been investigated to find the corresponding profile configuration that provides maximum stability. The profile (slope face geometry) has been divided into three straight lines (segments) with different lengths. The study involved the soil cohesion (c), angel of internal friction (∅) and the angle of the imaginary straight line linking the slope toe with slope crest (β) called herein slope inclination. The main results showed that using the three segments facing profile can increase the factor of safety (FOS) by up to 15% in comparison with the corresponding slopes of straight-line profile. Design charts has been introduced to be utilized by engineers and practitioners to obtain the geometrical parameters for the optimal profile as well as the expected improvement percentage in factor of safety.

**Keywords**: Geometrical profile, slope stability, strength reduction technique, slope geometry.

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## 1. Introduction

The stability of soil slopes is one of the most important problems that may encounter geotechnical engineers. Several methods for soil improvement have been developed during the last few decades to enhance the stability of soil slopes or embankments, such as soil compaction, chemical stabilization, retaining walls and reinforcement using soil nails [1] or geosyenthetics [2,3] and [4]. However, changing the slope geometrical profile or slope flattening still one of the most effective and economical measure to increase slope stability if space allowed [5]. For manmade slopes, it is common to see slopes with straight line slope facing. However, this may not be the best facing shape in terms of slope stability. Utili and Nova [6] have shown that log-spiral slope profile provides better stability than the corresponding straight line profile. Similar findings were found by Vahedifard et al. [7] who worked on a concave circular profile for geosynthetic-reinforced slopes. A probabilistic approach combined with the upper bound theorem of limit analysis showed that the best profile may comprises both concave up and down, especially for gentle slopes [8] and [9].

Based on the literature, this study investigates the geometrical combinations of three segments slope facing that provides maximum slope stability. Actually, this is a simplification of the profile found by [8] as shown in Figure (1), the latter used 20 points (21 segments) to describe the "optimal profile" resulting in a curved profile which might be difficult to construct. Also, the current study aims to provide charts that can be easily used by practitioners to obtain a feasible facing profile that provides maximum slope stability.

## 2. Methodology and software

The difficulty and limitations of using large scale embankments in research give rise to the use of computer software like (Optum G2). This software has been employed in this study to investigate the effect of facing profile on the factor of safety. Finite element analysis with strength reduction technique based on the work of [10] and [11] is one of the methods that can be performed using this software [12]. The soil strength parameters represented by the soil cohesion c and the frictional resistance parameter tan∅ are reduced by the same factor until the slope reaches the status of stability/instability. The factor of safety then can be calculated by the Eq. 1 as follow:

$$\mathrm{FOS} = \frac{c}{c_{red}} = \frac{\tan\emptyset}{\tan\emptyset_{red}} \quad (1)$$

Where FOS is the factor of safety, ($c_{red}$ and $\tan\emptyset_{red}$) are the reduced strength parameters at which the slope is on the verge of failure.

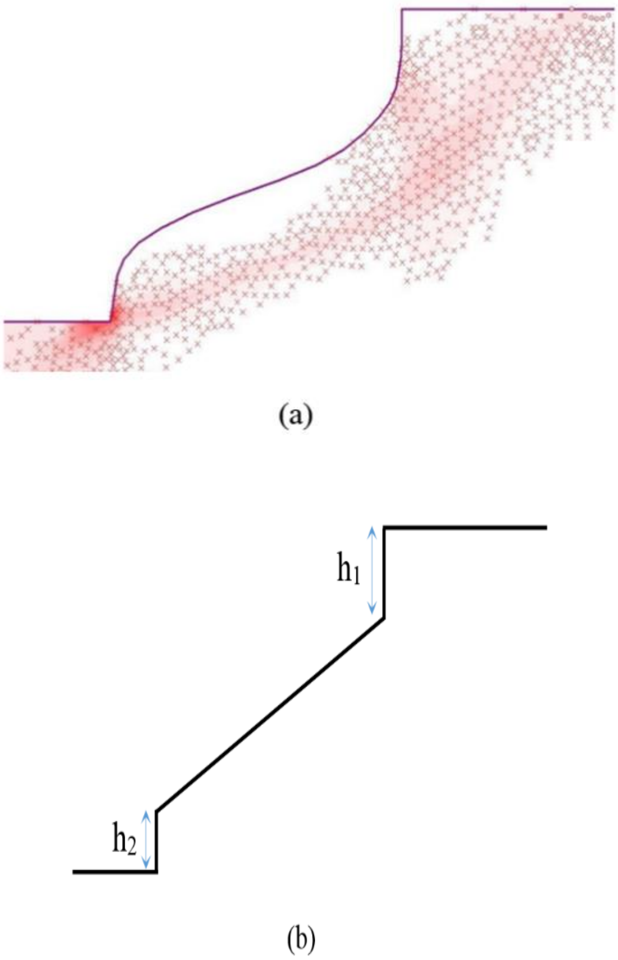



Figure 1. (a) Geometrical profile for best stability as found by [8],
(b) Geometrical profile proposed in this study

In the current study, a cohesion-frictional soil slope with 4m height (H) was modeled using the software (Optum G2 2020 2.0.36). Mohr-Coulomb material model is used with modulus of deformation E=30 MPa, Poisson's ratio of $\upsilon$=0.25, and unit weight of soil $\gamma$=18 kN/m3. Referring to Figure 2, both values of $h_1$ and $h_2$ vary from 0 to 0.6H with 0.1H increment. Once values that provide best stability is found then the increment refined to 0.05H for local adjacent values. Three values of angle of shearing resistance ∅=20°, 30°, and 40° and four values of slope inclination $\beta$=30°, 45°, 60°, and 75° along with four values of normalized soil cohesion $c/\gamma H$ =0.05, 0.1, and 0.15 are used. The factor of safety was computed for each possible combination accordingly. Mesh additivity starting with one thousand 6-node Gauss element is used and standard fixities are applied for the boundary conditions.

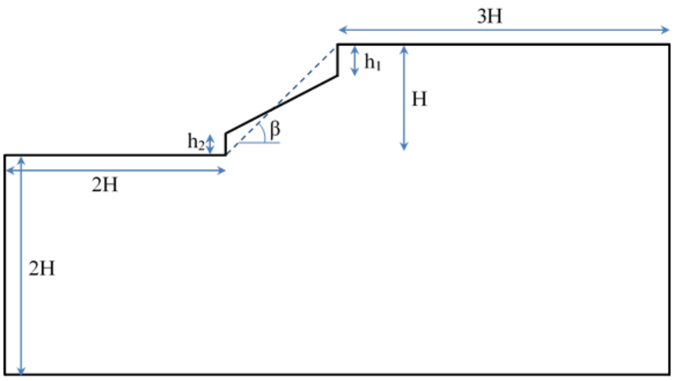
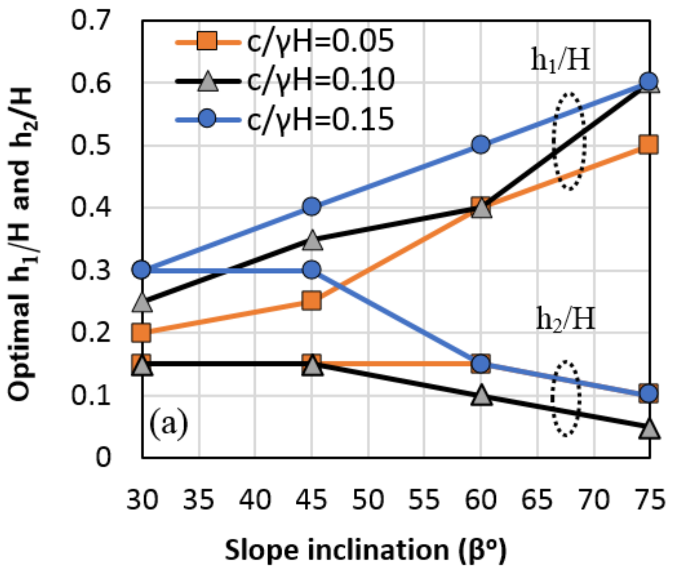


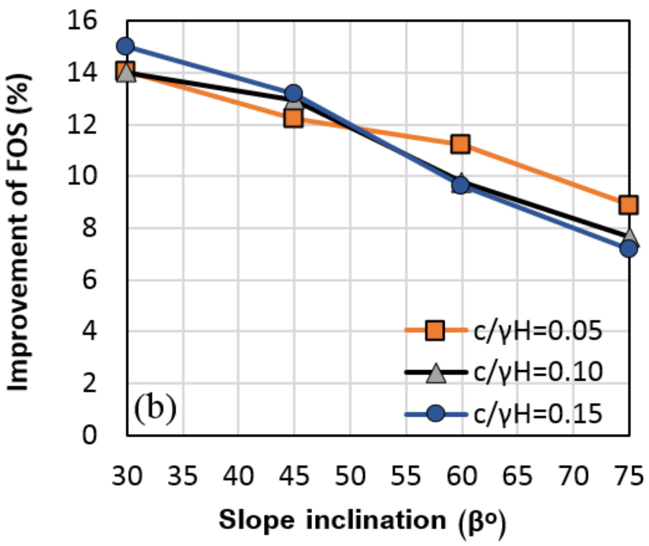

Figure 2. Geometrical parameters used in Optum G2

## 3. Results and discussion

The first trend to notice when scanning Figure 3, 4 and 5 is that $h_1$ increases and $h_2$ decreases with the increase of the angle of inclination (β). Furthermore, gentle slopes show better improvement than steep ones, mainly because gentle slopes provide more flexibility in altering the potential failing mass. The higher the soil cohesion the higher the value of $h_1$ and $h_2$. On the contrary, increasing the angle of shearing resistance Ø reducing the both $h_1$ and $h_2$. With $h_1$ increases from 0.2H to 0.6H and $h_2$ decreases from 0.3H to 0.05H. Figure 3, 4 and 5 can be used as charts by practitioners to find the geometrical parameters for the slope facing profile as well as the percentage of improvement expected when applying the new profile in comparison to the straight line one. For example, if an embankment of 3m in height to be constructed with inclination of 45° and soil strength parameters where c=6 kPa, Ø=20°, and soil unit weight was 20 kN/m3. The practitioner can use Figure 3 by applying c/γH=0.1 and draw a vertical lines starting from 45 at the x-axis to find out the corresponding $h_1$=0.35, $h_2$=0.15 and 12.2% of improvement in FOS in comparison with the conventional straight line facing profile. Figure 6 and 7 present a comparison between the failure mechanism of straight line slope and the optimal profile found in this study and for both gentle and steep slopes. It can be seen that altering the profile can decrease the driving mass near the slope crest and increase the passive pressure by increasing $h_2$ near the toe. Consequently, this lead to longer failure plane for slopes with "optimal" profile.




(a)




(b)

Figure 3. For soil with Ø=20° (a) shows $h_1$ and $h_2$ that provides max FOS, (b) relates the improvement in FOS when using the optimal values of $h_1$ and $h_2$ with slope inclination.

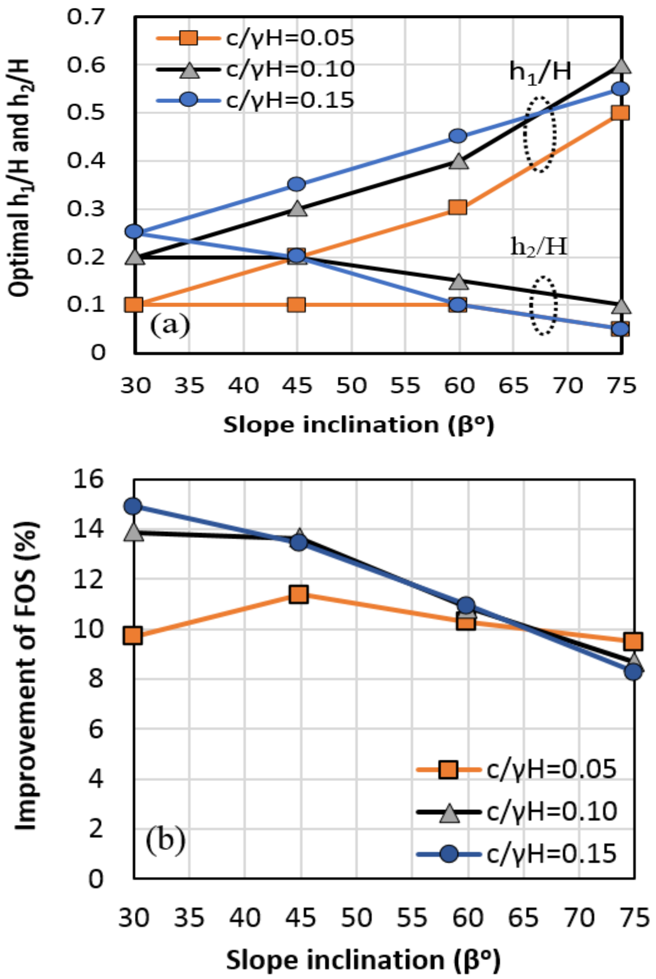
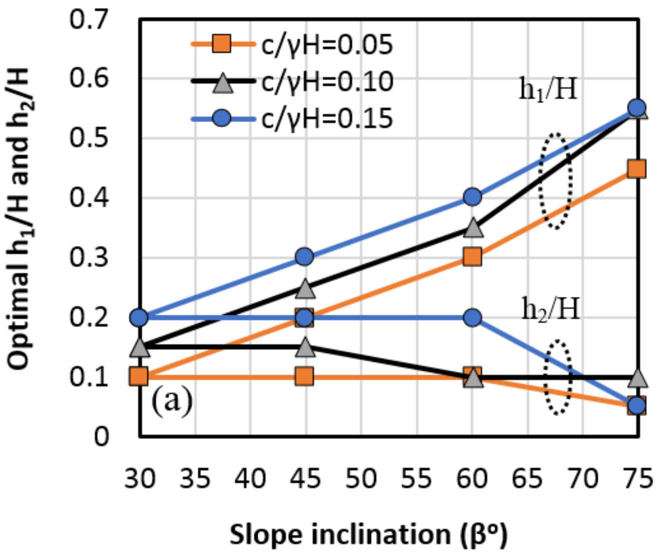



Figure 4. For soil with Ø=30° (a) shows $h_1$ and $h_2$ that provides max FOS, (b) relates the improvement in FOS when using the optimal values of $h_1$ and $h_2$ with slope inclination.



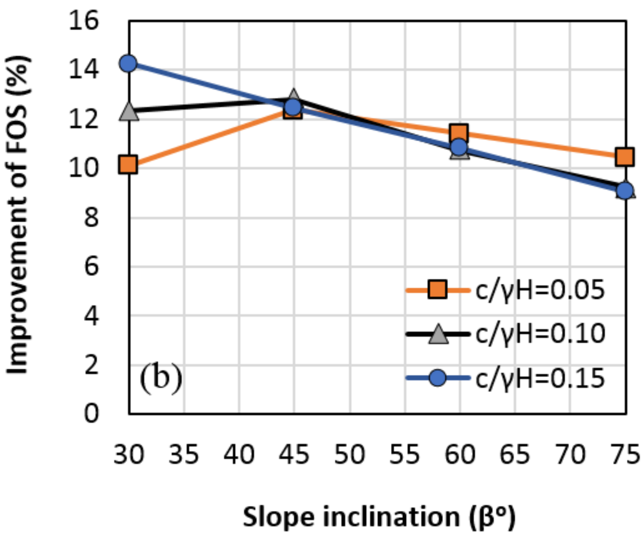
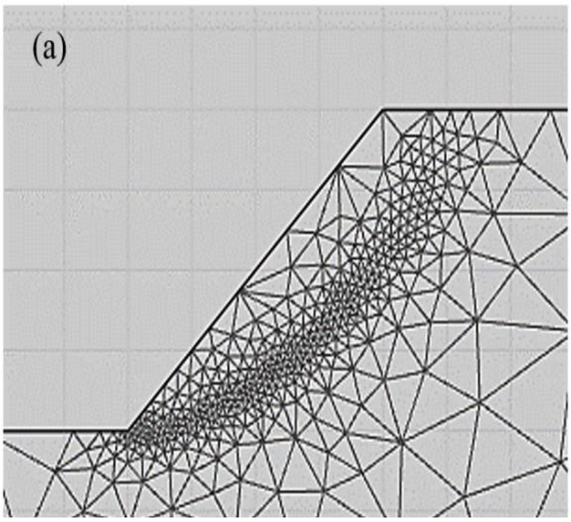




Figure 5. For soil with $\emptyset$=40° (a) shows $h_1$ and $h_2$ that provides max FOS, (b) relates the improvement in FOS when using the optimal values of $h_1$ and $h_2$ with slope inclination.



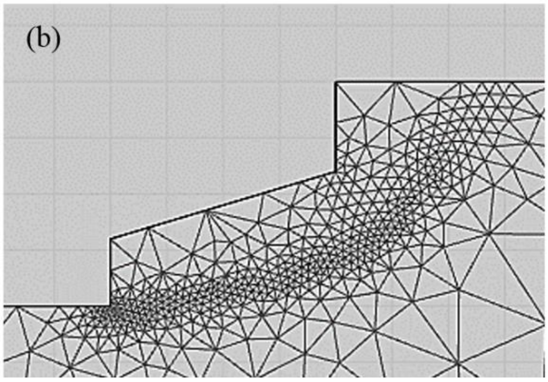



Figure 6. For Ø=20°, c/γH=0.05, and β=45° comparison of failure mechanism between conventional straight line profile and the optimal profile found in the current study.

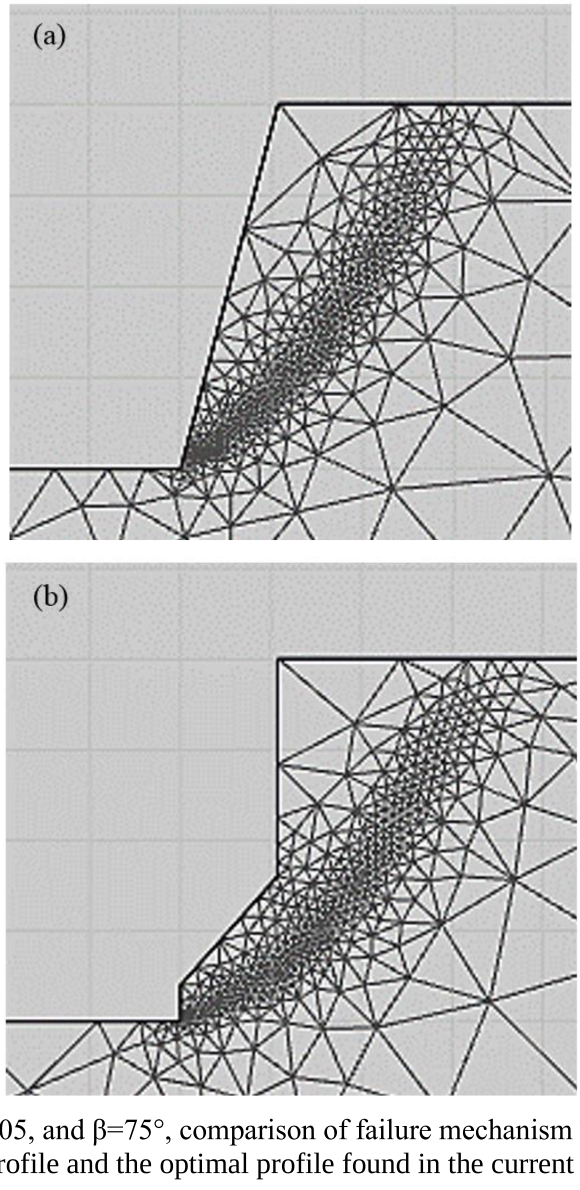



Figure 7. For Ø=20°, c/γH=0.05, and β=75°, comparison of failure mechanism between conventional straight line profile and the optimal profile found in the current study.

## 4. Conclusions

Based on the results, it can be concluded that the proposed three segments slope facing can provide up to 15% improvement in the factor of safety in comparison with the conventional straight line. It should be noted that geometrical restrictions have been imposed on these three line. The first line assumed to extend vertically downward of a distance $h_1$ from the slope crest, the second line assumed to extend vertically upward of a distance $h_2$ from the slope toe, and the third one links the ends of first and second lines together. Unlike steep slopes, gentle slopes show significant improvement in stability when applying the three segments facing. This is because for steep slopes, it is limited to reduce the gravitational driving force or increase the passive pressure by increasing the mass near the toe acting like a retaining force. Soil strength parameters have different effect on the optimal geometrical profile. The angle of shearing resistance has less effect on the factor of safety than soil cohesion which has a considerable impact. For steep slopes, with relatively cohesive soil, $h_1$ values can be up to 0.6 of the slope's height while $h_2$ is no more than 0.1H. The proposed geometry provides higher feasibility (in construction) than curved profiles, also it provides architectural beauty in comparison to the straight line profiles. The provided results in figures 3, 4, and 5 can be used as charts for practitioners to quickly obtain the geometrical parameters needed (i.e. $h_1$ and $h_2$) as well as the percentage of improvement.

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