Parametric Study of Global Stability of Benched Earth Slopes

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ABSTRACT

One of the available approaches for improving the stability of earth slopes is slope benching. Slope benching is often applied in construction of slopes associated with highway and railways projects as it decreases the overall slope steepness and consequently increases the mass stability leading to a higher factor of safety against global instability. In this paper, a parametric study of the global stability of a number of selected benched earth slope configurations was carried out using Slope/W Program. The limit equilibrium analysis approach using the well-known Modified Bishop’s method was adopted. Stability charts for various benched slopes were developed based on the obtained results from this study. Charts were prepared for slopes as functions of bench-width ratio, bench count, steepness, soil parameters and pore water pressure ratio parameters. The obtained charts are considered practical and could reasonably be used as a tool in preliminary slope benching design.

RÉSUMÉ

Le terrassement en gradins est l'une des approches disponibles pour améliorer la stabilité des pentes en créant des talus en gradins. Il est souvent utilisé dans les projets d’aménagement des pentes latérales aux abords des autoroutes et des chemins de fers, car il diminue l’inclinaison globale de la pente et augmente par conséquent la stabilité de la masse de sol. Un tel aménagement augmente le facteur de sécurité contre l'instabilité globale. Dans cet article, une étude paramétrique de la stabilité globale de certaines configurations de talus préalablement sélectionnés a été réalisée à l'aide du le programme Slope/W. L'approche d'analyse d'équilibre à l’état limite bien connue, Bishop Modifié a été adoptée. Pour différents talus en gradins, des diagrammes de stabilité ont été développés à partir des résultats obtenus à partir de cette étude. Des abaques ont été préparés pour les talus en fonction du rapport entre la largeur des bancs, le nombre de talus, l'inclinaison, les paramètres du sol et ceux du rapport de la pression interstitielle. Les abaques obtenus sont considérés comme pratiques et pourraient raisonnablement être utilisés comme outil dans la conception préliminaire des talus.

1 INTRODUCTION

Slope stability analyses are often carried out to study and verify the stability of man-made and natural earth slopes such as embankments and earth cuts for many projects. The mass stability of soil slopes can be enhanced by appropriate incorporation of terraces, benches, steps, and serrations. As per available geotechnical literature, the first stability charts for slope benching were developed by Taylor (1937). Slope benching is particularly important and well suited for large cuts and fill slopes, which are increasingly in demand in construction associated mainly with highway and railway projects. Slope benching decreases the overall slope steepness and consequently increases the mass stability. Benching of slopes reduces the hazard of falling rocks and debris on the roads (Giani 1992). Benching of slopes also provides favorable sites for establishment of vegetation and plants (Gray and Sotir, 1996), thus further improving stability. In the case of surficial erosion benching can result in decreased erosion, sediment trapping on the benches, and enhanced establishment of protective vegetation on the bench steps. However, there are some possible long-term downsides to benching that may conversely influence the stability, for instance, against surficial erosion and shallow sloughing (Schor and Gray, 2007). Benching has occasionally been used to protect faces of slopes such as tailings dams and mineral ore waste dumps. Over time, these benches tend to degrade by a process of “notching” in which the sharp break (sudden increase) in slope at the edges of the benches becomes the source or origin of destructive gullies. This time dependent notching process and gully development has been analyzed and modeled in detail by Hancock et al. (2003). Whereas benching may improve stability in the short run, it could also decrease long-term stability unless the edges of the benches are periodically inspected, protected and maintained against notching or channel incision. This phenomenon has not been considered and reflected in the stability charts developed in this study.

Analytical studies on the stability of stepped slopes are quite rare. In a report by Food and Agriculture Organization (FAO 1986) on land preparation for cultivation on sloping grounds, terraces and ditches are described as conservation methods of land treatment for agricultural use, with layout, construction and empirical design considerations of terraces presented. Federal Highway Administration also published a report on highway slope maintenance and slide restoration with some guidelines for slope benching as one of the approaches for increasing slope stability, particularly for reshaping steep slopes where flattening is difficult and sloughing often occurs (FHWA 1988). However, TIRRS (2001) reported the general ineffectiveness of these guidelines on slopes of decomposed soils with high groundwater due to excessive material sloughing.

Slope stability charts are routinely used as a quick means for preliminary analysis and design of homogenous slopes with well-defined inclination. Slope stability charts can also be used for checking the results of detailed analytical or numerical analyses. For uniform 2-D slopes, in geotechnical literature, various charts have been developed based on limit equilibrium analysis approaches; the charts differ in terms of the analytical models, theoretical assumptions, slip surface configurations and drainage conditions (Winterkorn and Fang, 1975, Abramson et al. 2002, Duncan and Stephen, 2005). Michalowski (2002) presented slope stability charts based on the kinematic approach of limit analysis which can be used for uniform 2-D slopes subjected to pore water pressure and seismic forces. More recently, Pantelidis and Psaltou (2013) published a paper and presented stability tables for homogeneous earth slopes with benches and summarized numerous references on this subject.

Along these lines, an in-depth analysis of benched slopes was carried out to produce a series of stability charts with respect to various parameters such as slope inclination, number of benches, bench width, soil cohesion, friction angle and pore water ratio.

2 BENCHED SLOPES MODEL

A schematic of a benched slope is shown in Figure 1 with defined geometrical parameters and assumptions. The parameters and values used in the slope stability analysis (static) in this parametric study are presented in Table 1.

Table 1. Parameters, Variables for Parametric Analyses

Parameter	Value	Unit
Slope Height (H)	10,50,90	m
Bench Ratio (S/H)	0.1,0.2,0.3	NA
Slope Angle (β)	30,45,60,75,90	(°)
Number of Benches (n)	1,2,3,4,5	NA
Pore- Water Pressure Ratio (r_u)	0, 0.25, 0.5	NA
Soil Strength (dry or drained)	C - Ø’ soil	NA

NA: not applicable.

Benches are assumed to be excavated horizontally and all have identical width and height; therefore, the bench height can be calculated as in Eq. 1.

$$h = H/(n + 1) \qquad [1]$$

Parameter X is the amount of retreat or setback at the crest caused by the benching as shown in Figure 1. The angle θ is called equivalent flattened slope angle, which is inversely proportional to the parameter n × S/H according to the expression in Eq. 2.

$$\theta = \tan^{-1}\{1/(\cot\beta + n \times S/H)\} \qquad [2]$$

Any distributed surcharge at the slope crest can be incorporated into the analysis by adding equivalent soil layer at the top of the bench.

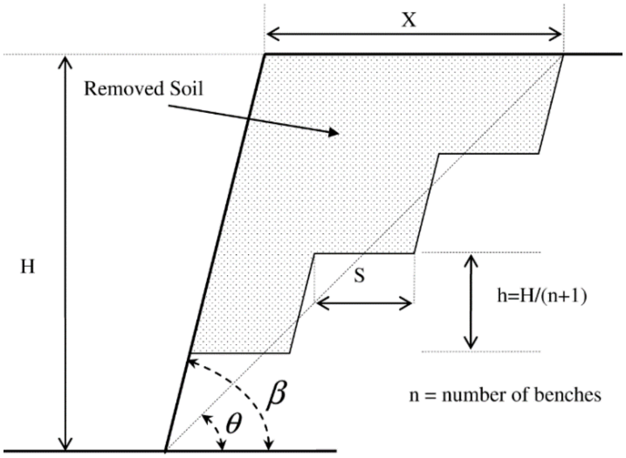


Figure 1. A schematic of a typical benched slope

2.1 Method of Analysis

The limit equilibrium analysis is utilized in this parametric study. This method assumes that soil conforms to linear (Mohr-Coulomb) or non-linear relationships between shear strength and the normal stress on the failure surface. The analysis provides a factor of safety (FS), defined as a ratio of available shear resistance to the shear stress required for equilibrium. If the value of the factor of safety becomes less than 1.0, the slope stability will be threatened. The most common limit equilibrium technique used in slopes analysis is the method of slices where the soil mass is discretized into vertical slices (Abramson et al. 2002, Zhu et al. 2003). The factor of safety results may vary due to different assumptions and satisfied equilibrium conditions of the slices (Abramson et al. 2002, UACE 2003, Duncan and Stephen, 2005). The analysis presented in the following section, the stability of benched slopes under dry or seepage conditions is examined based on the limit equilibrium approach using the Simplified Bishop's method of slices utilizing the 2-D stability code (Slope/W) program. This program is formulated in terms of moment and force equilibrium equations for the slices. The circular slip surface for steep slopes is recommended to be revised at the exit angles as depicted in Figure 2 in order to avoid convergence problems associated with parameter m_α in Bishop’s safety factor expression (Slope/W) ($m_\alpha = [\cos\alpha + \text{sine}\ \alpha \times \tan Ø’] / FS$) where α is the angle of inclination of the potential failure arc to the horizontal at the mid point of the slice. The influence of this assumption on the presented results is discussed later in the paper.

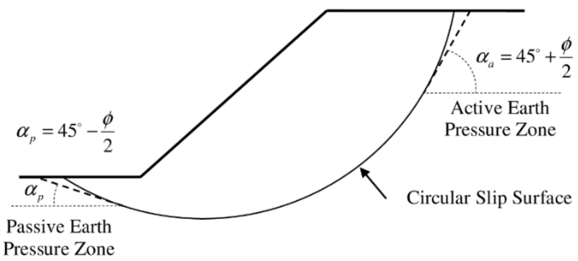


Figure 2. A schematic shows active and passive earth pressure zones

2.2 Development of Stability Charts

Stability charts developed in this parametric study are presented in terms of dimensionless strength parameters of FS/tan Ø’ and C/ɣ H × tan Ø’: where FS, Ø’, ɣ and H are safety factor, friction angle, cohesion, soil unit weight, and slope height; respectively. This selection of parameters eliminates the iterative procedure in determining the safety factor as proposed and used by Michalowski (2002). Three drainage conditions have been considered with the pore pressure ratio as $r_u=u/\sigma_v = 0, 0.25$ and 0.5; where u and σ_v are pore water pressure and total stress in the soil; respectively.

The charts are not suitable for short-term slope stability of saturated cohesive soils (undrained) with Ø = 0 as the term tan Ø appears in the denominator of FS/tan Ø.

Charts are grouped as sets of (r_u, n, S/H). Each set is comprised of plots of FS/tan Ø’ versus C/ɣ H × tan Ø’ for different values of slope angle *β*. Numerous analyses were performed with different values for various parameters in order to obtain sufficient data to draw the charts; these variables are presented in Table 1. An example of the generated plots with the data points is shown in Figure 3.

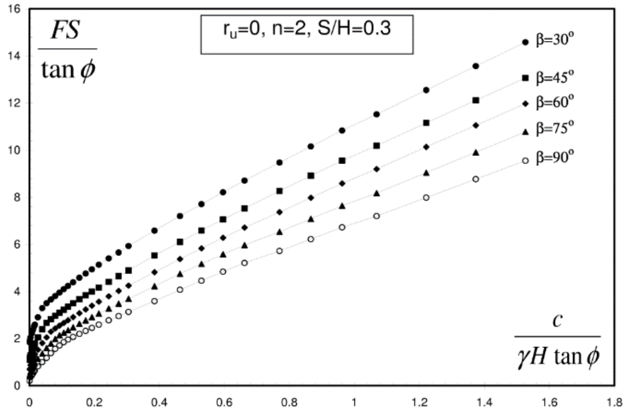


Figure 3. Typical graph illustrates number of points used for generating slope stability charts

2.3 Slope Stability Analysis Verification

In case of n = 0, there is no bench, and slope stability charts drawn for this condition should be similar to those already presented for uniform slopes. For the sake of verification, Figures 4 and 5 present some comparison between current and previously reported results for dry and saturated slopes; respectively. Figure 4 shows the variation of strength parameters FS/tan Ø’ and c /(ɣ × H × tan Ø’) for various slope angles using three different stability analysis approaches of Taylor (1937), Michalowski (2002) and this parametric study, which are based on the theory of Friction Circle, Limit Analysis, and Modified Bishop; respectively.

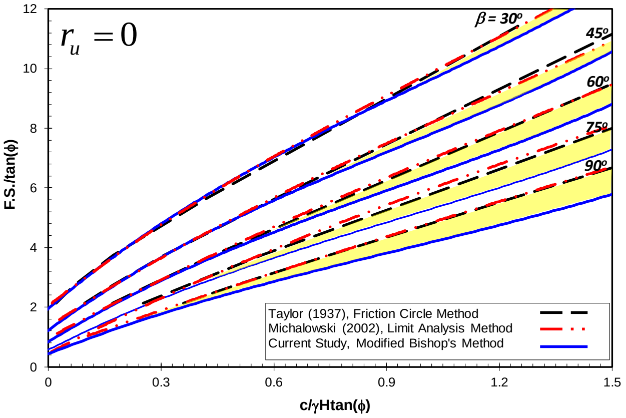


Figure 4. Slope stability charts based on different analytical methods for dry condition slopes

A similar result is obtained for saturated slopes (r_u = 0.5) based on this study and that by Michalowski (2002). While the results for Taylor (1937) and Michalowski (2002) follow closely, this study’s plots show lower determined safety factors for identical slopes and soil conditions. This trend becomes more pronounced for steeper slopes (*β*) with lower friction angles (Ø’) and/or higher cohesion (C) as depicted with shaded areas in Figure 5.

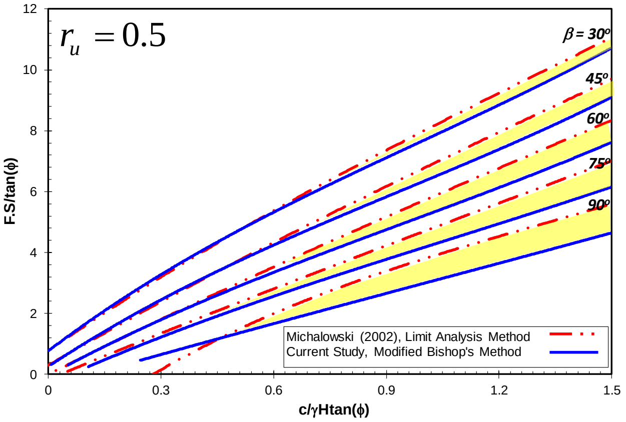


Figure 5. Slope stability charts based on different analytical methods for saturated condition slopes

This behavior appears to be related to the fact that the circular slip surfaces for steeper slopes in the two previous methods become almost very steep at the crest; therefore, they deviate significantly from what assumed in this study as the slip surface in the active zone as previously shown in Figure 2. The deviation of the plots in the above figures was investigated with further analyses of slope examples where the assumption of the slope surface configuration as shown in Figure 2 was changed to an assumption of complete circular slide surface as generally used in the slope stability analysis methods. Two cases of slope angles β = 75º and 90º which present the highest deviations were considered. These results are presented in Figure 6 and Figure 7 for the dry and saturated conditions; respectively.

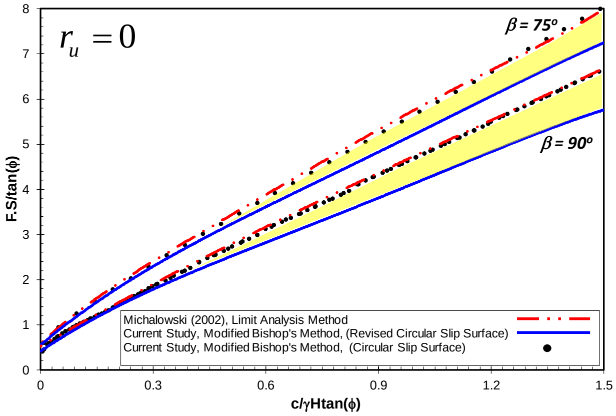


Figure 6. Influence of the assumed failure surface in Bishop's method on stability charts for dry condition (r_u = 0)

It turns out that the assumption of how the slip surface daylights on the slope crest (the exit angle) has considerable influence on the stability results, such that altering this assumption to be uniform across the methodologies creates convergence of the results. Nevertheless, the revision of the exit angle as presented in Figure 2 is valid because the corresponding calculated safety factor becomes lower and more conservative.

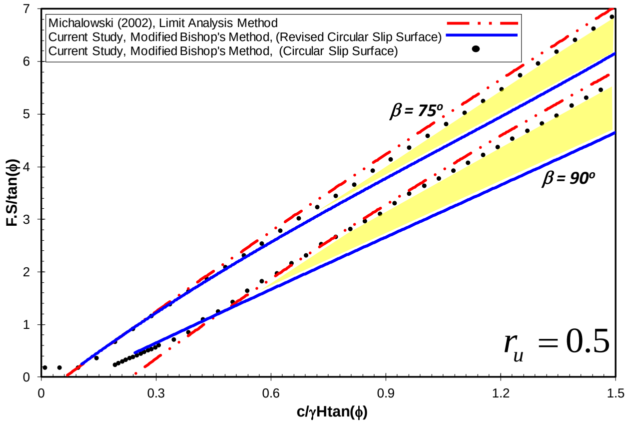


Figure 7. Influence of assumed failure surface in Bishop's method on stability charts for saturated condition (r_u = 0.5)

2.4 Influence of Slope Benching

The effect of benching on stability is illustrated with an example using a steepness of β = 75º in Figure 8 and Figure 9 to highlight the influence of bench count (for S/H = 0.1) and bench width (for n = 3); respectively. In both cases the safety factor is favorably improved by increasing bench number or bench width as the equivalent slope angle (θ in Figure 1) decreases and the slope crest sets back. The amount of this retreat (X in Figure 2) is often limited by various constraints; an optimal design should be made by examining different combinations of benches numbers (n) and width ratios (S/H) to meet the required stability as well as the surficial erosion resistance, environmental considerations, construction cost, constructability and geometric limitations.

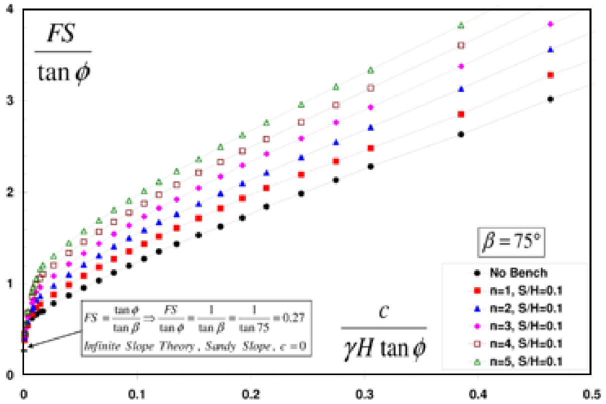


Figure 8. Influence of benching on slope stability for β = 75º and S/H = 0.1 case

For the case of c = 0 soil (e.g., cohesionless soil), all plots converge toward a point corresponding to FS/(tan Ø') = 1/(tan Ø') = 0.27 which defines the stability status of a 75º sandy slope based on the infinite slope theory. Clearly, benching has no effect in this condition as slope stability is governed by near surface shallow sliding.

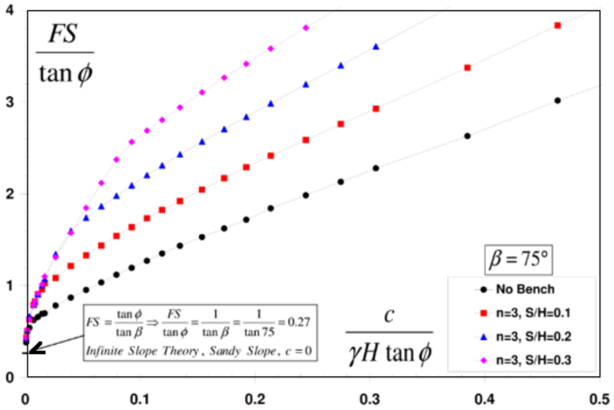


Figure 9. Influence of benching on slope stability for β = 75º and n = 3 case

As mentioned earlier in the paper, the overall effect of benching is nearly equivalent to slope flattening in terms of the stability. However, the benching method is more advantageous as it lessens surficial erosion by reducing the run-up distance for flowing water downward over the slope surface and also by trapping the eroded particles at the benches. In addition, the benches can be used as accessible roads for seeding or mulching operations, while decreasing the likelihood of falling rocks and debris impacting mountainous roads. From a constructability standpoint, creating benches is simpler than flattening the entire slope.

It appears that the safety factor for a benched slope is slightly larger than that for a “flat slope” with the corresponding steepness of *θ*. This is illustrated in Figure 10 for the example of *β* = 75º (presented in Figure 8 and Figure 9) in which several cases of benching corresponding to different equivalent slope angles (*θ*) have been examined in this study. It can be seen that all different benched slopes are more stable than their equivalent flat slopes. Also, for a given slope angle (*θ*) (or n × S/H), the stability of a benched slope decreases with increasing the bench number (n), which should ultimately reach the same safety factor of its corresponding equivalent flat slope as (n) becomes very large. The reducing rate, however, seems more pronounced at larger (*θ*) (or at smaller n × S/H). Therefore, slope benching can be considered as more appropriate than flattening in many aspects.

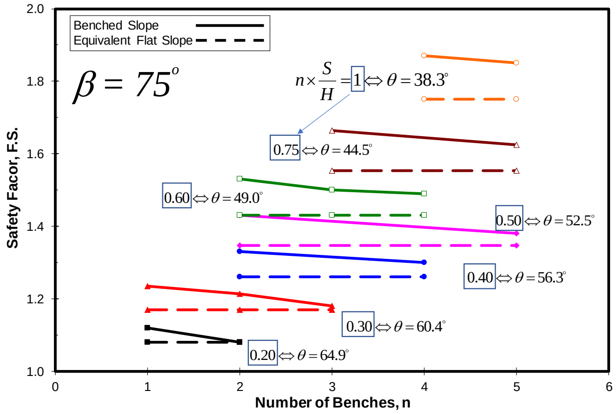


Figure 10. Stability comparison of different benched slopes with their equivalent flat slopes for *β* = 75º case

3 CONCLUSIONS

A wide-ranging parametric study was conducted on earth benched slopes based on limit equilibrium theory. This study used Modified Bishop’s method and revised circular slip surfaces in active and passive zones generally for C-Ø’ soils. The results are presented in a form of “Stability Charts as shown on Figures 11 to 16” for the static analysis of benched slopes. Various parameters such as bench number and width, slope angle and height, soil parameters, and pore water pressure ratios were studied. Unlike other common charts for stability analysis of flat slopes, the developed charts do not require iterative procedures in determining the safety factors of benched slopes.

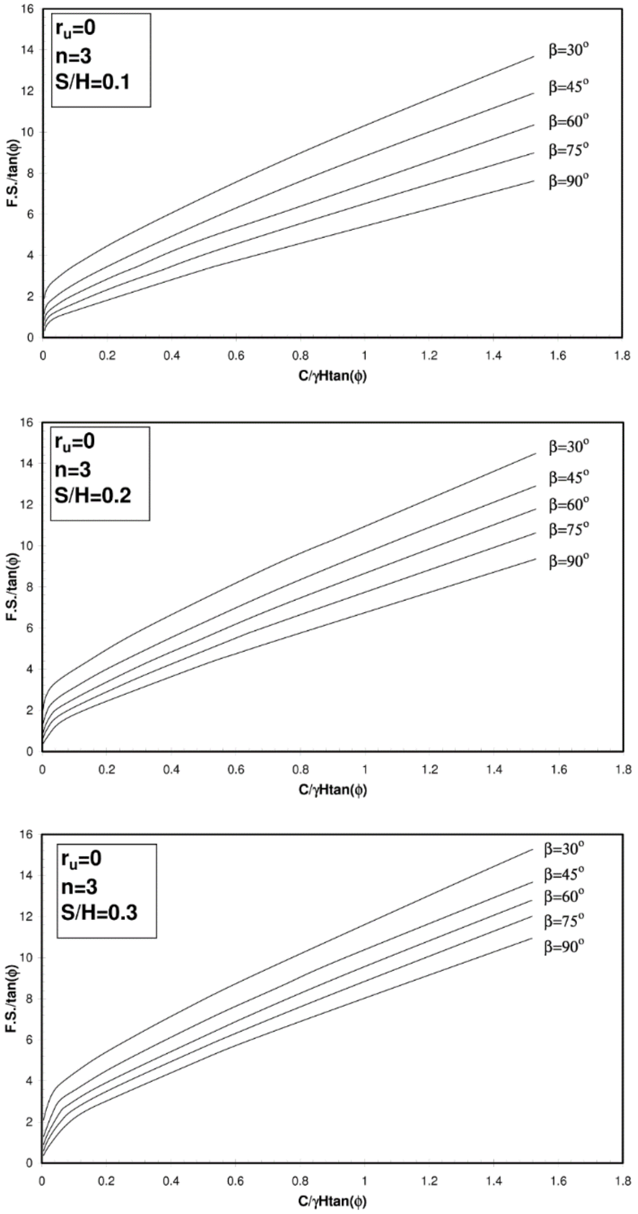
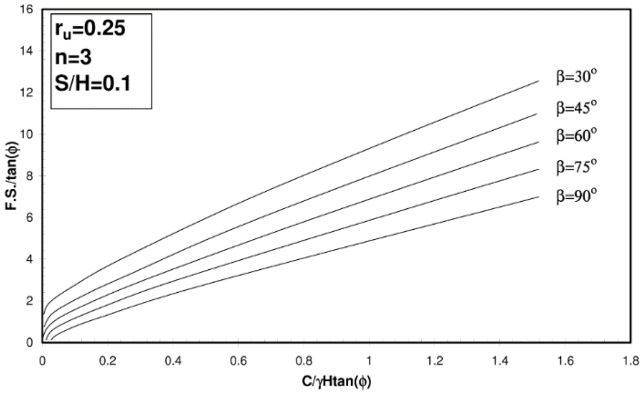


Figure 11. Stability Charts for r_u=0; n=3; S/H=0.1,0.2,0.3



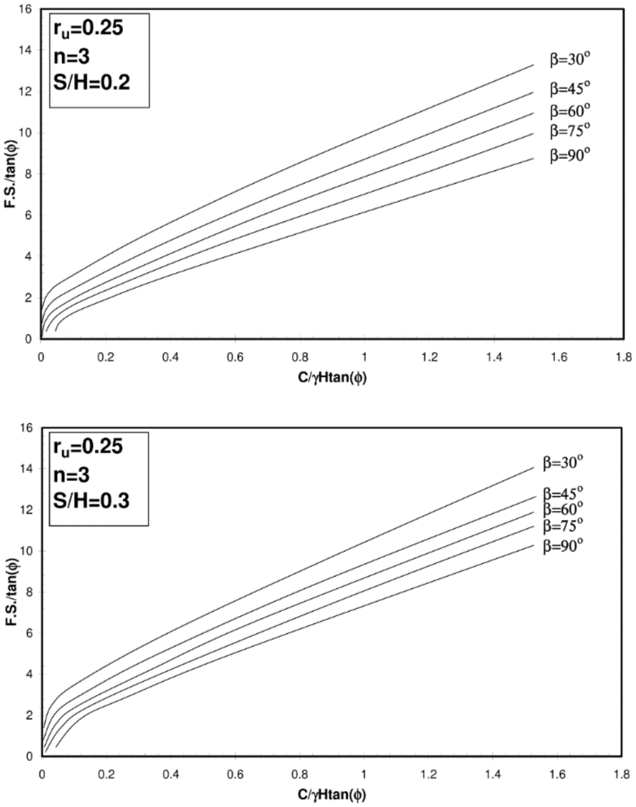
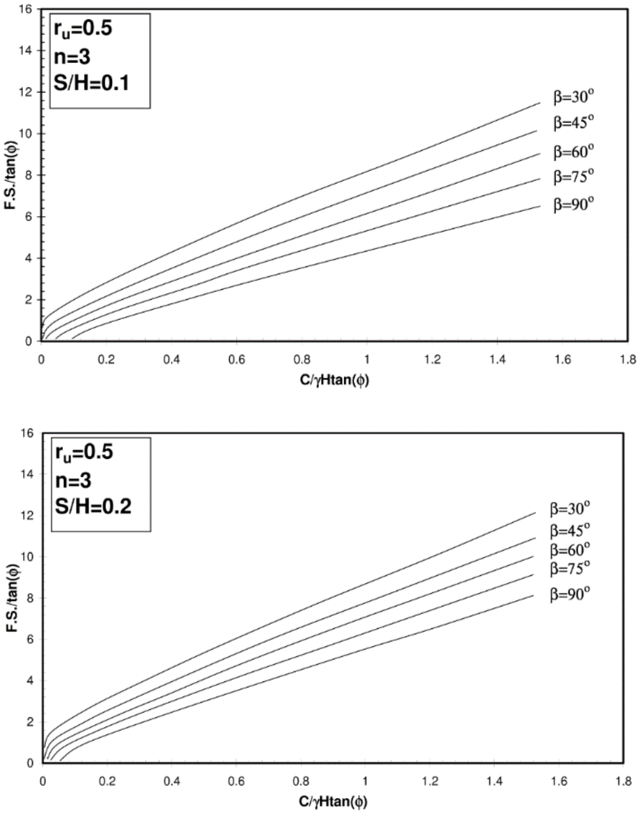


Figure 12. Stability Charts for r_u=0.25; n=3; S/H=0.1,0.2,0.3



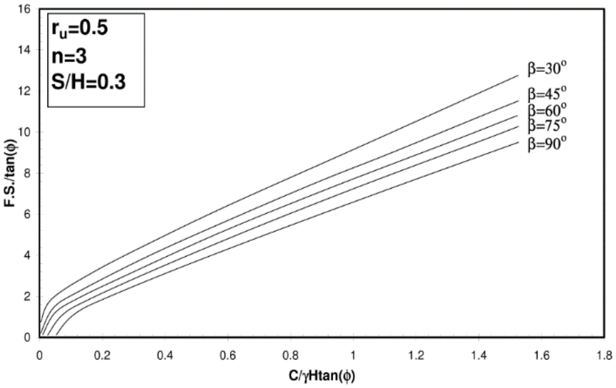


Figure 13. Stability Charts for r_u=0.5; n=3; S/H=0.1,0.2,0.3

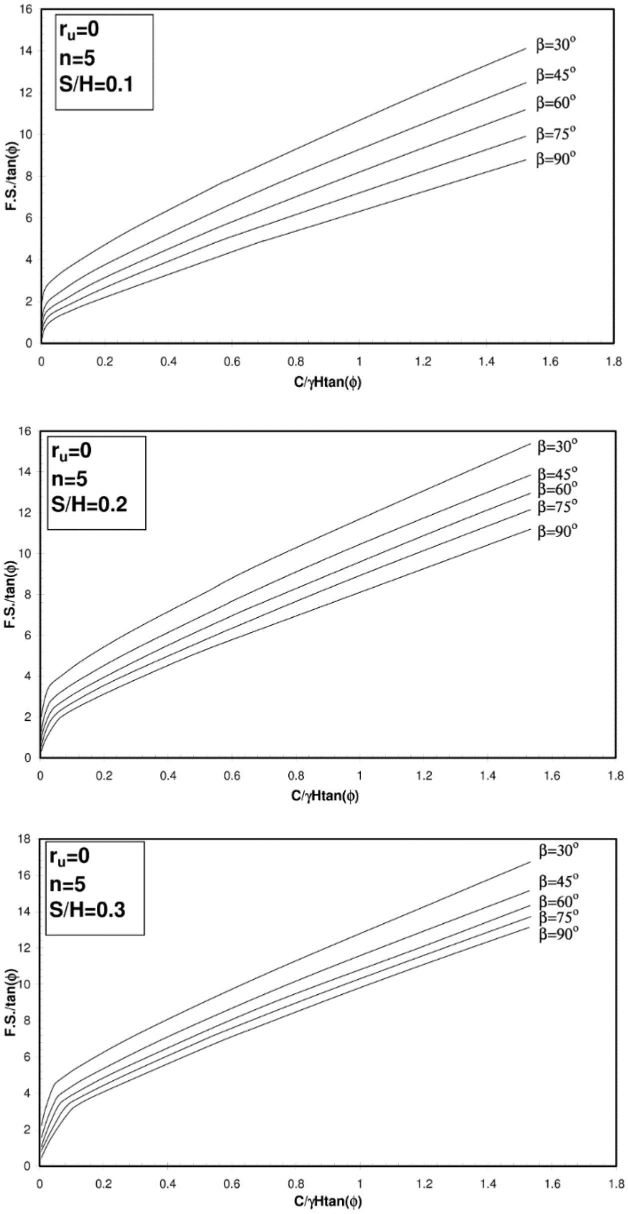


Figure 14. Stability Charts for r_u=0; n=5; S/H=0.1,0.2,0.3

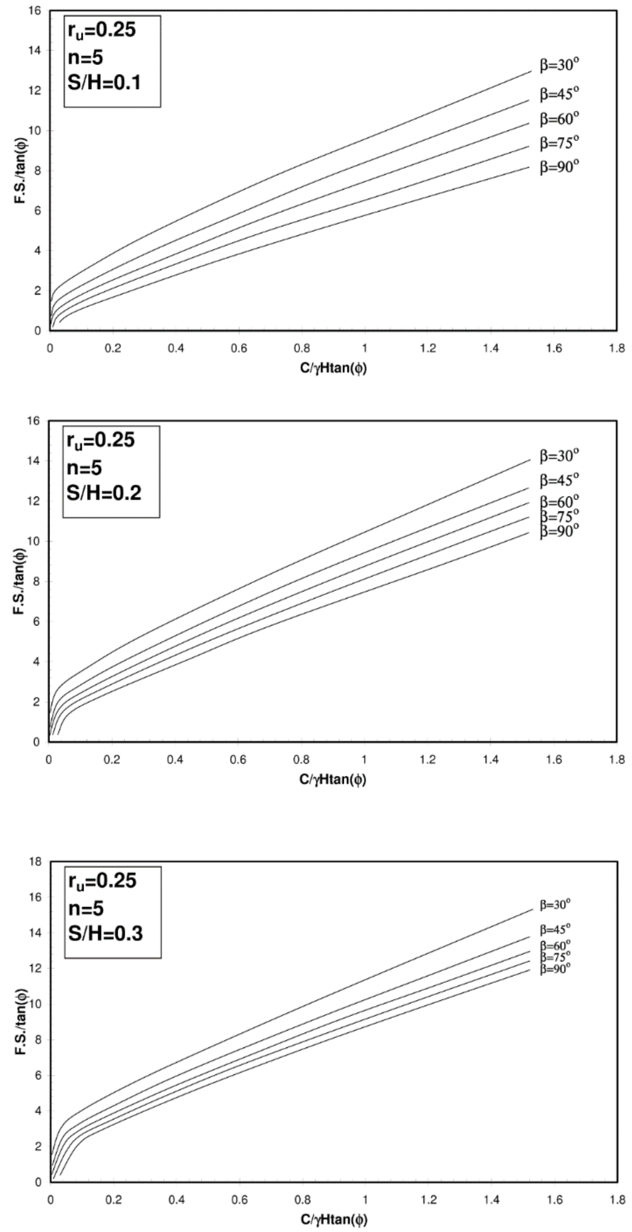


Figure 15. Stability Charts for r_u=0.25; n=5; S/H=0.1,0.2,0.3

The above presented slope stability charts could be utilized to preliminary optimize designs of fill or cut of earth benched slopes under dry or drained conditions. Results of the analyses in this paper show the importance of benching in increasing slope stability, which is quite equivalent to slope flattening. Slope benching contributes to slope stability increase and expected to mitigate surficial erosion, improve constructability and lead to reducing cost as a result. Slope benching helps with rock fall hazard diminution in mountain roads as well.

The slope stability charts (i.e., eighteen charts) of typical benched slopes presented herein are limited to bench numbers of n = 3 and 5 due to limited space in the paper.

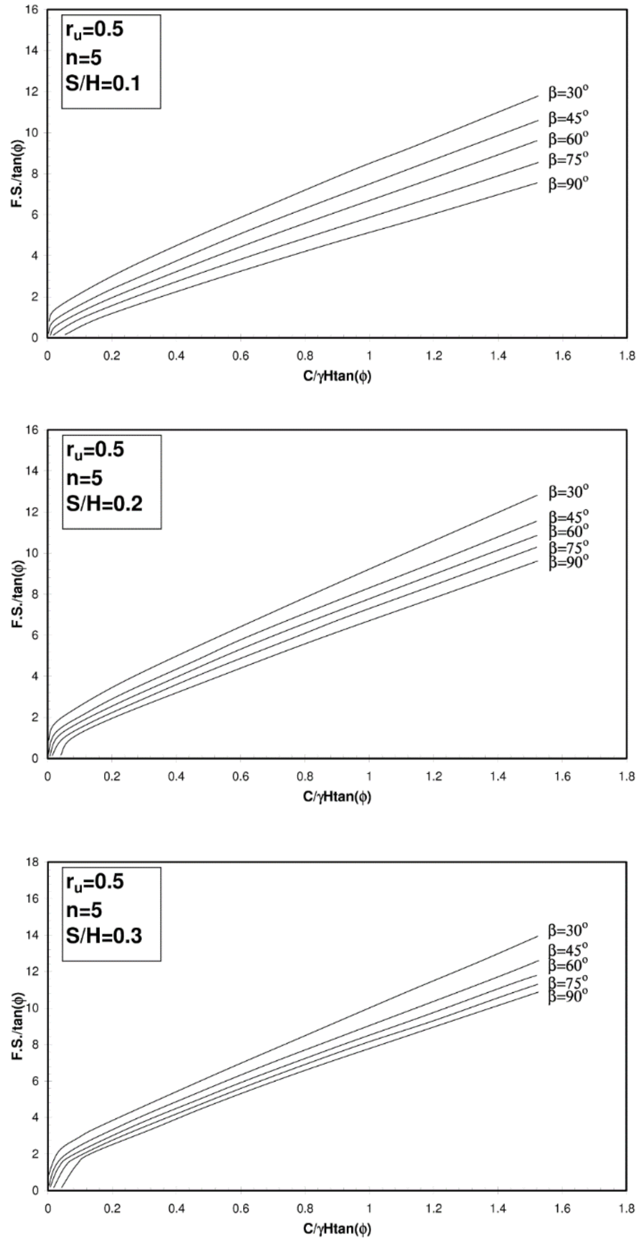


Figure 16. Stability Charts for r_u=0.5; n=5; S/H=0.1,0.2,0.3

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