A Study on the Influence of Vegetation Growth on Slope Stability

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Abstract: Vegetation plays a major role in terms of slope stability. Roots of grass and trees can increase the strength properties of soil which improves the stability of slope. A natural slope consists of grass and infinite number of trees inclined in different directions along with inclined roots. The aim of the paper is to study the effects of vegetation growth on slope stability for different root reinforced soil depth by varying tree inclination (along with roots), root spread and tree spacing for different slope geometry. The study involves determination of safety factor (FOS) of natural slope existing with and without vegetation growth (such as only grass, grass and trees). GeoStudio Slope/w software with limit equilibrium method was used for stability analysis of different slope inclinations. A tree was modelled as a point load and its roots were represented as reinforced soil properties with anchors and only as root reinforced soil. When compared to the bare slope, it was observed that there was an increase in FOS of slope on both the models of vegetation. Variations in FOS by varying root reinforced soil depth, tree inclinations and spacings were reported for different slope geometry and compared. Considering all these parameters, an empirical correlation for computation of vegetation influenced FOS has been developed. This study provides a mechanical accountability of vegetation cover on the stability of slopes.

Keywords: Slope stability, GeoStudio software, Tree spacing and inclinations, Root spread, Slope inclinations, Anchor reinforcement

1. Introduction
Slope stability analysis is an important step in defining slope failure. It is influenced by many factors and vegetation growth is one among them. Vegetation growth affects the stability of the slope hydraulically and mechanically. Roots act as anchor reinforcement and also it provides additional cohesion which enhances the stability of the slope by improving the soil strength.

Natural slopes consist a wide variety of vegetation with different tree inclination, at different spacing, root spread and they will not have a uniform posture of tree and the root. Root reinforces the soil at different depths within the slope and it also plays an important role in strengthening the soil as it has an ability to hold the soil particles tightly. Tree inclination contributes for resisting the forces but it can also affect the slope in a negative way by acting as a driving force.
2. Literature review
The elimination of soil moisture by evapo-transpiration through vegetation implies hydrological effects that can result in an improvement in soil suction or a decrease in pore water pressure, thus an improvement in shear strength. In addition to enhancing the strength of the soil by decreasing its water content, the weight of the soil mass is decreased by plant evaporation. In this study they analysed factor of safety for three tree positions on slope such as at toe, middle and crest of the slope. The presence of tree on slope acts as an additional shear resistance which is greater than shear stress developed in soil that leads to the movement of the slope and when factor of safety was analysed using SLIP4EX for three tree positions on slope such as at toe, middle and crest of the slope, it was observed that stability of slope under the influence of tree increases more when tree is located at the toe of the slope when compared to other locations [1].

Slope stability was found by varying root zone depth 1m, 1.5m, and 2m by considering the vegetation on entire ground, on top of the slope and only on slope and FOS is more in case of vegetation present on entire ground and then followed by vegetation only on slope. It was noted that due to the increase in the penetration of the plant root or increase in the depth of plant root results in the increase of factor of safety. When the trees or forests are cut down then the soil moisture present in that area is more when compared to uncut which results in the failure of slope [2].

Slopes are found to be stable due to the presence of vegetation which increases the shear strength of the soil in terms of cohesion and friction angle [3]. There is more resistance for soils with root compared to soils without roots and soil strength gets increased due to the presence of roots that undergo fewer deformations when subjected to vertical stresses [5]. Analysis for different root architectures like without vegetation, with semi-spherical vegetation, uniform vegetation and cylindrical vegetation was done and it was observed that rooted soil showed much improved values of factor of safety and shear strength than the soil without root [6]. Roots of the vegetation can reach up to the depths of 3m [4, 7, 9]. The zone of Soil with roots is represented in terms of root reinforced soil properties with anchors [8, 10] and only as root reinforced soil [8].

3. Methodology
GeoStudio 2021 slope/w software was used for numerical analysis of slopes with and without vegetation cases by adopting limit equilibrium method. Tree roots were considered as anchors and reinforced soil with additional shear strength properties in terms of cohesion and internal friction angle. The self-weight of the tree was considered as a point load.

For different slope inclinations by varying root reinforced soil depth, tree inclination, tree spacing and root spread angle, slope stability analysis was performed. All these aforementioned parameters were varied and their influence on the stability of the slope was observed. Around 420 slope models were analyzed and an equation was generated for given soil properties. All the parameters considered in the analysis are illustrated in figure 1.

3.1 Input Data
Slopes of different slope inclinations such as 25°, 30°, 35°, 40° were considered. The height of the slope is 10m. Soil properties of two layers such as, the lower layer with an unreinforced soil and the upper layer with root reinforced soil were given in Table 1. The self-weight of the tree and its root (anchor) parameters were given in the Table 2.
Figure 1. Parameters considered for analysis

Table 1. Properties of soil layer

| Properties of soil          | Lower layer [11] | Upper layer [8] |
|----------------------------|------------------|-----------------|
| Unit weight, $\gamma$ (kN/m$^3$) | 20               | 22              |
| Cohesion, $C$ (kN/m$^2$)   | 0                | 25              |
| Angle of internal friction, $\Theta$ (°) | 25               | 33.75           |

Table 2. Tree root reinforcement parameters

| Parameter                  | Values                          |
|----------------------------|---------------------------------|
| Tree load                  | 15 kN [8]                       |
| Tree inclination           | $50^\circ, 60^\circ, 70^\circ, 80^\circ, 90^\circ$ |
| Tree spacing               | 2m, 3m, 4m                      |
| Root tension               | 1.5 kN [10]                     |
| Root Length                | 0.5m, 1m, 1.5m, 2m, 2.5, 3m     |
| Root spread angle          | $30^\circ, 45^\circ, 60^\circ$  |

4. Analyses

A bare slope was initially modeled as represented in figure 2 for different slope inclinations such as $25^\circ, 30^\circ, 35^\circ$, and $40^\circ$ with the properties given in Table 1 and FOS was calculated by limit equilibrium method using GeoStudio slope/w software.

FOS was calculated for all the above slope inclinations with two layers as given in Table 1 by varying the depth of the upper layer (i.e. root reinforced soil depth) such as for the depths 0.5m, 1m, 1.5m, 2m, 2.5m and 3 m as shown in figure 3.
In this work, vegetation is represented in two ways, such as in terms of root reinforced soil considering cohesion, angle of internal friction along with anchor and only as root reinforced soil. A two layered slope with trees as point loads inclined with an angle of 50°, 60°, 70°, 80°, 90° in an anti-clockwise direction with respect to the ground, spaced at 2m, 3m, 4m and roots as anchors with different root spread angle of 30°, 45°, 60° were modeled. FOS was calculated for various combinations of those parameters. FOS was found varying in each case. An example of two layered slope model with tree load, tree spacing, tree inclination, root anchors and root spread angle is shown in figure 4. Around 420 models were analyzed in this study.

Initially a 25° slope was modeled and different cases or combinations of every root zone depths, tree inclinations, tree spacing and root spread angle were modelled and then for all those cases FOS was calculated. Similarly for different slope inclinations, FOS was calculated and compared. All the results are graphically represented as shown in figure 10, 11, 12 and 13.
Figure 4. A 30° slope with 2m root zone, root anchors, root spread of 60° and 60° inclined tree loads spaced at a distance of 2m before analysis.

5. Results and Discussion

It was observed that FOS shows much improvement in all cases where the vegetation is present when compared to bare slopes. An example of final output resemblance of FOS after analysis of different cases such as bare slope, slope with only root reinforced soil zone and reinforced soil zone along with root anchors which displays FOS values of 0.809, 1.354 and 1.538 respectively is represented as shown in figure 5, 6 and 7.

When compared between different slope inclinations, 25° and 30° slopes show higher FOS than 35° and 40° slope due to its steepness nature as shown in figure 8. It was observed that as the inclination of the tree decreases, FOS increases as it contributes to resisting forces and as the spacing between tree decreases, FOS increases because the interaction between the soil and the roots will be more.

Whereas the change in root spread angle in terms of anchorage has not shown any variation in FOS, hence the obtained curve for all the angles in graph are same as represented in figure 9. But in reality, the extent of root spread creates reinforced soil zone. Here, in this study, it has been considered that reinforced soil is found to exist all along the length of the slope. The root reinforced soil only to different geometry of root zones has confined [6].

Figure 5. Bare slope of 30° inclined slope after analysis
Figure 6. A 30° slope with 2m root zone after analysis.

Figure 7. A 30° slope with 2m root zone, root anchors, root spread of 60° and 60° inclined tree loads spaced at a distance of 2m after analysis.

Figure 8. FOS for different slope inclinations at various root zone depths.
Figure 9. FOS for different root spread angle at varied root zone depths

(a) For 1 m root zone depth

(b) For 1.5 m root zone

(c) For 2 m root zone

(d) For 2.5 m root zone
Figure 10. FOS for different tree inclinations spaced at 2m, 3m, 4m for root zone depths of 1m, 1.5m, 2m, 2.5m, 3m for a 25° slope model.
Figure 11. FOS for different tree inclinations spaced at 2m, 3m, 4m for root zone depths of 1m, 1.5m, 2m, 2.5m, 3m for a 30° slope model.
Figure 12. FOS for different tree inclinations spaced at 2m, 3m, 4m for root zone depths of 1m, 1.5m, 2m, 2.5m, 3m for a 35° slope model
Figure 13. FOS for different tree inclinations spaced at 2m, 3m, 4m for root zone depths of 1m, 1.5m, 2m, 2.5m, 3m for a 40° slope model.

The maximum FOS observed was 1.976 in case of 25° slope with 3m root zone depth along with anchors and tree inclination of 50° spaced at 2m distance. The minimum FOS observed was 0.857 in case of 40° slope with only 0.5m root zone depth.

An equation for FOS was generated using multiple regression analysis for given C, Ø parameters by analyzing all the models with a variation of slope inclination(i), root zone depth(ZR), Anchor length(AR), tree load(TL), tree inclination(Ti), tree spacing(ST) as represented below.

\[
\text{FOS} = (-0.0343) i + (0.1866) Z_R + (-0.0210) A_R + (0.0288) T_L + (-0.0031) T_i + (-0.0279) S_T \quad \ldots \quad (1)
\]

\[ R^2 = 0.981 \text{ (or 98.1%)}, \text{ Standard error} = 0.03 \]

R² and standard error were obtained through regression analysis by incorporating various aspects of vegetations and slope geometry considered in the 420 models analysed in the present study. R² represents the accuracy of FOS obtained from the (1) by comparing the FOS obtained from numerical analysis. And the standard error represents the variation between FOS values obtained through numerical analysis and eqn. (1).

FOS obtained for 420 models with varying vegetation and geometry parameters were tabulated and the multiple linear regression analysis has been performed. The mathematical equation was obtained. The obtained equation may be used to determine FOS, if prevailing vegetation conditions are known.

6. Conclusions
The study has involved in quantifying the effects of vegetation by considering various parameters like slope inclination, root zone depth, root spread angle, Anchor length, tree load, tree inclination and tree spacing. The effects are as follows:

- As the slope inclination decreases, FOS increases. This is because as the steepness of the slope decreases, the slope gets more stable.
- Maximum FOS was found at a greater root zone depth and anchor length as it is found that at deeper root zone, higher shear strength to soil is induced.
- As tree inclination decreases towards the slope with respect to the ground it contributes to resisting forces, hence FOS increases.
Slope becomes more stable as the spacing between the trees are less as the number of anchorages along the slope increases.

Change in Root spread angle has shown no influence on slope stability in all different slope models. But in the actual field condition Root spread angle decides the horizontal spread of reinforcement.

Even though there is an increment in FOS due to reinforcement, the tension offered by the root anchors has minor effect, whereas the contribution of reinforced soil is more when compared.

Therefore, all the cases with the presence of vegetation showed good increment FOS when compared to slopes without vegetation cases.

7. Future scope
Additional effects of construction of roadway in between the natural slopes, trees uprooting on slope stability can be analyzed. By varying the cohesion and internal friction angle along with other parameters, an equation including the effect of shear parameters can also be obtained.

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