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Modelling the Effects of Vegetation on Stability of Slopes

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Summary: It is well understood that vegetation influences slope stability in two ways: through hydrological effects and mechanical effects. Hydrological effects involve the removal of soil water by evapotranspiration through vegetation, which lead to an increase in soil suction or a reduction in pore-water pressure, hence, an increase in the soil shear strength. The shear strength of the soil is also increased through the mechanical effects of the plant root matrix system. The density of the roots within the soil mass and the root tensile strength contribute to the ability of the soils to resist shear stress. The effects of soil suction and root reinforcement has been quantified as an increase in apparent soil cohesion. This paper investigates the effects of vegetation on the stability of slopes using the finite element method. Two key vegetation-dependent parameters have been incorporated in the finite element slope stability analysis, namely, apparent root cohesion (c_R) and depth of root zone (h_R). Parametric studies were performed to assess the sensitivity of the stability of a slope to the variation in the key vegetation and soil parameters. Results show that vegetation plays an important role in stabilising shallow-seated failure of slopes, and significantly affects stability.

INTRODUCTION

Slope instability is one of the major problems in geotechnical engineering where disasters, like loss of life and property, do occur. The majority of these slope failures are of vegetated or forested natural slopes. A natural slope is different from an embankment or a man-made slope in that the effects of vegetation and soil variability play an important role in their stability.

The effects of vegetation on the stability of slopes are well recognised. Vegetation affects slope stability through modification of the soil water regime, which in turn causes a variation in soil suction or pore pressure. Vegetation can also enhance the stability of a slope by root reinforcement. Wu *et al.* (1979) investigated the stability of slopes before and after removal of forest cover and concluded that the shear strength contributed by tree roots is important to the stability of slopes. The study indicated that vegetation could contribute shear strength to the slopes through root reinforcement. Wu *et al.* (1979) showed that slope failure would have occurred if the effects of vegetation were not taken into account in slope stability analyses.

Natural slopes are subjected to inherent variability both in the soil and the vegetation. It is unlikely that the underlying soil profiles of natural slopes are completely uniform or homogenous. Even within a homogenous soil layer, soil properties tend to vary from point to point (Vanmarcke, 1977). The growth of vegetation is sensitive to environmental conditions and changes. Typically different types of vegetation grow on a natural slope, such as a mixture of grasses, herbs, scrubs and trees. Their differences in size and physical properties will affect the slope stability in different ways. Therefore, the use of a single input value for the vegetation-dependent parameters in analyses is best viewed as a first approximation of the field conditions.

This paper investigates the effects of vegetation on the stability of slopes using the finite element method. The finite element method allows the extent of the vegetation effects to be defined by the user due to the nature of the method where slope geometry is dicretised into small elements. To limit the scope of this paper, only the effects of root reinforcement are incorporated in the slope stability analysis. The variability in the vegetation and soil properties are not considered in this paper. A 2:1 homogenous slope (angle of inclination 26.57°) is used to investigate the effects of vegetation on slope stability. Two key vegetation-dependent parameters are incorporated in the finite element slope stability analysis, namely, apparent root cohesion (c_R) and depth of root zone (h_R). Parametric studies were performed to assess the sensitivity of the stability of the slope to the variation in the key vegetation and soil parameters.

PREVIOUS ANALYSES OF THE EFFECTS OF VEGETATION ON SLOPE STABILITY

Model of Root Reinforcement

For the past three decades, research has focussed on utilising plant root reinforcement to stabilise slopes. The ability of plant roots to strengthen a soil mass is well known. The inclusion of plant roots with high tensile strength increases the confining stress in the soil mass by its closely spaced root matrix system. The soil mass is bound together by the plant roots and the shear strength is increased by this effect. The contribution of root reinforcement to shear strength is considered to have the characteristics of cohesion (Wu *et al.*, 1979). Wu *et al.* (1979) proposed a simplified perpendicular root model to quantify the increased shear strength of soil due to root reinforcement. The increase in shear strength of the soil, S_r, was expressed by the following relationship:

$$S_r = t_R (\cos \theta \tan \phi' + \sin \theta) \quad (1)$$

where S_r = shear strength increase from root reinforcement, t_R = average tensile strength of root per unit area of soil, θ = angle of shear rotation, and ϕ' = friction angle.

Since the mechanical effect of plant roots is to increase the cohesiveness of the soil mass, S_r can be considered as equivalent to an apparent cohesion of the soil, known as *apparent root cohesion* (c_R). Typical values of apparent root cohesion (c_R) range from 1kPa to 17.5kPa (Coppin and Richards, 1990). These values were obtained from the studies of several investigators using different techniques including back analysis, direct shear tests, root density information combined with vertical root model equations, and back analysis combined with root density information. The values of apparent root cohesion (c_R) are dependent on the type of vegetation and in-situ soil conditions.

Previous Slope Stability Analyses

Wu *et al.* (1979) incorporated the effects of vegetation in slope stability analysis by using conventional limit equilibrium method. In limit equilibrium methods, the shear strength of the soil along a potential slip surface is assumed to be fully mobilised at the point of failure. The Mohr-Coulomb equation is used to describe the shear strength of the soil:

$$\tau = c' + (\sigma - u) \tan \phi' \quad (2)$$

By incorporating the effect of root reinforcement, Equation (2) becomes:

$$\tau = (c' + c_R) + (\sigma - u) \tan \phi' \quad (3)$$

Wu *et al.* (1979) incorporated the apparent root cohesion (c_R) in their infinite slope analysis and found an increase in the factor of safety (FOS) for some slopes. The results indicated that tree roots improved the stability of forested slopes. There have been no published studies using numerical formulations to analyse root reinforcement effects. The present study employs numerical analysis which allows limiting the extent of the root zone. By assigning different values of apparent root cohesion (c_R) to the root zone, its significance on the FOS is evaluated.

DESCRIPTION OF NUMERICAL STUDY USED TO MODEL VEGETATION EFFECTS

In the present study, the effect of vegetation on the stability of slopes has been investigated using the finite element method. The discretisation process of the finite element method breaks down the slope geometry into small elements and this facilitates the incorporation of the effects of vegetation in the slope stability analysis. The effects of vegetation are taken into account in the slope stability analysis by modifying the soil properties of the individual soil element that is affected by vegetation. For example, the soil elements in the top layer of the slope can have a higher cohesion value due to the additional apparent cohesion from root reinforcement. Variation of soil suction caused by vegetation can also be incorporated in the finite element analysis. The flexibility in locating the vegetation-affected elements means that the variable and random nature of vegetation can be modelled effectively. In this paper, the work is limited to the effects of root reinforcement on the stability of slopes.

The Finite Element Model

The finite element model in the present study assumes 2-dimensional plane strain conditions. The program used in this study was developed by Smith and Griffiths (1998) and it uses eight-noded quadrilateral elements. An elasto-plastic model with Mohr-Coulomb failure criterion is assumed. This program has been used to analyse several slope stability problems including the influence of layering and free surface on slope and dam stability (Griffiths and Lane, 1999). The program computes the factor of safety (FOS) of the slope by using the non-convergence solution, coupled with a sudden increase in nodal displacements as an indication of failure conditions (Griffiths and Lane, 1999).

In this study, a 2:1 homogenous slope (26.57°) with a height of 10 metres is used to investigate the effects of vegetation on the stability of a slope, as shown in Figure 1. The soil properties are as follows:

$$\phi' = 25°$$
$$c' = 0$$
$$\gamma = 20 \text{ kN/m}^3$$

Two additional vegetation-dependent parameters used in the slope stability analysis are apparent root cohesion (c_R) and depth of root zone (h_R). Apparent root cohesion (c_R) is the apparent soil cohesion caused by the plant root matrix system. The depth of the root zone (h_R) is defined as the effective distance beyond which plant roots cause little or no effects on the soil shear strength. Two scenarios are considered: (1) vegetation confined to the slope surface only; and (2) vegetation extending over the entire ground surface. Parametric studies are performed to assess the sensitivity of the stability of the slope to the variation in key vegetation-dependent parameters.

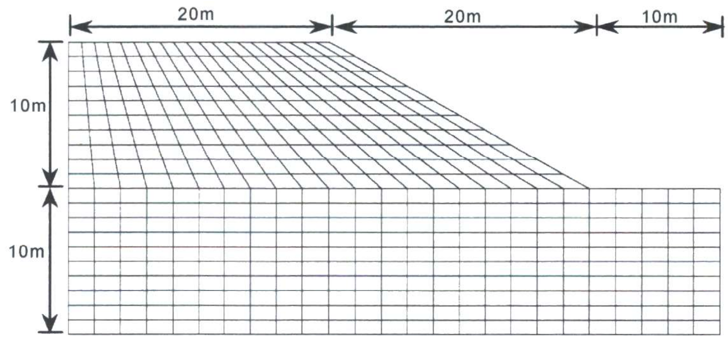

Figure 1. Mesh for a 2:1 Homogenous Slope with a Slope Angle of 26.57°, $\phi' = 25°$, $c' = 0$.

RESULTS OF ANALYSES

Slope without Vegetation Effects ($c' = 0$, $c_R = 0$)

The stability of the 2:1 homogenous slope without vegetation was analysed using both the finite element method and the limit equilibrium method. The limit equilibrium method was performed using the GGU-Stability program (Buß, 1999) where Bishop's simplified method of slices was adopted. The results of the analyses are summarised in Table 1.

Table 1. Factor of Safety for the Slope Using Different Methods.

METHOD	FOS
Finite Element Method	0.95
Limit Equilibrium Method	0.93

The results in Table 1 show that both methods give comparable results, although the limit equilibrium method gives a slightly lower value compared to the finite element method. Figure 2 shows the deformed finite element mesh of the slope at failure, and the corresponding FOS = 0.95. It can be observed that the failure mechanism is a shallow planar failure. The failure occurs within the first two layers of the elements, extending to 2 metres below the slope surface.

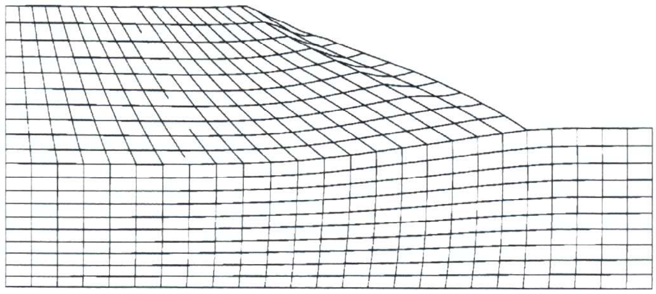

Figure 2. Deformed Mesh at Failure for the Slope with $c' = 0$.

Slope with Vegetation Effects ($c' = 0$, $c_R = 5$ kPa, $h_R = 1$ m)

Case 1 – Vegetation Confined to the Slope Surface Only

The first case involves a scenario where vegetation grows on the slope surface only. The horizontal ground surfaces, on the slope itself as well as beyond the slope toe, are not covered by vegetation. The effect of root reinforcement is considered by using apparent root cohesion (c_R) of 5 kPa. The depth of root zone (h_R) is considered to be 1 metre. Accordingly, the zone modelled with the additional root strength is confined to the first layer of the finite elements beneath the slope surface. Thus, the first layer of elements in the finite element model, shown as shaded in Figure 3, has a higher value of soil cohesion compared to all other elements in the finite element mesh.

The slope stability analysis gave a result of FOS = 0.97. The deformed mesh of the slope at failure is shown in Figure 3. Since the slope is protected by vegetation on the slope surface only, failure was, in this case, initiated from the slope toe (element T). A failure slip surface then developed along the soil layer beneath the root zone, as this soil layer is the top of the weak zone in the slope after introducing a root zone. Although the increment in the FOS is small, it can be noted from Figure 3 that the critical slip surface has been shifted deeper below the ground surface, being located between the second and third layers of the finite elements. The shallow planar failure at the slope surface is no longer critical, because of the present of the root zone.

When the slope toe element (element T in Figure 3) is treated as a vegetated soil element (assigned higher apparent cohesion), the FOS for the slope increases to 1.02. This shows that toe failure is the critical failure mechanism for the case where vegetation is confined to the slope surface only. The increase in the FOS is not significant if the slope toe is not vegetated. Therefore, the extent of the root zone to the slope toe region is an important factor to be considered when vegetation is used to improve the stability of a slope.

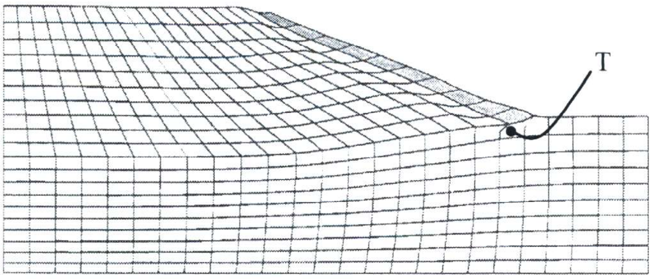

Figure 3. Deformed Mesh at Failure for the Slope with Vegetation on Slope Surface Only ($c' = 0$, $c_R = 5$ kPa, $h_R = 1$ m).

Case 2 – Vegetation Extending Over the Entire Ground Surface

A more common scenario in natural slopes is the case where vegetation grows everywhere on the ground surface, which extends from the upper slope region to the slope toe. Similarly, an apparent root cohesion of 5 kPa and depth of root zone of 1 metre were adopted. In this case, the root reinforcement effect extends everywhere on the ground surface in the finite element model, as shown in Figure 4.

The finite element analysis yielded a FOS = 1.03, showing a significant increase due to the presence of the root zone located everywhere on the ground surface. The slope that was initially unsafe (FOS = 0.95) is now marginally safe (FOS > 1) due to the root reinforcement effects. The deformed mesh of the slope is shown in Figure 4. It is noted that the critical slip surface is no longer planar but is circular.

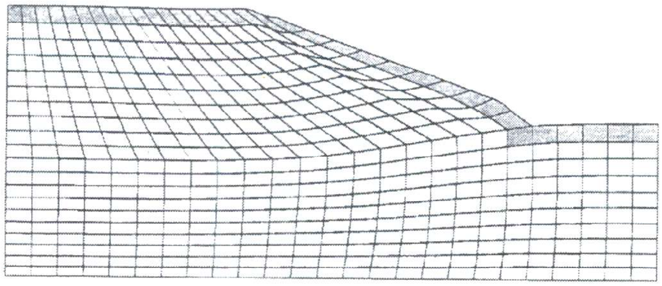

Figure 4. Deformed Mesh for the Slope with Vegetation Extending Over the Entire Ground Surface ($c' = 0$, $c_R = 5$ kPa, $h_R = 1$ m).

The above examples have shown that root reinforcement can improve the stability of a slope. By incorporating the apparent root cohesion in the root zone of the slope, the FOS of the slope is increased. The contribution of root reinforcement to the stability of slope is significant. Referring to the 2:1 homogenous slope in the above examples, this slope would be unstable if the effect of vegetation is not taken into account. In reality, there are many slopes that would fail, based on the stability analysis using the field or laboratory soil data, but remain intact for a long period of time. A case in point is the Thredbo landslide (Hand, 2000). The presence of vegetation on such slopes is clearly one of the major contributions to the stability of these slopes.

PARAMETRIC STUDIES

Parametric studies were performed for a range of the vegetation and soil parameters. The apparent root cohesion (c_R) was varied over the following range:

$$0 \leq c_R \leq 20 \text{ kPa} \quad (4)$$

Three values of depth of root zone (h_R) were used, namely:

$$h_R \in \{1 \text{ m}, 2 \text{ m}, 3 \text{ m}\} \quad (5)$$

For the soil properties, only the effective cohesion (c') was varied. The values of effective cohesion (c') considered were as follows:

$$c' \in \{1 \text{ kPa}, 2 \text{ kPa}, 3 \text{ kPa}, 4 \text{ kPa}, 5 \text{ kPa}\} \quad (6)$$

The results of the parametric studies are summarised in Figure 5 to 7.

Figure 5 shows the variation of the values of FOS with the apparent root cohesion (c_R) where $c' = 0$ and vegetation is confined to the slope surface only. Two sets of results are presented in this figure. The broken lines represent the results for the case where vegetation is confined to the slope surface only, without extending to the slope toe. The solid lines are the results for the case where the slope toe element (element T in Figure 3) is assumed to be affected by vegetation.

Generally, the values of FOS increase when apparent root cohesion (c_R) increases. For the case where the slope toe is not protected by vegetation, the FOS increases slightly initially, but drops to a lower value after reaching a maximum value of FOS. The FOS remains constant regardless of any increase in the apparent root cohesion. For a cohesionless soil slope ($c' = 0$), the failure mechanism is a shallow planar failure. This failure mechanism is prevented when plant roots are present. As the apparent root cohesion increases, the critical slip surface shifts deeper below the ground surface. When the critical slip surface is beyond the extent of the root zone, any increases in apparent root cohesion do not lead to an increase in FOS for the slope. Since the slope toe is not protected by vegetation, this region is the weak zone, and as the apparent root cohesion in the root zone increases, failure is initiated from this region. This eventually triggers failure due to a different mechanism – toe failure. When the slope toe is protected by vegetation, the FOS increases as the apparent root cohesion increases. Therefore, the slope toe appears to be the most critical region where vegetation needs to be considered in slope stabilisation. Thus, in order to ensure improved stability of a slope using vegetation, the root zone needs to extend beyond the toe region.

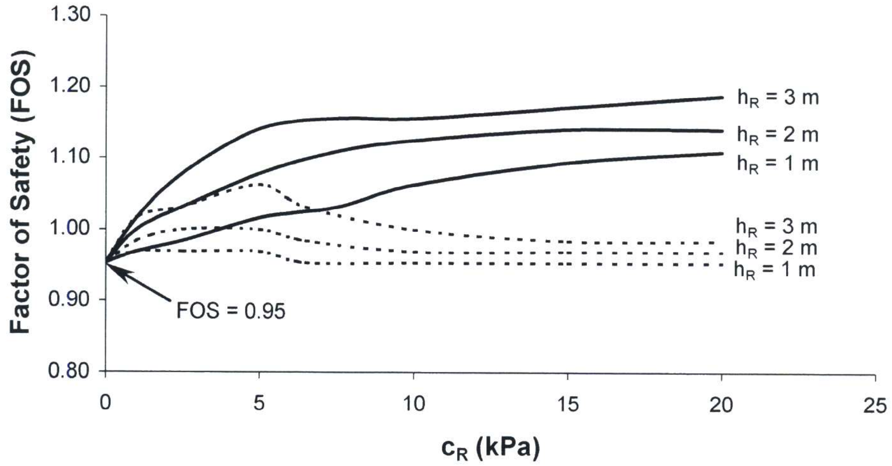

Figure 5. Variation of FOS for the Case where Vegetation is Confined to the Slope Surface Only ($c' = 0$).

Figure 6 shows the variation of the values of FOS with the root cohesion (c_R) where $c' = 0$ and vegetation extends entirely over the ground surface, including the upper slope, slope surface and slope toe. The FOS increases as the apparent root cohesion (c_R) increases. It is noted that, when the entire slope is protected by vegetation, the effects on FOS are significant. For example, when $h_R = 1$ m the FOS is increased by 26% for $c_R = 20$ kPa. The increase is even more significant with a deeper root zone (higher h_R), as shown in Figure 6.

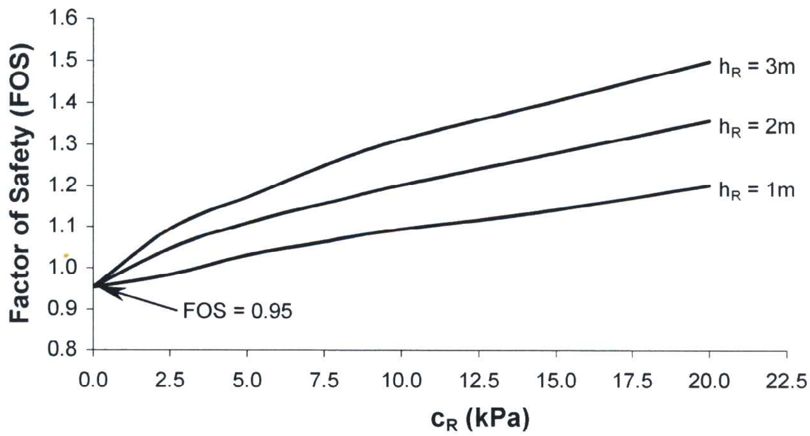

Figure 6. Variation of FOS for the Case with Vegetation Extending Over the Entire Ground Surface ($c' = 0$).

Figure 7 shows the variation of the FOS with the dimensionless parameter c_R/c' for the case where the effective cohesion of the soil $c' \in \{1 \text{ kPa}, 2 \text{ kPa}, 3 \text{ kPa}, 4 \text{ kPa}, 5 \text{ kPa}\}$. The analyses were performed for the case where vegetation extends everywhere on the ground surface and $h_R = 1$m. The analysis was terminated at $c_R = 20$ kPa for each value of c'. It is worthwhile to note that the increase in the FOS is more significant for a slope with a low effective cohesion ($c' = 1$ kPa) compared with a slope with a high effective cohesion ($c' = 5$ kPa). Examination of the deformed meshes showed that, in the case of slopes with higher values of effective cohesion

(c'), failure occurred along a deep-seated rotational slip surface. This implies that vegetation has less of an effect on deep-seated failures when the depth of root zone (h_R) is shallow.

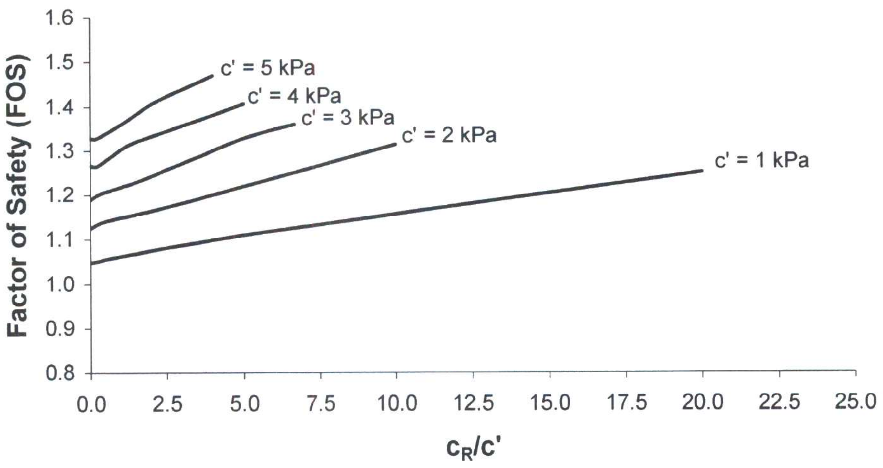

Figure 7. Variation of FOS for the Case with Vegetation Extending Over the Entire Ground Surface ($c' > 0$, $h_R = 1$ m).

FUTURE WORK

By incorporating the effects of root reinforcement in slope stability analysis, significant influence on the stability of slopes has been observed. To model a natural slope more accurately, the influence of soil suction and soil variability should be taken into account. This work will be carried out in this ongoing research project, in particular, to incorporate variability of the vegetation and soil properties within the finite element framework.

SUMMARY AND CONCLUSIONS

Vegetation plays an important role in the stability of slopes. Root reinforcement has been considered as an increase in apparent soil cohesion. The apparent root cohesion (c_R) has been incorporated in the slope stability analysis using the finite element method. The extent of the vegetation effects has been characterised by the depth of root zone (h_R). The stability of a slope is sensitive to both the apparent root cohesion (c_R) and depth of root zone (h_R). The stability of slopes is improved with an increase in the values of c_R and h_R. In addition, results showed that the improvement in FOS for a slope with vegetation cover over the entire ground surface is higher compared with vegetation cover on the slope surface alone. The study has also shown that the effects of vegetation are more significant in slopes with low values of effective cohesion where shallow planar failures are likely to occur. Correspondingly, vegetation has less of an effect on deep-seated failure.

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