Finite element analysis of the stability of artificial slopes reinforced by roots

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Abstract

The paper deals with the assessment of vegetation contribution to slope stability, with particular emphasis on the mechanical effects provided by the root system. As it is well known, the presence of roots within the soil increases, with respect to the case of soil without vegetation, the material effective cohesion with no significant change in its friction angle. Such mechanical effect can be introduced in the Mohr–Coulomb failure law through an “apparent cohesion” term, which adds to the soil effective cohesion.

The contribution of root reinforcement to the soil shear strength has been investigated in slope stability finite element analysis, modifying the soil properties of individual slope elements including vegetation. This approach allowed quantifying the effect of the mechanical root reinforcement on the slope factor of safety and assessing the sensitivity of slope stability to the variation of apparent cohesion and root zone depth assumed in the numerical simulations.

Keywords: slope stability, root reinforcement, apparent cohesion, finite element method.

1 Introduction

The presence of a root system into the soil plays an important role on the stability of natural and artificial slopes, which are covered with vegetation. It affects the stability of a slope essentially through hydrological and mechanical effects. Regarding the latter aspect, the density of roots within the soil mass and their tensile strength contribute to improve the capacity of the soil to resist shear
loads (Figure 1). The maximum tensile strength or pull-out resistance of the roots, together with an assessment of the root size and distribution (Root Area Ratio), can be used to evaluate the appropriate root reinforcement values to be used in the stability analysis of a slope. Many authors have provided values of root systems depth and tensile strength of different species of herbaceous and shrub type. In particular, the experimental data obtained from direct shear tests performed on blocks of soil containing roots have shown that the presence of vegetation produces an increase in soil cohesion, leaving its friction angle unchanged (Wu et al. [1], Faisal and Normaniza [2]).

\[ \tau = (c' + c_R) + \sigma' \tan \phi' = (c' + c_R) + (\sigma - u) \tan \phi' \]  

(1)

where $\tau$ is the shear stress on the failure plane, $\sigma'$ represents the effective stress normal to this plane (equal to the difference between the total normal stress $\sigma$ and the pore water pressure $u$), $c'$ is the effective cohesion, $c_R$ the apparent cohesion and $\phi'$ is the effective friction angle of the soil.

The apparent cohesion $c_R$ can be expressed as (Norris and Greenwood [4]):

\[ c_R = 1.2 \, T_R \left( A_R / A \right) \]  

(2)

where $T_R$ is the mean tensile strength of the roots and $A_R/A$ is the cross-section of soil occupied by the roots (Root Area Ratio).

Wu et al. [5] have studied the stability of slopes before and after the removal of forest cover, incorporating the apparent cohesion due to roots in the limit equilibrium analysis of infinite slopes. The authors have shown how it is possible in this way to increase the safety factor of the analysed slopes, therefore concluding that the contribution to shear strength provided by the root system is crucial in studying the stability of natural slopes.

Recently, Chok et al. [6] have analysed the mechanical effect due to vegetation on the stability of ideal slopes, using a numerical code based on the finite element method (Zienkiewicz and Taylor [7]). The method, widely
employed for the numerical solution of different engineering problems, allows
the user to easily define the extent of the vegetation effects, being the slope
geometry discretised into small elements. Moreover, the approach provides
information about the overall stability of the slope as the value of the factor of
safety (FOS) on the critical slip surface can be derived through the
c’–ϕ’ reduction technique (Griffiths and Lane [8]).

The work describes the analysis of the mechanical effect of root systems on
slope stability using the finite element code PLAXIS 2D [9] and adopting an
approach similar to that proposed by Chok et al. [6].

2 Tensile and shear strength of roots

2.1 Tensile strength

According to the literature, the values of roots tensile strength generally depend
on various factors: species, dimensions, morphology and spatial directions (Figure 2).

Figure 2: Morphological differences between root systems of different
shrubby species (from Mattia et al. [10]).

Stress–strain curves obtained by traction tests have been processed to obtain
the peak tensile strength values. The laboratory data show that the tensile
strength generally decreases with root diameter, as reported in Figure 3: root
strengths are lower for large diameters and higher for small diameters (Bischetti
et al. [11], Gray and Barker [12]). Moreover, root strength depends on the
biological components of the root: smaller diameter roots have more cellulose
than larger diameter roots and therefore are characterised by higher strength
(Genet et al. [13]).

Regarding the distribution of roots in soil deposits, the observed values of
Root Area Ratio (RAR) show a very high variability with species, location and
depth. RAR is strongly influenced by genetics, local soil, climate characteristics
and forest management; in addition, randomness must be accounted for. However, RAR usually decreases with depth as a consequence of a decrease of
nutrients and aeration, and because of the presence of more compacted layers
(Bischetti et al. [11]).
2.2 Apparent cohesion

The reliable benefit of apparent cohesion is limited to shallow depths as root distribution is mainly concentrated within 1m from the ground surface (Figure 4). The use of an enhanced value of the soil cohesion is appropriate for grass and shrub areas where fine root distribution with depth is consistent and easily defined (Norris and Greenwood [4]).

Field studies of forested slopes (O’Loughlin [14]) indicate that the fine roots, 1 to 20mm in diameter, are the ones that contribute most to soil reinforcement. Grasses, legumes and small shrubs can have a significant reinforcing effect down to depths from 0.75 to 1.5m (Faisal and Normaniza [2]).

Some researchers have attempted to compute the values of apparent cohesion due to the presence of the roots in the ground by designing and developing in situ shear tests for different types of root systems (O’Loughlin and Ziemer [16], Norris and Greenwood [17], van Beek et al. [18]).
3 Vegetation effect on the stability of an ideal slope

The contribution of root reinforcement to soil shear strength has been investigated by numerical stability analyses of ideal slopes in plane strain conditions using the two-dimensional finite element code PLAXIS 2D [9]. This approach has allowed to quantify the effect of the mechanical root reinforcement on the slope factor of safety (FOS), assessing the sensitivity of slope stability to the variation of apparent cohesion ($c_R$) and root zone depth ($h_R$) assumed in the numerical simulations. In particular, a slope characterised by the absence of water has been initially considered. The presence of vegetation has been simulated by attributing to the elements of the mesh representing the layer with presence of roots a value of effective cohesion higher than the one of the surrounding soil. The weight of the plants has been neglected, as in the case of herbaceous or shrubby vegetation; in the case of trees, it should be taken into account. Subsequently, an ideal slope with a water table at ground surface has been analysed.

3.1 Case A: slope characterised by the absence of water and $c'=0\text{kPa}$

The first case studied (Case A) is relative to an ideal slope with an inclination angle $\beta$ equal to 26.5°, composed by a homogeneous material ($c'=0\text{kPa}$, $\phi'=25^\circ$ and $\gamma=20\text{kN/m}^3$) and characterised by the absence of water. The geometrical configuration of the slope and the adopted finite element mesh are shown in Figure 5.

![Figure 5: Adopted mesh for Cases A and B.](image)

At first, the stability of a homogeneous slope without vegetation ($c_R=0\text{kPa}$) has been assessed. The results of this analysis have been taken as reference for the evaluation of the mechanical effects due to the presence of vegetation on the slope. Figure 6 shows the contour lines of shear strains at failure obtained at the end of the $c'-\phi'$ reduction analysis. The obtained shear strain values relate to a condition close to collapse and, therefore, have no physical meaning. Nevertheless, they indicate the development of a planar and shallow failure mechanism inside the slope, with a maximum concentration of shear strains at its toe. The depth of the critical surface, measured at the centre of the slope, is equal to 1.4m from ground level. The slope is characterised by a FOS close to one, consistently with what has been obtained by a limit equilibrium analysis.
Figure 6: Contour lines of shear strains at failure for a slope without vegetation (Case A).

The effect of the presence of vegetation on slope stability has been initially analysed attributing a value of apparent cohesion equal to 5kPa to a layer of soil elements disposed along the slope surface for a depth $h_R=1$m.

The introduction of vegetation confined along the slope surface only results in a small increment of the safety factor. In particular, the obtained FOS is equal to 1.02, with an increase of 5.9% with respect to the case of slope without vegetation. From the contours lines of shear strains shown in Figure 7, it can be clearly observed how the presence of vegetation produces a downward shift of the critical surface, which is characterized by a depth of 2m. If the slope toe elements are also treated as vegetated soil, the increment of the slope safety factor is more significant. The FOS reaches a value of 1.05 with an increase of 9.2%, while the critical surface is characterized by a depth of 2.4m.

Figure 7: Contour lines of shear strains at failure for a slope with vegetation confined along the slope surface only (Case A).

Finally, the introduction of vegetation extending over the entire ground surface for a depth of 1m gives to the slope a FOS equal to 1.08 (an increase of
11.5% compared to the case without vegetation), producing an additional downward shift of the critical surface to a depth of 2.6m. The analysis shows how the presence of roots distributed uniformly throughout the slope have a positive effect on its stability, with a significant increment of the FOS. The effect increases as much as the root apparatus extends in depth, reaching the zones where the failure mechanism is initiated. Consequently, the critical slip surface is shifted deeper below the ground surface, becoming circular, as shown in Figure 8.

Figure 8: Contour lines of shear strains at failure for a slope with vegetation extending over the entire ground surface (Case A).

Parametric studies have been performed for a range of apparent root cohesion. Figure 9 shows the evolution of the slope FOS with the apparent root cohesion for $h_R=1m$, when $c'=0kPa$ and the vegetation is confined i) to the slope surface only, ii) slope and toe and iii) vegetation extends over the entire ground surface. The values of the critical surface depth with $c_R$ are shown with dashed line in the same figure.

Figure 9: Evolution of FOS and critical surface depth with $c_R$ for $h_R=1m$ (Case A).
Assuming a value of $h_R=2m$, the results of the FE simulations, reported in Figure 10, indicate that the values of FOS and critical surface depth are larger for the same apparent cohesion.

![Figure 10: Evolution of FOS and critical surface depth with $c_R$ for $h_R=2m$ (Case A).](image)

3.2 Case B: slope characterised by the absence of water and $c' = 5kPa$

Case B regards the same ideal slope of Case A ($\beta=26.5^\circ$, $\phi'=25^\circ$ and $\gamma=20kN/m^3$), but composed of a soil with $c'=5kPa$. In this situation, the limit equilibrium analysis provides a critical slip surface that is no longer parallel to the surface, but circular and deep, with an associated FOS equal to 1.34.

This is confirmed by the contour lines of shear strains obtained through the finite element analysis, as shown in Figure 11. The critical surface starts from the toe of the slope, deepening up to 3.6m from the ground level. In this case, the mechanical effect of vegetation on slope stability has been investigated by assigning a value of apparent cohesion of 10kPa to the soil elements affected by root reinforcement.

![Figure 11: Contour lines of shear strains at failure for a slope without vegetation (Case B).](image)
If the vegetation is only present on the slope surface for a depth $h_R=1\text{m}$, the increase in the FOS is just equal to 0.1\% with respect to the case of slope without vegetation. The depth of the critical surface does not change significantly (Figure 12). This confirms the limited effect of vegetation on slope stability when the sliding mechanism is deep and the root reinforcement is limited to the first layers below the surface.

![Figure 12: Contour lines of shear strains at failure for a slope with vegetation confined along the slope surface only (Case B).](image)

Assuming the presence of vegetation also at the toe of the slope, the FOS becomes equal to 1.37 (an increase of 2\% compared to the case without vegetation) and the failure surface reaches a depth of 3.8m.

Finally, if the vegetation covers the entire ground surface the slope safety factor reaches a value of 1.39, with an increase of 3.2\%. The depth of the corresponding failure surface (Figure 13), however, remains almost similar (3.8m) with respect to the case of vegetation covering slope surface and toe.

![Figure 13: Contour lines of shear strains at failure for a slope with vegetation extending over the entire ground surface (Case B).](image)
Figure 14 shows that, whatever value of $c_R$ is used, the FOS and the depth of the critical surface remain practically unchanged when the vegetation covers the slope surface only ($h_R=1$ m). They increase if the vegetation is introduced at the toe or is distributed over the entire ground surface. The sensitivity analysis indicates that the vegetation mechanical effects are less significant in slopes with high values of effective cohesion where deep-seated failure mechanisms are likely to occur, as the FOS increments with $c_R$ are proportionally lower than the ones obtained in the case of the same slope with $c'=0$ kPa.

![Figure 14: Evolution of FOS and critical surface depth with $c_R$ for $h_R=1$ m (Case B).](image)

The deepening of the root system to a depth of 2 m does not produce any improvement if the vegetation is confined along the slope surface only (Figure 15), unless it extends also to the toe of the slope and to the entire ground surface.

![Figure 15: Evolution of FOS and critical surface depth with $c_R$ for $h_R=2$ m (Case B).](image)
3.3 Case C: slope characterised by the existence of water and $c'=0\text{kPa}$

The introduction of a water table at the ground surface in the slope of Case A would produce a significant reduction of soil effective stress, leading to a FOS below one. The slope angle assumed in Cases A and B (26.5°) is, in fact, too high to account for the presence of a water table inside a homogeneous slope characterised by a soil friction angle of 25° and a cohesion equal to zero.

![Figure 16: Adopted mesh for Case C.](image)

The geometry of the ideal slope has been therefore changed, assuming, for the same slope height of 10m, a slope angle of 14° and a soil friction angle of 30°. The adopted finite element mesh is shown in Figure 16.

The reference case is now represented by an ideal slope composed by a homogeneous material with strength parameters $c'=0\text{kPa}$ and $\phi'=30°$, characterised by the presence of a water table at the ground surface in steady state conditions and without vegetation ($c_R=0\text{kPa}$). In such a case, the FOS of the slope is equal to 1.10 and the corresponding critical surface, which develops from the toe of the slope, is almost parallel to the ground surface, with a depth of about 1.3m (Figure 17).

![Figure 17: Contour lines of shear strains at failure for a slope without vegetation (Case C).](image)

As in the previous cases, different distributions of root reinforcement along the slope have been considered, assigning an enhanced value of cohesion ($c_R=5\text{kPa}$) to soil elements with presence of vegetation.
When the vegetation covers only the slope surface for a depth of 1m, the FOS slightly increases to 1.13. It corresponds to a failure surface 1.8m deep which remains approximately parallel to the ground surface, as shown in Figure 18. The presence of vegetation produces, therefore, an increase of FOS equal to 2.1% and a deepening of the failure mechanism that is forced to develop below the vegetated soil.

The effect of the increase of the safety factor and deepening of the critical surface is even more evident if the vegetation includes also the toe of the slope. In this case the FOS becomes 1.16, with an increase of 5.4%, while the depth of the critical mechanism appears to be equal to 2.3m.

The sliding surface deepens (2.5m) when the roots extend over the entire ground surface (Figure 19) and tends to assume a circular shape. The corresponding FOS increases of 7.5% with respect to the case of slope without vegetation, assuming a value of 1.19.
As for Case A and B, parametric studies have been performed also in Case C changing the value of the apparent root cohesion. The evolution of FOS and depth of the critical surface with apparent root cohesion (for \( h_R = 1 \text{m} \)) is shown in Figure 20 and the results are similar to those of Case A. Without vegetation the failure mechanism is shallow and planar. When the vegetation is confined along the slope surface only, the increase of \( c_R \) initially produces an increase of FOS and critical surface depth, which remain almost constant afterwards. A continuous increase of FOS can be observed if the vegetation extends over the entire ground surface. Correspondingly, the sliding surface tends to become deeper and circular.

![Figure 20: Evolution of FOS and critical surface depth with \( c_R \) for \( h_R = 1 \text{m} \) (Case C).](image)

The stabilizing effect produced by vegetation is more evident when, for the same apparent cohesion, the depth of root zone is assumed equal to \( 2 \text{m} \), as shown in Figure 21.

![Figure 21: Evolution of FOS and critical surface depth with \( c_R \) for \( h_R = 2 \text{m} \) (Case C).](image)
4 Conclusions

The work investigates the influence of vegetation on slope stability, with particular emphasis on the mechanical effects due to the presence of roots into the soil. The increase of the slope safety factor provided by root reinforcement has been evaluated using a two-dimensional finite element code enhancing the effective cohesion of individual slope elements with presence of vegetation.

When the failure mechanism inside a slope without vegetation starts from its toe and is planar and shallow, the introduction of vegetation confined along the slope surface only results in small increments of the safety factor. If the slope toe elements are treated as vegetated soil or the vegetation extends over the entire ground surface, the increment of the slope safety factor is more significant. In these cases, the effect increases as much as the root system extends in depth, reaching the zones where the failure mechanism is initiated. Consequently, the critical slip surface is shifted deeper below the ground surface, becoming circular. The sensitivity analysis indicates that the vegetation mechanical effects are less significant in slopes with high values of effective cohesion where deep-seated failure mechanisms are likely to occur. Moreover, the existence of a water table at the ground surface does not generate any considerable change in the general framework observed during finite element analyses of slopes without water.

References


