THE ROLE OF ROOT REINFORCEMENT IN SLOPE STABILITY: A REVIEW

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ABSTRACT
The role of root reinforcement in slope stability issues has been the subject of extensive research and often considerable debate within the forestry, geotechnical, pedologic, and plant biology fields. There have been many varied approaches to the quantification and modeling of root strength and architecture in order to investigate the effects of various soil parameters on root anchorage and reinforcement. A detailed review of the literature has identified a progressive change in the way in which root reinforcement has been treated, from simple field studies investigating root decay after disturbance to sophisticated numerical modeling of root reinforcement. Many of these studies view the effect of roots as a “root cohesion” factor but the authors argue that the role of root reinforcement should not be considered in isolation but as an integral “root-groundwater-soil” interaction process.

RÉSUMÉ
Le rôle de l’armature de racines dans la stabilité des pentes a été le sujet de recherches approfondies et de débats considérables dans les domaines de la foresterie, géotechnique, pédologie et de la biologie des plantes. Il y a eu plusieurs démarches pour quantifier et modéliser la résistance et l’architecture des racines et pour étudier l’effet des différents paramètres des sols sur l’ancrage et l’armature des racines. Une revue détailler de la littérature scientifique a identifiée un changement progressif dans la façon dont l’armature de racine est traité, d’une simple recherche de terrain étudiant la pourriture des racine suite a un remaniement jusqu'à une modélisation numérique sophistiquer de l’armature de racines. Plusieurs de ces études considère l’effet des racines comme un facteur de ‘cohésion de racines’ mais les auteures maintiennent que le rôle de l’armature de racines ne devrait pas êtres considéré en isolement mais comme parti intégrale d’un processus d’interactions ‘racines - eau souterraine - sol’.

1. INTRODUCTION

Quantifying the reinforcing effect of roots on soil has been the subject of extensive research but there continues to be controversy and uncertainty on how to best to represent root strength within slope models (Wu et al., 1979; Sidle and Swanston, 1981; Buchanan and Savigny, 1990). For root reinforcement to mobilize a resisting force in many studies, it is required that roots cross a possible slip surface in order to provide anchorage to the sliding mass (Ziemer, 1981a). Along with vertical anchorage, the lateral roots of many plants and trees can create a dense network that acts as a thin reinforcement zone in surficial soils or as long, fibrous binders in weak soil (Ziemer, 1981a). Abe and Ziemer (1991) note that the horizontal component of the root tensile stress directly enhances the shear stress with a vertical component contributing to the normal stress.

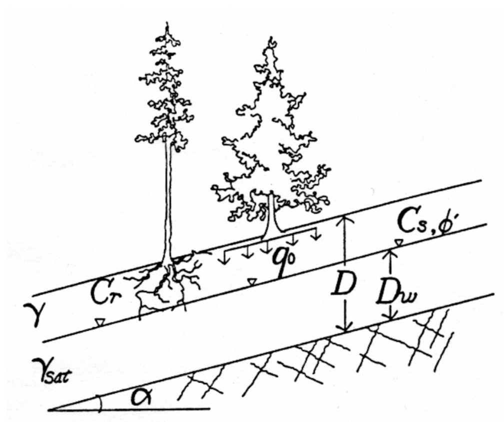
When quantifying the role of root strength in slope stability, many authors refer to a ‘root cohesion’ effect (Schmidt et al., 2001; Sakals and Sidle, 2004). Referring to this increase in shear strength within the slope mass as a cohesive force may be misleading as ‘true cohesion’ refers to the inter-particle attraction most often caused by weak electro-static forces between particles (Brady and Weil, 1999). There is also an apparent cohesion effect from matric suction within the particle matrix in unsaturated soil conditions or during periods of negative pore pressures (Fredlund, 2000, Ridley et al., 2003).

Values of ‘root cohesion’ derived experimentally or through back-calculation analyses are then input into various forms of the Effective Stress equation as a constant ‘root cohesion’ value, such as

$$\tau = c' + (\sigma - u)\tan\varphi + c_r' \qquad [1]$$

where c_r' represents apparent cohesion provided by roots. This type of analysis has also been incorporated into the infinite slope equation for forested or vegetated terrain, as shown in the infinite slope model LISA in Figure 1, developed by Hammond et al. (1992) for the United States Forest Service. Often, ‘root cohesion’ is used interchangeably with ‘root reinforcement’ but this usage is not strictly correct, as the terms each invoke a different physical process (cohesion versus friction). As well, root strength is well known to degrade within months to years of harvesting or tree death. O’Loughlin (1974) determined that small roots can lose over half their original tensile strength within 3-5 years after forest harvesting (see Figure 2).

Root reinforcement should be considered as the frictional resistance between roots, root hairs and the soil matrix. The role of groundwater in reducing the frictional resistance of soils is well understood, but it must also have an effect on the frictional resistance of a root-soil interface. The role of root reinforcement has been investigated in multiple disciplines such as geotechnical and civil engineers in their studies into biostabilization, botanists (root architecture) and forest geoscientists/engineers in their studies of how logging



$$F = \frac{Cr + Cs'\cos^2\alpha\left[qo + \gamma(D - Dw) + (\gamma sat - \gamma w)Dw\right]\tan\phi'}{\sin\alpha\cos\alpha\left[qo + \gamma(D - Dw) + \gamma sat.Dw\right]}$$

where Cs' = Soil Cohesion
q_o = Surcharge
Cr = Root Cohesion
γ, γ_w = Bulk and saturated unit weights
ϕ' = Soil friction
D_w = Height of water table above bedrock or till

Figure 1. Commonly used infinite slope model after Hammond et al (1992)

affects mass wasting. Selected research will be reviewed here.

2. ROOT DETERIORATION AND ROOT COHESION

It has been widely documented that there is an increase in landslide activity after forest harvesting operations (Bishop and Stevens, 1964; and Sakals and Sidle, 2004). There is, however, debate as to the extent to which root reinforcement plays a significant role in promoting slope stability or whether the increase in failure activity is a result of increased hydrologic response. Methods of determining root cohesion / root strength values are highly variable (Wu et al., 1979; Terwilliger and Waldron, 1991; Ekanayake and Phillips, 1999) and are used in various ways.

In their study of logged terrain in Alaska, Bishop and Stevens (1964) found that the loss of continuity in the network of tree roots in the surface soils may weaken the surface mantle. In the disturbed and discontinuous root network, the remaining thick anchor roots cannot absorb the additional shearing load resulting from the degradation of the root hairs and finer roots after harvesting and so failure rates will increase. O'Loughlin (1974) found that forests deplete soil moisture to a considerable depth and can maintain a depressed water table. Deterioration of tree roots and changes which occur within the subsurface hydrostatic status of soils are the most significant logging-related factors involved in accelerated mass wasting on recently deforested slopes. O'Loughlin also states that the mineral portions of many forest soils, although essentially cohesionless, can be considered to be cohesive due to the effects of tree-root networks.

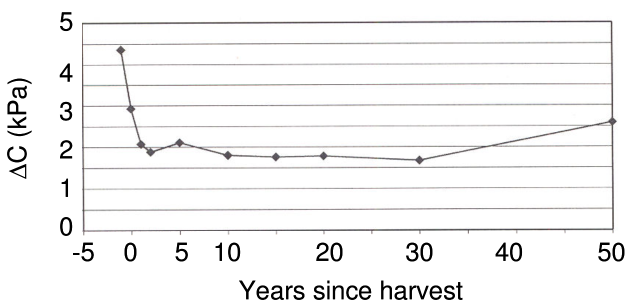


Figure 2. Loss of root cohesion with time since harvest, after Sakals and Sidle, 2004.

Wu et al. (1979) considered shallow surface soils on Prince of Wales Island, Alaska as an important source of mass wasting on steep slopes. They note that soils fail at the depth of weathered soils as a rotational slip located on upper slope and are more frequent on clearcut slopes. It was observed that lateral roots usually occurred in the B horizon and smaller roots grew downwards from these lateral roots into the unweathered C horizon. These smaller roots were observed to fail during shearing along slip surface. They analyzed forested slopes with a root cohesion factor set at 5.9 kPa, and obtained factors of safety significantly greater than 1.0, and therefore concluded that the removal of the forest cover during harvesting can significantly affect the stability of the slopes.

Sidle and Swanston (1981) performed a back analysis of a slide that occurred in an instrumented forested slope after a moderately intense storm in Alaska. Back analysis of this event determined that for the undisturbed slope to be stable an apparent cohesion of 2.0 kPa must have existed in the slope and this was most likely attributable to root strength. They noted that there were no large roots exposed in the headscarp and the debris slide was attributed to the distribution and short-term intensity of the storm in contributing to the development of pore-water pressures in excess of 2.0kPa.

Buchanan and Savigny (1990) attempted to define a "root cohesion" 'C_r' value for four dominant vegetation communities occupying avalanche-disturbed sites. They identify soil matrix suction as a significant contribution to slope stability, and note that during rainstorms the loss of this suction and loss of root cohesion results in a decrease in soil shear strength. Root cohesion was observed to be naturally low in wet drainage depressions, and root cohesion was not uniform across a slope. Back calculation analysis of the failures was performed in order to derive a root cohesion value for each of the vegetation communities.

Terwilliger and Waldron (1991) discussed shallow (less than 1 meter deep) soil slips which were believed to generate the greatest volume of earth movement in their study region in California. They suggested that roots in deep-seated landslides contributed little to soil cohesion as they did not penetrate to the failure surface. They differentiated surface soil conditions from deeper soils, indicating that root reinforcement effects in surface soils had little to no influence on deep-seated slides. The study examined the shear strength differences of root-permeated and rootless soils and concluded that vegetation type determines the distribution of soil shear strength across a landscape. Larger vegetation with fewer and larger woody roots provides zones of high and low shear strengths, whereas grasses provide a more even distribution of reinforcement across a landscape. The calculated average root reinforcement values in Terwilliger and Waldron (1991) were very low (0.6 – 3.0kPa) as compared to other studies.

Sidle (1991) using calculation of simultaneous growth and decay functions modeled the decay of roots after vegetation removal where understory vegetation is being re-established in the same area. Dense networks of small to medium roots were found to reinforce the upper soil horizon and act as a membrane of lateral strength reinforcement. Sidle recognized that models must have a temporal component that adequately accounts for both temporal and spatial alterations in root strength produced by past land management techniques. He suggested that understory vegetation may account for 30-50% of total old growth root cohesion. His model indicates that the cumulative effects of vegetation management, such as selected harvest systems, can result in a net loss in maximum root strength, existing for proportionally less time during each successive rotation. On poor sites, shorter timber harvesting rotation periods and slow root regrowth cause a steady temporal decline in site root strength through time.

Krogstad (1995) investigated the mechanical strength of the lateral root mat using a pipe-model theory to model the relationship between the distribution of fine roots and the cross-sectional area of roots crossing the failure boundary. Schmidt et al. (2000) show how root cohesion varies with vegetation type, stand age and disturbance in the Oregon Coast range. They found that harvested forests dominated by deciduous vegetation had median root cohesion values ranging from 6.8-23.2kPa, while old growth forests had a root cohesion values ranging from 25.6-94.3kPa. Clearcut areas had root cohesion values of less than 10kPa. They concluded that even 100 year-old harvested forests have root cohesion values and lateral root mat characteristics resembling a 10 year-old clearcut rather than an old-growth forest.

Johnson and Wilcock (2002) studied areas of naturally declining red cedar stands in coastal Alaska. They noted that cedar decline areas were found to be saturated longer than other areas, possibly leading to greater root deterioration. Landslide frequency had increased 3.8 times more in areas of cedar decline and increased saturation than in surrounding healthy forests on similar slopes. They observed that 70-90% of cedar roots smaller than 1.0 - 3.0mm were decayed in trees that had been dead for 14 years or more. Sakals and Sidle (2004) noted that root cohesion follows the same spatial distribution as root volume. A 79 year-old forest for example, with 400 stems per hectare (large roots and an extensive root network) had an average root cohesion of 4.36 kPa whereas a plantation of 10-year-old trees with 2000 stems per hectare (smaller roots and a less developed network) growing in a clearcut had an average root cohesion of 1.80 kPa. Tokgoz (2005) describes how the soil reinforcement effect is due to transfer of sliding stress in the soil to the tensile strength of the roots.

The root cohesion data calculated these papers have been compiled and entered into an on-going root database. Typical values of root cohesion reported in the literature are shown in Table 1. The range of calculated root cohesion values is quite small, with a few extreme values, but this chart demonstrates a common difficulty in the choice of a root cohesion value as root cohesion also varies with both disturbance type and land management regimes. In addition, root cohesion values may be appropriate for modeling a lateral root mat but may not be an accurate value for vertical tap-roots. If root cohesion values are to be used in slope stability analyses it is very important to adequately characterize the vegetation communities and root characteristics.

3. SHEAR DISPLACEMENT MODELS

Abe and Ziemer (1991) investigated the effect of tree roots on shear zones by performing direct shear tests on harvested shore pine roots (*Pinus contorta* Dougl.var.*contorta*) buried in fine sand. The direct shear tests showed that root-free sand demonstrated shear resistance starting at 17mm of shearing up to a peak shearing resistance at 70mm of deformation. The additional shear strength due to root cohesion, ΔS, increases rapidly in response to stretching of the roots before yielding or slipping. The root reinforced sand exhibited increased shear resistance when compared to the un-rooted samples, and yield was not reached at 88mm. Their study concluded that root deformation in sheared soils increases as the number of roots and the size of the roots decreased. Roots were found to induce a widening of the shear zone, which can result in an increase of the internal angle of friction (φ).

Table 1. Typical reported root cohesion values

Root Cohesion kPa	Comments	Source
2.02	Calculated through back-analysis of instrumented slope	Sidle & Swanston, 1981
4.90	Apparent cohesion from laboratory analysis	Sidle & Swanston, 1981
1-20	Post-harvesting loss in small roots strength of 300-500 kPa per month	O'Loughlin & Ziemer, 1982
5.0	Harvested Douglas Fir and Sitka Spruce	Sidle, 1991
3.2	Thinned Douglas Fir and Sitka Spruce	Sidle, 1991
3.0	Maximum value for chaparral	Terwilliger & Waldron, 1991
2.7	Maximum value for burned chaparral	Terwilliger & Waldron, 1991
2.4	Maximum value for grassland	Terwilliger & Waldron, 1991
6.8-23.2	For industrial forests	Schmidt et al., 2000
25.6-94.3	For natural forests	Schmidt et al., 2000
0.6+/-0.11	Untreated, un-vegetated mine dump slopes	Chaulya et al, 2001
0.98+/1.4	Grasses spread for biostabilization of dump slopes	Chaulya et al, 2001
0.45-0.57	Pullout, calculation by method of slices	Greenwood et al., 2004

Ekanayake and Phillips (1999) suggested that the limit-equilibrium method of slope analysis may not adequately account for stand-age characteristics and changes through time of root-reinforcement. They noted that in past research on this topic there appears to be a high uncertainty in the choice of values for the internal angle of friction and cohesion, and that the relationship between shear and normal stresses is not always linear as indicated by the Mohr-Coulomb equation. They stated that adding root reinforcement as a "cohesive" force may not be appropriate as peak soil strengths in fallow soil and soil with roots are mobilized at different shear displacements, and the shear-displacement curves have different shapes.

Soils with roots often display longer, flatter displacement curves, indicating that soil-root systems have the ability to withstand greater shear-displacements near the peak stress than soil without roots. They believe that this longer maximum stress peak before failure may provide time for slopes to equilibrate through pore water drainage. Ekanayake and Phillips (1999) consequently proposed an "Energy Approach" method of analysis that attempts to avoid the need to quantify factors that are inherently difficult and/or labour intensive to define, such as material properties or root architecture. Their model is aimed at describing young forests where large roots and "buttressing" effects typical of older/mature forests have not yet developed. The model examines energy consumed during shearing as the shape of the shear-displacement curve determines factors controlling stability (Figure 3). The total energy consumed by deformation is determined by mathematically integrating the area under the curve of the shear-displacement curve.

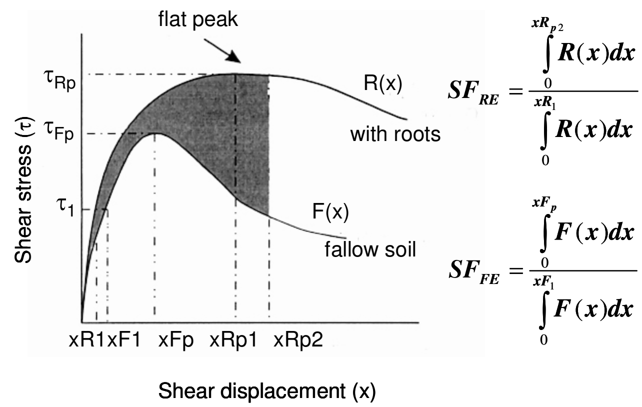


Figure 3. The Energy Approach used in the calculation of the safety factor of a shear plane on an infinite hillslope for both fallow and soil with roots, after Ekanayake and Phillips (1999).

4. ROOT ARCHITECTURE AND MORPHOLOGY

Many studies on root reinforcement examine the role of roots in plant anchorage. For roots to act as a resisting force, models frequently assume that the roots cross the slip surface and provide anchorage to the sliding mass (Ziemer, 1981b). Root anchorage is also important where plants are subject to an applied force (lateral or vertical) such as due to wind loading or vertical pullout through animal grazing. In such scenarios the role of the lateral root mat and root morphology becomes increasingly important. It may also be considered to be equally important in slope stability.

Ennos (1989) stated that tension exerted on a plant from either upward pulling (herbivore grazing) or horizontal loading (wind, surcharge) will be transferred to the soil via friction. He noted that previous studies have considered root-pullout in terms of friction, and found that the presence of root hairs resulted in higher frictional values. Tension travels along a root fibre as a failure front until it is balanced by friction or the residual matrix strength when the fibre will either pullout or break. Which occurs will depend on the morphology of the fibre; longer, thinner fibres having larger surface areas are "more likely to break". Ennos (1989) describes three failure modes exhibited by roots:

- Root-soil adhesion < strength of the matrix leading to 'debonding failure' where the fibre breaks away from the material

- Root-soil adhesion > strength of the matrix leading shear failure of the matrix.
- Matrix tensile failure, where the tensile strength of the fibre is much less that the matrix shear strength and a cone of matrix attached to the fibre may break off.

Bailey et al., (2002) examined the role of the lateral root mat and root hairs in plant anchorage. Uprooting tests on *Allium cepa* (onion) and *Arabidopsis thaliana* (Mouse-ear Cress) indicated that uprooting resistance could be resolved into a series of individual root breakages and that restricted lateral root development, such as in a mutant root variant of Arabidopsis, resulted in a 14% reduction in peak pullout resistance.

In their study on the effect of flexure on root and shoot morphology, Mickovski et al. (2003) found that stem diameter increased significantly in the flexed trees with a greater increase in the direction parallel to flexing. The control (unflexed) trees stem diameters were more concentric in growth shape. In the flexed trees, the total major lateral roots cross-sectional area was higher than that of the control population, especially in the direction parallel to flexure. There were also more lateral roots present in the flexed trees than in the control trees. They propose that an increased number of lateral roots results in a transfer of the hinge point of the stressed trees farther away from the tree and a faster transfer of stresses from the tree, and that these lateral roots preferentially received more of the tree's resources. The flexed stems tended to have stiffer and stronger wood but usually adapted to increased loading through changing morphology, not material properties.

Coutts et al. (1999) also emphasised the role of symmetry of root systems in the stability of shallow rooted trees and suggested mechanisms of simulating the often observed asymmetry using "spoke geometries". Chiatante et al. (2004) investigated the influence of steep slopes on root system development and show how trees respond to mechanical overturning forces on steep slopes by developing an asymmetrical root architecture referred to as a bilateral-fan shape.

Dupuy et al. (2005a) found that the pull-out resistance of a root cannot be well correlated to a single property, such as cross-sectional area, soil properties, or rooting depth. They suggest that uprooting tests of live plants are not able to take root morphologies into consideration. They identify 3 main types of geometric branching exhibited by root structures (non-branching, herringbone-like structure, and dichotomous branching roots). Strain analysis was performed using the finite element analysis software ABAQUS and showed that pull-out resistance depended on the strength of roots, plastic properties of soil and resistance at the root-soil interface. Dupuy et al. (2005a) concluded that either the basal diameter or volume of the root pattern combined with the number of root branches/axes correlated most strongly with pull-out resistance.

5. COMPUTER MODELING AND ANALYSIS

As computer technology and programming have developed, various approaches to modelling root reinforcement have been used. Simple limit equilibrium models based on the infinite slope equation are used to calculate the Factor of Safety in forested slopes and may include a 'root cohesion' constant to represent root reinforcement. Programs such as LISA (Level I Stability Analysis) developed by the United States Forest Service, estimate the probability of slope failure through a Monte Carlo simulation of the infinite slope equation. This program has been enhanced by Haneberg (2006) to incorporate digital elevation models for watershed analysis. Renamed PISA, the program divides the forest cover into units with unique sets of tree root cohesive strengths and tree surcharges. DLISA and GIS-based slope stability programs, such as SINMAP, developed by Pack et al. (1998), incorporate root cohesion based on the infinite slope equation. In contrast, when developing the program SHALSTAB, Dietrich and Montgomery (1998) completely eliminated a root cohesion factor as it was deemed too variable and difficult to accurately quantify.

A new direction for root reinforcement modeling is the use of continuum numerical finite element or finite difference codes (Easson and Yarbrough, 2002). The benefit of such techniques is that the material (soil and/or roots) can yield and flow and the grid can be modeled to move with material that is deformed. Groundwater flow and pore pressure development within deforming root reinforced hillslopes can simulated using this type of modeling program.

Cofie et al. (2000) discussed the role of root reinforcement in increasing the bearing capacity of the forest floor, especially in roads and in reducing soil compaction resulting from vehicle traffic. They modelled the root mat as a geotextile mat using the finite element code PLAXIS. The root mat was modeled as a stiff uniform root-soil layer at 15 centimetre depth and essentially acted as a curved tension membrane enhancing the ability of the road to spread the load due to multiple vehicle passes. The extreme longitudinal stress resulting from vehicle loading was determined to be 6.54MPa. Conclusions of this study included: i) that the diameter of thick roots has no effect on the failure stress and strain values, ii) reinforcement effects increase with increased root layer stiffness and decreased with the depth of the reinforcing layer, iii) shallow root mats are important for preventing soil compaction.

Chaulya et al. (2001) investigated the role of grasses and vegetation in a dump slope stabilization at the Mandaman dump, near Dhanbad, India. The soil cohesion and internal angle of friction were calculated from the results of shear-jack tests. The slopes were modelled using FLAC 2D (Itasca, 2000) with grassed areas represented as a layer located at 0.5metres depth with cohesion and internal friction angles as determined from the field tests. The shear stresses occurring within the slope were calculated and the model indicated that the presence of vegetation increased the factor of safety from 1.2 to 1.4. Chaulya et al. (2001) noted that fine roots contributed significantly to soil reinforcement whereas larger roots appear not to play a major role. They made three important comments on the role of root reinforcement in soil slopes:

i. water is removed from the soil by the plants for biological function, effectively increasing the frictional resistance of the soil
ii. contribution of organic matter to the soil allows the soil to absorb water without reaching critical soil saturation that could trigger instability
iii. removal of water near the roots promotes the formation of negative pore pressures, which can contribute to increased slope stability

Easson and Yarbrough (2002) studied roots in the riparian zone. Past data indicates that unreinforced and reinforced soils exhibit similar shear stress responses at low confinement pressures and as such, the benefits of root reinforcement are not realized until higher stresses are mobilized. They modeled lateral root strength in FLAC (Itasca) by setting a “tension acting between grid elements” factor. The factor was set at 20.0 kPa across the top 1 meter of soil to model root mat. The model indicated that an apparent increase in tensile strength due to root reinforcement varied with depth and distance from tree. The higher root-area ratio in top 40 cm of soil increased soil strength by an average of 148 kPa. The model indicated that a marginally stable slope with no roots became stable when only 20kPa of reinforcement was added. Dupuy et al. (2005b) developed a method to construct three-dimensional virtual root architecture (SIMULBR). They used this technique to generate four schematic root patterns, heart-, tap, herringbone and plate-like root systems. Three dimensional finite element numerical modelling was then undertaken to investigate the mechanics of tree anchorage – specifically the response of root/soil interaction subjected to bending moments. Results of their models indicated that changes in the soil friction modify the location of the axis of rotation during tilting of root/soil plates. The resistance to overturning was found to be greatest in heart and tap root systems.

6. ROOT-GROUNDWATER-SOIL INTERACTION

Bishop and Stevens (1964) identify three ways in which pore water may reduce shear strength:

i. buoyancy reduces effective intergranular pressure and friction
ii. capillary tension destroyed upon saturation
iii. seepage pressures of percolating groundwater result from viscous drag between liquid and solid grains

Swanston (1970) studied till soils of Southeast Alaska and determined that slope gradients and pore-water pressure (or stress) were the primary factors in initiation of debris avalanches in harvested areas. He noted that seepage occurs along interconnected soil voids and root spaces. He also observed that during periods of high rainfall, lateral seepage of water can increase the shear stress along a potential sliding surface by increasing the unit weight of the soil materials and by decreasing the shear resistance resulting from increased pore-water pressures in the soil.

Beven and Germann (1982) describe macropores as being laterally and vertically continuous for several meters and note that they may lead to spatial concentrations of water flow through unsaturated soil. Iverson and Major (1986) determined that the seepage force vector, the body force proportional to the hydraulic potential gradient, is responsible for destabilizing hillslopes and that horizontal seepage can occur above poorly permeable strata. They showed that vertically upward seepage components of seepage vectors can result in static liquefaction. Convergent topography and seepage vector analysis has shown that depressions in the topography are often locations of landslide initiation. Research has shown that in areas of high apparent cohesion, landslides in steep terrain are often restricted to locations with either excess pore water pressure or thick (topographic) hollows.

Groundwater may thus affect root reinforcement in two major ways:

- Reducing the frictional resistance at the root-soil interface
- Promoting seepage forces that disrupt or erode the root-soil interface

Moisture content has been also been reported to affect root strength (O'Loughlin, 1974, Cofie et al., 2000). Makarova et al. (1998) showed that roots lost water under repeated loading, such as occurs on forest roads. The fraction of moisture lost was dependent on root diameter, with the finest roots losing up to 60% of their water content. It was determined that root reinforcement was diminished as a result. Casadei, Dietrich and Miller (2003) show through back-calculations and field observations that lateral root strength is a primary control on size and location of shallow landslides in soil. Landslide width increases with increasing root strength and decreasing slope as larger soil masses are required to overcome resisting forces provided by root reinforcement. As pore water pressure reduces the frictional strength of the slope, the drier the soil, the larger the slide. The location of the slide depends on local patchiness of soil thickness, root strength and topographically-driven relative saturation.

Van Beek et al. (2005) simulated both direct shear tests and full hillslope scale failures using the FLAC2D code (Itasca, 2005). They developed a root reinforcement model that could be incorporated with in the FLAC numerical solution. After constraining the reinforcement model based on simulation of direct shear tests, they then modeled hillslopes subject to landslides under three conditions of root reinforcement - no roots, digitally input observed tree roots and fully rooted. Two groundwater conditions were simulated - fully saturated and an assumed constant piezometric surface. Using the shear strength reduction technique of Dawson et al. (1999), Van Beek et al. (2005) derived factors of safety for all simulated scenarios. They suggest that when the root reinforcement model is applied at the hillslope scale and under critical hydrological conditions, root pullout becomes the dominant root failure mechanism and the slip plane is located at the weathering depth of the soil where root reinforcement is negligible.

Tsutsumi et al. (2004) undertook three-dimensional numerical modeling combining root system development and soil water flow in a hillslope. Their study emphasized simulation of environmental controls on root elongation and symmetry and has direct relevance to the changing role of root reinforcement with time. As water flows preferentially through macropores and soil voids (enhanced by root growth), we can infer that seepage erosion will occur close to or in contact with roots. The erosive capacity of the seepage forces may act on the root-soil bond, reducing the frictional contact between the roots and the soil. Therefore, groundwater flow through a rooted soil can have significant impact on the reinforcement effects of the roots, and in turn on the stability of the slopes.

7. CONCLUSIONS

A considerable amount of research has been undertaken over the last forty years and yet the influence of root reinforcement on the stability of harvested slopes is still controversial. Much of the earlier work involved the testing of the tensile strength of roots and the shear strength of root reinforced soil. More recently this has been supplemented by pull-out tests. Early analysis incorporated root cohesion into a simplified infinite slope model as an additional basal cohesion due to root penetration across a potential failure surface. This has been clearly shown to be an oversimplification and the influence of lateral cohesion is now accepted. Recent research has involved detailed studies on the characterization and influence three dimensional root architecture in slope reinforcement. Coupled with this has been a major increase in the use of root reinforcement-groundwater numerical models. To a large extent these advances have resulted from initiatives such as The European Ecoslopes project (2005). This research project has among its prime objectives i) examining the stabilizing and reinforcing effects of vegetation on soil, ii) investigating the effects of vegetation removal on slope hydrological processes and soil erosion, iii) evaluating the role of vegetation in zones of landslides and iv) evaluating the impacts of forest fires on vegetation, soil properties and erosion. These objectives are without doubt extremely relevant to the role of root reinforcement in the forest-harvested slopes of Western Canada. Further research in Western Canada is being conducted by the authors focusing on field observations, improved methods of characterizing the root mat and the numerical modeling of root-soil-groundwater interaction processes. The authors suggest that the accepted 'root cohesion' paradigm requires refinement to allow an adequate consideration of both the importance of groundwater flow and the three dimensional architecture of root systems. As well, further investigation will allow simpler incorporation of the root mat into routine slope stability analysis.

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