THE IMPORTANCE OF ROOT STRENGTH AND DETERIORATION RATES UPON EDAPHIC STABILITY IN STEEPLAND FORESTS

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ABSTRACT

The additional strength provided by roots to the soil is generally considered to be in the form of a cohesive strength ΔC which may range in magnitude from 1 kPa to 20 kPa. Studies of the tensile strength of tree roots show that small roots sampled from living trees range in mean tensile strength from about 10 MPa to about 60 MPa. After tree felling small roots lose their strength at average rates between 300 and 500 kPa per month. Root biomass also decreases rapidly after clearfelling. The reduction in ΔC after forest removal is a prime cause of landsliding on many steep slopes.

INTRODUCTION

The importance of plant root systems to the stability of sloping soils has received considerable attention over recent years, particularly from the viewpoint of forest removal influences on slope and soil stability. Several investigators have recognised a relationship between forest harvesting and increased frequency of small shallow landslides with time after logging. For instance, in southeast Alaska, Bishop and Stevens (1964) identified a 4-to 5-fold increase in the number and acreage of shallow landslides within 10 years after clearfelling They attributed the increased frequency of landsliding to root deterioration. The importance of roots to the stability of steepland soils under intact coniferous forests and after forest removal in western North America has been further elucidated by Swanston (1974a, 1974b), O'Loughlin (1974b), Zlemer and Swanston (1977), Burroughs and Thomas (1977), Wu *et al.* (1979), Wu and Swanston (1980), Ziemer (1981) and Gray and Megahan (1981). In short, these studies generally indicate that the continued stability of soils on many steep forested slopes depends partly on reinforcement from tree roots, especially when soils are partly or completely saturated. After forest removal the gradual decay of tree roots often predisposes forest soils to failure.

Similar conclusions have been reached in Japan (Kitamura and Namba, 1966; Endo and Tsuruta, 1969; Nakano, 1971, and in New Zealand (O'Loughlin and Pearce, 1976; Selby, 1981; O'Loughlin *et al.*, 1982).

Research related to root strength and slope stability has Seen mainly channelled into four distinct areas of endeavor:

1. Direct field and laboratory measurements of the contribution imparted by roots to soil strength.
2. Indirect computations of the contribution made by roots to soil strength using root strength, root density, root distribution and root morphology data.
3. Development of theoretical slope stability analyses in particular "back-analyses", using slope and soil physical data to estimate the contribution made by roots to soil strength.
4. Laboratory studies of individual strengths of roots sampled from living trees and the rates at which root strength is lost after tree cutting.

Despite this seemingly comprehensive approach to the appraisal of the root reinforcement effect in soil stability, the mechanics of slope stabilisation by root systems and the real importance of tree roots to soil stability under different conditions of slope, climate, vegetation and soil are generally poorly understood. The physical difficulties in investigating subsurface root distributions and morphology and the great heterogeneity in soil physical properties and in root densities in steepland forest soils, largely account for this lack of progress. Furthermore, in addition to providing a reinforcing root system, forests can influence soil stability in other ways not the least of which is by modifying soil moisture conditions.

In this paper we attempt to review the interactions of root systems with slope materials and outline the importance of roots to slope stability in different intact and disturbed forest ecosystems.

RELATIONSHIP BETWEEN SLOPE STABILITY AND FOREST VEGETATION

It is generally believed that erosion rates are lower under forests than under other vegetation covers and land uses on similar terrain with similar climate. Although this is true, erosion rates under forests may vary over several orders of magnitude, from less than 1 m^3 km^{-2} a^{-1} to over 13 000 m^3 km^{-2} a^{-1} as illustrated by the examples cited in Table 1. Mean annual erosion rates can be misleading. Mass wasting on steep forest slopes, particularly debris or soil slides, avalanches and flows, and stream channel bank collapses supply most of the sediment in the New Zealand and western United States examples. Such mass erosion events are episodic. Clearly, in many environments, a forest cover does not prevent high erosion rates.

Table 1. Sediment yields from selected forest areas in New Zealand, Malaysia and the United States.

Location	Record Length (yrs)	Drainage Area (km^2)	Precip. (mm)	Sediment Yield ($m^3km^{-1}s^{-1}$)	Source
New Zealand					
Big Bush	2	0.1	1500	5	O'Loughlin et al.,1978
Tawhai	2	0.03	2600	55	O'Loughlin et al., 1978
Ruahine Range	23	7	2500	2700	Mosley, 1976
Hokitika R.	13	352	9400	17000	Griffith, 1979
Malaysia					
Cameron Hinds.	2	?	2500	7	Shallow, 1956
Gombak R.	2	140	2500	67	Douglass, 1968
United States					
Fernow	20	0.3	1500	0.3	Patric, 1976
Zena Creek	6	4	723	6	Megahan and Kidd, 1972
H.J. Andrews	8	0.6	2300	20	Fredricksen, 1970
Caspar Creek	14	5	1000	240	Rice et al., 1979
Van Duzen R.	35	560	1800	1340	Kelsey, 1977

Root reinforcement is often cited as the most important forest influence maintaining soil stability. In order to place the importance of tree root systems to soil stability in perspective it is necessary to consider the main influences of forest vegetation on soil.

An undisturbed forest appears to affect the stability of slopes in a number of ways:

1. By windthrowing and root wedging. Although trees may be frequently overturned on steep slopes or ridges exposed to strong winds thereby creating disturbance to the soil mantle and initiating landslides, generally the beneficial effects of tree roots to soil stability greatly outweigh the adverse effects. Notable examples of the triggering effect of tree toppling on landsliding are presented by Schweinfurth (1967) for the New Zealand Fiordland region and White (1949) for the volcanic mountains of Hawaii.

Wind also exerts a drag force on the forest. When the wind blows in a downhill direction calculations by Wu *et al.* (1979) indicate that the downslope acting shear stress transmitted to the soil is likely to be less than 1 kPa.

2. By increasing the surcharges on a sloping soil mantle. Calculations by Bishop and Stevens (1964) and O'Loughlin (1974) show that the shear stresses acting downslope produced by the weight of a mature forest crop may be negated by the increased soil shear strength due to the surcharge. Moreover, in many forest ecosystems the total weight of the soil above a potential failure plane far exceeds the weight of a forest crop. Calculations by Bishop and Stevens (1964), O'Loughlin (1974), Wu *et al.* (1979) and others suggest that the vertical stresses resulting from tree crop surcharge range between 1 and 5 kPa and often averages about 2 kPa. Ellison and Coaldrake (1954) claim that creep rates on tree-covered slopes in Queensland rain forests were higher than on grass covered slopes. A detailed mathematical analysis of soil creep by Brown and Sheu (1975) also suggests that the overburden of a tree crop raised downslope movement rates of forest soils subject to creep deformation. However, Swanston (1981) reports an increase in creep rates following removal of the mature forest.

3. By modifying soil moisture distribution and soil pore water pressure. Forests deplete soil moisture to considerable depth through evapotranspiration (Douglass, 1967; Ziemer, 1968; Helvey *et al.*, 1972) and may depress perched water tables which sometimes rise after clearcutting (Stone et al., 1978). The combination of transpiration and interception by forests may tend to delay or mitigate soil saturation on steep slopes (Hallin, 1967) while tree root networks provide pathways for rapid transmittance of water (Aubertin, 1971; Beasley, 1976; Mosley, 1979). However, landsliding on forest lands is usually associated with large storms (Caine, 1980; O'Loughlin *et al.*, 1982) which produce more than adequate water to fill all available soil and vegetation storages.

4. By providing an organic forest floor layer. Under most temperate forests the forest floor, consisting of accumulated litter, humus and tree *roots*, protects the underlying mineral soil from raindrop impact and surface wash. Permeable forest floors may also help maintain high hydraulic conductivities in upper soil horizons and encourage rapid percolation of water through the upper soil mantle.

5. By mechanically reinforcing the soil with tree roots. This aspect forms the central theme of this paper and is discussed in some detail in the following sections.

MECHANICS OF SOIL REINFORCEMENT AND SLOPE STABILISATION BY TREE ROOTS

A soil's strength or resistance to failure is described by the Mohr-Coulomb equation (Sowers and Sowers, 1970; Lambe and Whitman, 1969) which can be written:

$$S = c' + [\sigma-\mu] \tan \phi' \qquad \text{..... (1)}$$

where S = soil shear strength (kPa)
c' = effective soil cohesion (kPa)
σ = normal stress (kPa)
μ = soil pore water pressure (kPa)
ϕ' = effective internal friction angle (degrees)

The cohesive component (c') is the result of cementation, weak electrical bonding of clays and organic colloids and capillary tension, while the frictional component (ϕ') is an expression of the frictional interaction of individual particles and the interlocking of particles. The normal stress σ is caused by the weight of the soil, soil moisture and forest cover above a potential failure surface; whereas the soil pore water pressure μ reduces the normal stress by buoyancy.

It is generally claimed that root systems contribute to soil strength by providing an artificial cohesion ΔC and have negligible influence on the frictional component of strength (Endo and Tsuruta, 1969; O'Loughlin, 1974(a,b); Swanston, 1974(a,b); Waldron, 1977; Gray and Megahan, 1981; O'Loughlin *et al.*, 1982; Waldron and Dakessian, 1981). In a root-permeated soil the Mohr-Coulomb equation can be modified to include ΔC:

$$S = [c' + \Delta C] + [\sigma-\mu] \tan \phi' \qquad \text{..... (2)}$$

More complex soil-root shear strength models are presented by Wu *et al.* (1979) and Luckman *et al.* (1982). The latter authors present an analysis which indicates that both the cohesion and friction components are increased by the presence of roots. Where a root crossing a shear zone (Figure 1) is placed in tension, t_r, the tensile stress can be resolved into components perpendicular and parallel to the shear zone (σ_r and τ_r).

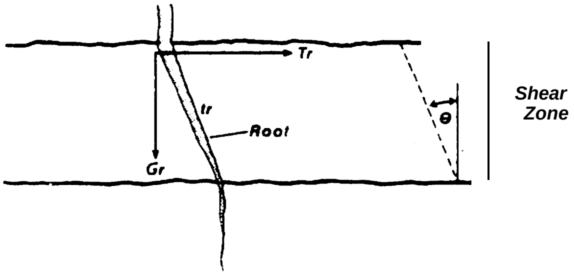

Figure 1. A well-anchored root stressed in tension where it crosses a soil shear zone.

$$\tau_r = t_r \sin\theta; \text{ and } \sigma_r = t_r \cos\theta \quad \ldots\ldots (3)$$

where θ = the angle of shear distortion,

According to Luckman *et al.* (1982) σ_r increases the normal stress which, in turn, increases the frictional component of soil strength. Their soil-root shear strength model has the form

$$s = [c' + c_r] + [\sigma - \mu + e_r] \tan\phi' \quad \ldots\ldots (4)$$

where c_r and e_r are factors dependent on the tensile stress in the roots, the number of roots and the strain (extension) of the roots at failure.

Wu *et al.* (1979) devised a very useful relationship which can be used to determine ΔC based on the stress distributions shown in Figure 1.

$$\Delta C = T_r [\cos\theta \tan\phi' + \sin\theta] \quad \ldots. \quad (5)$$

where $T_r = \Sigma t_{ri}/A$ = the total tensile stress of roots per unit area of soil shear zone

As the quantity $[\cos\theta \tan\phi' + \sin\theta]$ is insensitive to changes in θ and is close to 1.2 for a large range of θ it is acceptable to write

$$\Delta C = 1.2\, T_r \quad \ldots.. \quad (6)$$

Direct measurement of the shear strength of soil-root systems has revealed some information about the mechanics of root reinforcement. Large metal shear boxes of various sizes and designs capable of shearing in *situ* undisturbed blocks of soil in fieid situations have been employed by Endo and Tsuruta (1969), O'Loughlin (1974a,b), O'Loughlin *et al.* (1982) and Ziemer (1981), while Waldron (1977) and Waldron and Dakessian (1981) used a direct shear device in the laboratory to shear cylindrical columns of root-soil systems.

in a study of the shear strength of a uniform nursery soil densely planted with *Alnus glutinosa* with an average stem diameter of 16 mm, Endo and Tsuruta (1969) found that the artificial cohesion due to the roots increased in proportion to the fresh weight of roots per m^3 of soil. Their data indicates that the presence of roots (root content ranged from approximately 4 kg to 12 kg of fresh roots per m^3 soil) raised the soil shear strength between 5 and 10 kPa.

Ziemer (1981) used a larger metal shear box than Endo and Tusurta which sheared soil blocks along two parallel vertical planes, to study the effects of *Pinus contorta* roots on the shear resistance of coastal sands in northern California. The dry root biomass (kg/m^3) in the 18 soil blocks tested was found to explain 79 percent of the variation in soil strength (kPa). The linear prediction equation relating strength and biomass of roots was:

Soil Strength = 3.13 + 3.31 Biomass

A third field shear box study of the importance of roots to soil shear strength was conducted by O'Loughlin *et al.* (1982) on steep hill country soils. A metal shear box with open sides and base was used to shear the sides and bases of carefully prepared in situ soil blocks, One series of 19 tests was carried out on a beech *(Nothofagus)* forest-covered soil and another 17 tests were completed on a similar site but where the forest had been clearfelled and burnt 36 months previously and the tree roots were in an advanced state of decay. The results of the shear tests, illustrated by a sample of shear stress-displacement curves (Figure 2), indicated that roots imparted added strength to the soil and a resilience which enabled soils to maintain considerable resistance to failure after substantial shear displacement had occurred. The curves for intact forest soils show only small declines in shear resistance after reaching the peak because roots continued to stretch and readjust their positions. In several tests larger roots over 20 mm diameter did not fail but tore the soil block as the test proceeded. In other instances poorly anchored roots were either pulled out of the block or the surrounding soil but did not break, The majority of the roots which broke failed in tension rather than in shear, a finding which conforms with the observations of failed roots around landslide scars (Swanston, 1974; O'Loughlin, 1974; Gray and Megahan, 1981; O'Loughlin *et al.,* 1982).

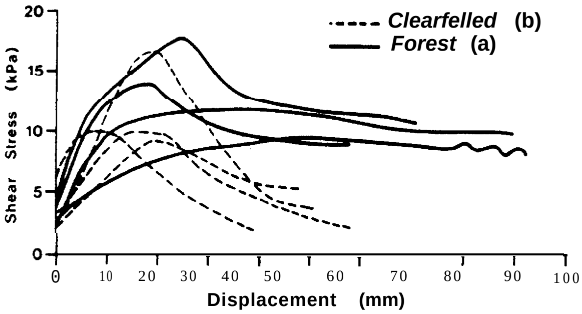

Figure 2. Shear stress displacement curves for field shear tests: (a) under intact beech forests, (b) on a slope clearfelled 36 months before testing.

Tests were conducted under a range of confining stresses to enable construction of plots of peak shear stress vs total normal stress (normal to the shear planes) from which estimates of the cohesion and internal friction angle could be made from the fitted curves shown in Figure 3 which represent Mohr-Coulomb failure envelopes for the two conditions of soil, the shear strength parameters presented in Table 2 were derived.

Table 2. Shear strength parameters for NZ beech forest soils with and without competent roots

	Intact forest with competent roots	Clearfelled and no competent roots
Apparent cohesion	6.6 kPa	3.3 kPa
Internal friction angle	36^{o}	36^{o}

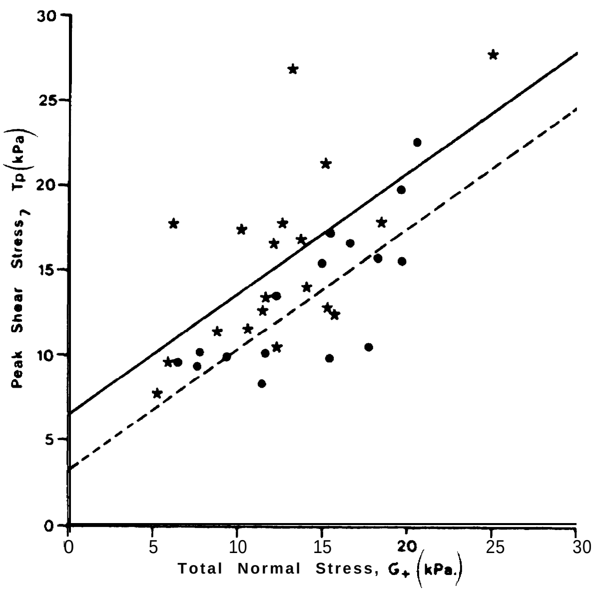

Figure 3. Fitted curves of peak shear stress vs total normal stress for field shear tests in the soil root zone; (a) beech forest (★ ———), (b) clearfelled (● - - - - -).

The data indicate that roots increased the cohesion but did not influence the internal friction angle. It should be mentioned that the deteriorated roots on the clearfelled sites and small living *roots* of fireweeds and planted *Pinus radiata* seedlings obviously imparted some additional strength to the soils. Consequently the cohesion difference shown in Table 2 underestimates the total contribution to soil strength provided by competent tree roots.

In their laboratory study of soil-root reinforcement Waldron and Dakessian (1981) found that roots of barley and pine do increase the strength of small saturated soil columns but that the strength of the soil-root bond limited the root reinforcement. In other words root slippage or roots pulling out of the soil before their maximum tensile strength is reached, limits their contribution to soil strength. This effect was not so noticeable in the field tests conducted by O'Loughlin *et al.* (1982) and Ziemer (1981) where roots penetrated large distances (metres) through the soi1 and often followed tortuous routes around stones and other roots, thus providing good soil-root bonding.

Estimates of AC have also been made by Swanston (1970) and by O'Loughlin (1974a, b) by performing stability analyses on failed slopes. They used appropriate physical soil and slide geometry data in simple slope stability models, assumed a factor of safety of 1.0 at failure and by back-calculation derived values for AC.

Table 3 presents a summary of the magnitude of reinforcement tree roots impact to soils.

Table 3. Results of studies of root strength factor AC

Investigator	Soil-Vegetation Situation	ΔC kPa
Swanston 1970*	Mountain till soils under conifers in Alaska	3.4-4.4
O'Loughlin 1974b*	Mountain till soils under conifers in British Columbia	1.0-3.0
Endo and Tsuruta 1969*	Cultivated loam soils (nursery) under alder	2.0-12.0
Wu et al. 1979°	Mountain hill soils under conifers in Alaska	5.9
Waldron and Dakessian 1981*	Clay loams in small containers growing pine seedlings	c.5.0
O'Loughlin et al. 1982*	Shallow stony loam hi11 soils under mixed evergreen forests, NZ	3.3
Gray and Megahan 1981°	Sandy loam soils under conifers in Idaho	c.10.3
Burroughs and Thomas 1977+	Mountain and hill soils in West Oregon and Idaho under conifers	3.0-17.5

* AC based on direct shear tests; ° AC based on equations 5 and 6;
• AC based on back-calculations; + AC based on root density information

Although the foregoing section illustrates that the influence of roots on soil strength has received some quantification the broader concept of the influence of roots on regolith stability has not been studied in the same detail. Nevertheless, investigations in USA, Japan and New Zealand suggest that tree roots act in several ways to reinforce regolith stability.

1. <u>By bonding unstable soil mantles to stable subsoils or substrata.</u> Where a potential weak failure surface occurs within the rooting zone, tree roots crossing the potentially critical surface can maintain stability. By way of example, stratified tephra soils consisting of different-aged volcanic ash layers, each separated by well marked interfaces, developed a severe landsliding problem after the death of the montane mixed evergreen hardwood forest in the Kaimai Range, north-eastern New Zealand. Landsliding was most common along a weak surface separating two ashes at depths between 1 and 2 metres. Under intact healthy forest conditions tree roots crossing the weak interface maintained a reasonable degree *of* stability.

2. <u>By providing a laterally-strong covering soil-root mantle.</u> Tree root densities often tend to be greatest in the top 50 cm or so of soil. In NZ beech *(Nothofagus* steepland forest soils, for instance, a dense interwoven root network develops in the organic horizons in the upper 30-50 cm of forest soil. In deeper mineral soil. horizons roots tend to be relatively sparse. After forest removal landsliding on steep slopes often occurs along slide planes beneath the zone of dense root networks. However these networks appear to create- a reinforced surface layer of soil which provides a type of membrane strength or lateral-acting-strength which holds the underlying soil in place. This mechanism also seems to be important where shallow steepland forest soils overlie compacted substrata such as the till soils

of southeast Alaska and the Coast Mountains of British Columbia.

3. By providing very localised centres of great reinforcement in the close vicinity of individual trees. Where tree roots are firmly rooted into a stable substratum beneath a potential failure plane, a soil arching restraint model has been applied by Gray and Megahan (1981) to account for increased stability. Soil arching in the soil mechanics sense refers to the phenomenon of stress transfer through mobilisation of shear strength in soils (Wang and Yen, 1974; Craig, 1979) and the theory behind soil arching has been developed to quantify the reinforcing effects of pins and piles. If tree roots are considered as buttresses, then it is possible to apply the soil arching restraint theory to determine critical spacing of trees to obtain maximum stabilisation.

Generally, the scant information on root morphology and root densities does not enable accurate estimate of the relative importance of these stabilising mechanisms in various steepland forest environments. However, the limited information available suggests that mechanism 2 is the most significant in many unstable forest slope environments.

ROOT DETERIORATION AND ITS EFFECT ON SLOPE STABILITY

Several studies of the rates of root strength deterioration after forest cutting have been completed. In Alaska the change in root strength of western hemlock *(Tsuga heterophylla)* and Sitka spruce *(Picea sitchensis)* has been studied by Ziemer and Swanston (1977). Both of the species showed rapid loss of root strength among small roots less than 25 mm diameter. After a 10-year period, Sitka spruce roots had reached a more advanced state of decay than had hemlock roots. By 10 years even large roots had lost appreciable strength. The pattern of decline of mean strength of residual hemlock and Sitka spruce roots was complicated by the increased importance of decay-resistant resinous roots in the residual root fraction with time after logging. This resulted in an apparent increase in mean strength of roots found in the soil between 2 and 4 years after logging Sitka spruce and between 4 and 6 years after logging hemlock. However, when the strength of these roots was weighted by the proportion of remaining root biomass, about 50 percent of the strength initially contributed by hemlock and 60 percent of the strength by Sitka spruce was lost within 24 months after felling (Fig. 4).

Burroughs and Thomas (1977) demonstrated that the tensile strength of Douglas-fir roots in western Oregon and in central Idaho declined rapidly after tree cutting. Seventy-five percent of the roots 10 mm or less in diameter were lost within 24 months after felling in western Dregon and within 60 months after felling in central Idaho. The authors concluded that smaller roots in the 1 to 10 mm diameter size class are most effective *in* maintaining the stability of timbered slopes. The decline in strength and number of these small roots closely match the high frequency of landslides during the first few years following timber harvest. Similar findings are reported by Ziemer (1981) who studied the decline of root strength and root biomass after forest cutting in the mixed conifer forests of the Klamath Mountains, northern California. It appeared that the reduction in conifer root strength and biomass after felling followed an exponential curve, a finding that is in close agreement with the results of O'Loughlin and Watson's (1979) study of root strength reduction in *Pinus radiata* in New Zealand. In the Klamath Mountains about half the original root reinforcement was lost within 2-3 years after logging.

In New Zealand direct measurements of the tensile strength of root segments sampled from living trees and cut stumps, has enabled root strength deterioration curves to be drawn for *Pinus tadiata,* beech *(Nothofagus fusca* and *N. truncata*) and rata *(Metrosideros umbellata)* (O'Loughlin and Watson, 1979, 1981). Similar techniques *were* used to study root strength deterioration rates in Douglas-fir and western red cedar in the Coast Range of British Columbia, Canada (O'Loughlin, 1974b). These data and data produced by Turmanina (1965), Burroughs and Thomas (1977), Ziemer (1981) and Ziemer and Swanston (1977) show that small roots up to 25 mm diameter sampled from living trees range in mean tensile strength from c. 10 MPa to c. 60 MPa and that, on average, small tree roots lose their strength at an average rate of between 300 and 500 kPa per month (Figure 4) after tree felling. Generally living conifer roots are weaker than equivalent-sized hardwood roots,

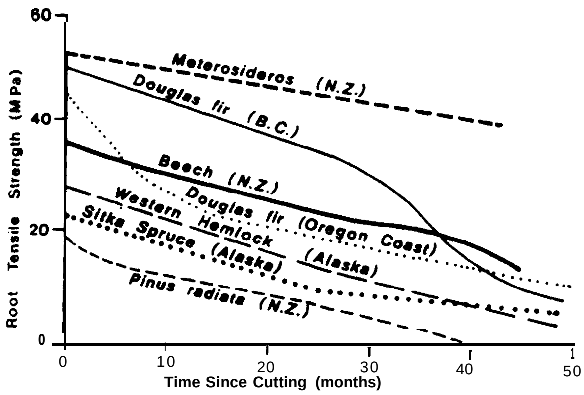

Figure 4. Curves of mean tensile strength vs time elapsed since tree felling for small roots of various conifer and hardwood trees,

As competent-root tensile strengths are measured in megapascals and soil shear strenghts are normally orders of magnitude less in the range of tens of kilopascals, it is probable that inter-species differences in the tensile strength of living roots are less significant to slope stability than the differences which may occur in root densities and root morphology. However, it appears root strength loss rates are similar among several species, and initially very strong roots retain considerable strength several years after cutting whereas initially weak roots lose almost all their ability to reinforce soils in a few years.

Ziemer (1981) showed that soil strength increased linearly with root biomass. In mixed conifer forests in northern California dead root biomass declined rapidly after logging. In terms of relative reinforcement (the product of root strength summed over size and species classes and root biomass) dead roots <17 mm diameter declined exponentially and about half the original reinforcement was lost 2 to 3 years after logging. Dead conifer root reinforcement had disappeared within 25 years after logging. In New Zealand most *Pinus radiata* roots <30 cm diameter had disappeared 40 months after logging (O'Loughlin and Watson, 1979).

On logged areas in northern California, Ziemer (1981) also assessed the importance of shrub hardwoods such as *Ceanothus* sp. which occupied cutovers 7 years after logging and completely reveqetated cutblocks 12 years after logging. At this stage root reinforcement recovered to about 70 percent of the original uncut forest reinforcement (Figure 5). If revegetation by shrub hardwoods had been curtailed in an attempt to establish conifers more quickly, root reinforcement of the soil would have been much lower.

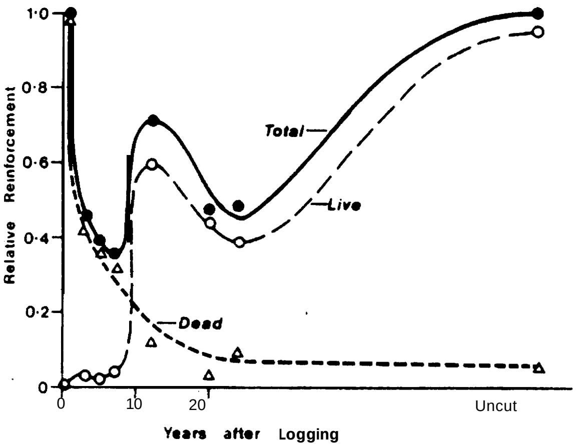

Figure 5. Relative reinforcement of soils by live roots generally increased while that by dead roots rapidly decreased with time after clearfelling. The total reinforcement by live and dead roots dropped to a low point about 7 years after logging (after Ziemer, 1981).

The accelerated incidence of landsliding between 3 and 10 years after forest removal (on steep slopes in Alaska, British Columbia, Oregon, Japan, Idaho and New Zealand), which coincides with the time after cutting when roots of smaller diameter have undergone advanced deterioration (Figure 4) provides a strong indication that it is the smaller roots less than 20 mm diameter which are most important to soil and slope stability. Furthermore, studies of the size and frequency of dead tree roots in soils cleared of their forest cover (Burroughs and Thomas, 1977; O'Loughlin *et al.*, 1982) and of dead roots exposed on landslide scars (Gray and Megahan, 1981), provide additional evidence that roots under 20 mm diameter are most important to slope stability.

SLCPE STABILITY ANALYSES

Slope stability analyses, which consider the various movement-promoting and movement-resisting forces operating on slopes, can be used to provide indexes of stability or factors of safety. A relatively simple infinite slope stability model has often been used to investigate the stability of forest slopes where shallow translational failures are the main type of mass wasting. An infinite slope is approximated where the thickness of the soil mantle or unstable layer of the regolith is small compared to the height of the slope. Under infinite slope conditions the failure plane is assumed to be parallel to the slope. Figure 6 depicts the main forces operating on a forested infinite slope.

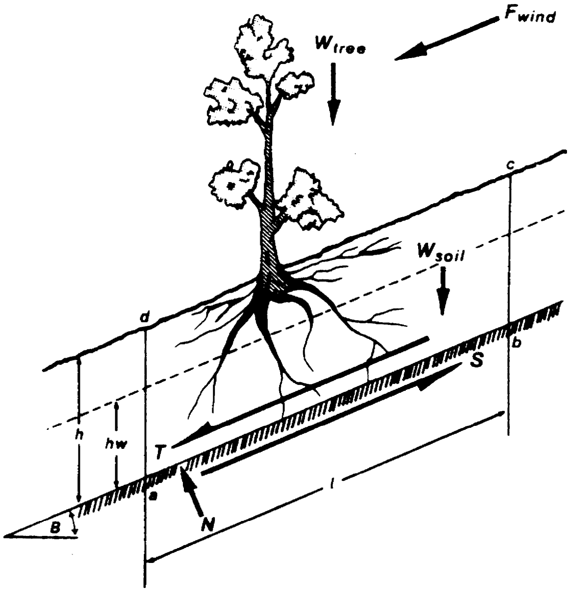

Figure 6. Part of a forested infinite slope showing forces operating on a sliding soil mass.

The stress resisting failure along potential shear plane a-b is dependent on the soi1 strength S.

where $S = [(c' + \Delta C) + (\sigma - \mu) \tan \phi'] \ell$ . . . . (7)

$\sigma = \frac{N}{\ell}$; and $\mu = \gamma_w h_w$

The stress promoting downslope failure is dependent on the weight of the trees, soil and the wind force.

$T = (W_{trees} + W_{soil}) \sin \beta + F_{wind}$ ..... (8)

The factor of safety $FS = \frac{S}{T}$ .... (9)

A factor of safety >1.0 implies stable slope conditions; a FS of <1.0 indicates imminent failure

A large number of different stability analyses have been developed in soil and rock mechanics, most being more complex than the example cited above. The application of such analyses to forested natural slopes has usually been fraught with problems because of the heterogeneous conditions of soil, vegetation and geology. Such variability usually leads to low degrees of reliability of measured input variables such as effective soil cohesion c', effective internal friction angle ϕ', normal stress σ, and artificial cohesion due to roots ΔC. Neverthelesss stability analyses have been most useful for providing a general appreciation of the likelihood of failure on forested and deforested slopes and an understanding of which strength and slope parameters are most influential to stability. By making ΔC the dependent variable and setting FS >1.0 it is also possible to estimate values of ΔC required to impart stable soil conditions. The factor of safety is sensitive to changes in c', ΔC, soil depth h, slope angle S, and soil pore water pressure μ and relatively insensitive to changes in W_{trees}, and φ'. Removal of existing forests or establishment of a forest cover on previously forest-free land has marked influence on ΔC, W_{trees}, F_{wind} and probably to a lesser extent on μ.

Application of slope stability models to help elucidate the factors controlling landsliding on unstable deforested slopes has shown in southeastern Alaska (Swanston, 1970, 1974a,b) and in western New Zealand (O'Loughlin *et al.,* 1982) that even under intact forests some soils are only marginally stable under saturated soil conditions. The estimated reductions in ΔC are more than sufficient to reduce factors of safety to values <1.0.

IMPORTANCE OF ROOTS TO FOREST SLOPE STABILITY - EXAMPLES FROM NEW ZEALAND AND ALASKA

Mixed Beech *(Nothofagus)* Forests, North Westland, New Zealand

The steepland evergreen mixed beech forests of the northwestern South Island, New Zealand are frequently disturbed by landslides; a result of steep slopes, heavy rainfall and periodic earthquakes. When the forest cover is removed, landslide incidence is accelerated.

In a long-term study of the slope stability conditions on 8 small instrumented experimental catchments O'Loughlin et al. (1982) showed that, over a 7-year study period, 97 percent of the slope failures in terms of volumes of materials that moved downslope, occurred on slopes which had been clearfelled of their beech forest cover for more than 20 months. The catchment slopes are short (80 m to 130 m long), steep (average 36^{o}) and are underlain by firmly-compacted, weathered conglomerates of early Pleistocene age. Soils are shallow (usually less than 1 m deep) podzolised yellow-brown earths with a substantial upper horizon of permeable fibrous organic humus. A sharp boundary usually occurs between the base of-the soil profile and the underlying conglomerate. In most instances of landsliding the basal failure plane coincided with the soil-conglomerate interface.

The beech-podocarp-hardwood forest is multitiered and dominated by hard beech *(Nothofagus truncata),* red beech *N. fusca*), kamahi *(Weinmannia racemosa)* and rimu *(Dacrydium cupressinum).* Generally, the forest *trees* are shallowly rooted and most of the roots are confined to the top 50-60 cm of soil. Roots seldom penetrate into the conglomerate substratum.

During 86 months of monitoring (November 1974 to December 1881), 97 percent of the total landsliding occurred during an intense storm on 2-3 December 1979 when 136 mm of rain fell in 24 hours. At the time of the storm, 6 catchments had been clearfelled of their forest cover and in 4 of these catchments, all of which had been clearfelled 20 months or more, the storm triggered 18 landslides which deposited 1400 m^{3} of soil and rock materials in the catchment strearnbeds. No landsliding occurred on the undisturbed control catchments, nor on the catchments clearfelled only 12 and 10 months respectively before the storm, even though the landslide-causinq rainfall was remarkably uniform across the set of catchments. As the catchments varied only in the strength of their root networks and root biomass (previous surveys had shown that their topography, physical soil characteristics and geology were similar) these factors appeared to be the major cause of the different slope responses to rainfall,

Studies of root strength decline and root biomass changes after clearcutting (O'Loughlin *et al.,* 1982) showed that, on failed clearfelled slopes, the dead tree roots had lost approximately 50 percent of their original tensile strength and total root biomass in the upper 50 cm of soil had reduced from an average of 20 kg dry weight of mainly live roots per m^{3} soil to only 7 kg dry weight of mainly dead roots per m^{3} soil, at the time of the storm. Field shear strength tests indicated that these changes amounted to a decrease in ΔC of 3.3 kPa on average. The application of theoretical slope stability analyses using these data and other slope and soil data revealed that under intact forest, the soils were marginally stable (factors of safety ranged between 1.2 to 2.1) but at the time of the storm slopes clearfelled more than 30 months had factors of safety less than 1.0 under conditions of saturation,

The shallow rooting habits of the beech and associated tree species and the fact that landslides occurred where the soil was relatively deep in slope depressions, causing basal failure planes to be beneath the main rooting zone, suggested that, under intact forests, tree roots primarily provide a laterally-acting type of membrane strength which holds the soil in place. The decline of root strength and root biomass after forest removal will inevitably lead to soil failure on slopes over 30^{o}.

Conifer Forests, Southeast Alaska

The steep slopes of the outer islands of southeast Alaska (Prince of Wales, Chichagof and Baranof) are subject to shallow landsliding, particularly where the conifer forests have been removed. Considerable information on the slope stability conditions and processes has accrued from the studies on Prince of Wales Island by Bishop and Stevens (1964), Patric and Swanston (1968), Swanston (1970, 1974a, 1974b), Wu and Swanston (1980), Ziemer and Swanston (1977) and Wu *et al.* (1979).

The forest vegetation is dominated by mixed stands of Sitka spruce *(Picea sitchensis)* and western hemlock *(Tsuga heterophylla).* Compacted unweathered glacial till mantles the steep slopes up to altitudes of approximately 500 m and forms the parent material for soil development. Typically, a thick organic surface layer is underlain by shallow (<1 m), podzolised, permeable, inorganic soils which have gravelly to silt loam textures. Like the forest soils in the western New Zealand steeplands, drainage is mainly subsurface. Commonly, the principal failure plane for debris avalanches and debris avalanche-flow combinations is at the interface separating the weathered, ironstained B-horizon of the soil and the compacted, unweathered, cemented till. Excavations have indicated that trees root densely in the organic layers and roots occasionally concentrate between the bottom of the B-horizon and the top of the unweathered till with sinkers freely penetrating into the upper 15-30 cm of the compacted till. Under intact forest conditions tree roots serve a dual function in the stability of the soils; (1) the sinker roots anchor through the soil mass and into seams and fractures in the compacted till, and (2) root channels facilitate rapid lateral drainage and lessen the opportunity for soil saturation during heavy rainfall.

Studies of root strength loss after clearfelling show that marked strength decreases occur 3 to 5 years after logging. This roughly corresponds to the time lag between logging and widespread debris avalanching.

Wu *et al.* (1979) developed a model to describe the shear strength of the soil-root system on southeastern Alaskan slopes. The model indicated that roots (ΔC) contributed about 5.9 kPa to the shear strength of the soil. Furthermore, their stability analyses showed that, under autumn storm rain conditions, the soils would be generally highly susceptible to failure if the root reinforcement factor was removed (AC = 0).

CONCLUSIONS

1. The various protective functions of forest covers, including the reinforcement provided by tree roots, causes erosion rates under forests to generally be lower than rates under other vegetation covers and land uses on similar terrain with similar climate. Nevertheless, erosion rates under forests may vary over several orders of magnitude.

2. The additional strength provided by roots to the soil is generally considered to be in the form of a cohesive strength ΔC which may range in magnitude from about 1 kPa to 20 kPa. The strength of a root-permeated soil can be expressed by a modified Mohr-Coulomb equation with the form

$$S = (c' + AC) + (\sigma - \mu) \tan \phi'$$

3. Studies of the tensile strength of tree roots show that small roots sampled from living trees range in mean tensile strength from about 10 MPa to about 60 MPa. After tree felling small roots lose their strength at average rates between 300 and 500 kPa per month. Total root biomass also decreases rapidly after clearfelling.

4. Detailed field studies on recently clearfelled slopes and theoretical slope stability analyses have shown that the relative stability of steeply sloping forest soils as expressed by a factor of safety are very sensitive to changes in AC. The reduction in AC after forest removal is a prime cause of landsliding on many steep slopes.

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