THE ROLE OF VEGETATION IN THE STABILITY OF FORESTED SLOPES

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SUMMARY

Vegetation helps stabilize forested slopes by providing root strength and by modifying the saturated soil water regime. Plant roots can anchor through the soil mass into fractures in bedrock, can cross zones of weakness to more stable soil, and can provide interlocking long fibrous binders within a weak soil mass. In Mediterranean-type climates, having warm, dry summers, forest evapotranspiration can develop a substantial soil moisture deficit which can reduce both piezometric head and slope mass. Pore water pressures change seasonally in response to precipitation and are often the driving mechanism which ultimately leads to slope failure. When trees are cut, the root system begins to decay, and the soil-root fabric progressively weakens. The loss of root strength or increased soil moisture content or both after-tree removal can lower the slope safety factor sufficiently that a moderate storm and associated rise in pore water pressure can result in slope failure. After trees are removed, the frequency of landslides can increase.

KEYWORDS: Landslides; soil water; root strength; forests; slope stability.

INTRODUCTION

Landslide frequency can increase after trees are removed from forested slopes (Croft and Adams, 1950; Kawaguchi and Namba, 1956; Bishop and Stevens, 1964; Swanson and Dyrness, 1975; Wu, 1976). Vegetation can modify slope stability by mechanically reinforcing slopes through plant roots, modifying soil moisture distribution and pore water pressures, adding slope surcharge from the weight of trees, and levering and wedging soil by roots (Gray, 1970). The first two factors increase stability of slopes, the third may increase, decrease, or have no influence on stability, and the fourth decreases stability.

Soil materials are transported from natural forested slopes to stream channels chiefly by mass erosion. From soil mechanics theory, mass erosion results if the shear stress acting on the material exceeds the available shear strength of that material (Swanston, 1974). Shear stress (τ) along a basal zone of sliding can be expressed as:

$$\tau = W \sin \alpha \quad \ldots\ldots\ldots\ldots \quad (1)$$

where W is the effective weight of the soil and α is the slope of the failure surface. Shear strength (S) can be expressed as:

$$S = C + W \cos \alpha \tan \phi \quad \ldots\ldots\ldots\ldots \quad (2)$$

where C is the effective soil cohesion and ϕ is the angle of internal friction.

The increased shear stress produced by the weight of a mature forest on an unsaturated cohesionless soil is balanced by an equal increase in soil shear strength by the tree surcharge (Bishop and Stevens, 1964). For most mature forests, the weight of the soil overlying a potential failure plane far exceeds the weight of the trees and any additional surcharge contributed by the trees will have little effect on slope stability (Kawaguchi, et al., 1951; Gray, 1970; Swanston, 1970; O'Loughlin, 1974). If weight does become a problem, it is usually in cohesive soil during heavy rain when the weight of increased soil moisture increases shear stress.

The shear stress contributed by trees subjected to an 80 km/h wind is not likely to exert a strong influence on slope stability (Wu, 1976).

ROOT REINFORCEMENT

Plant roots can help stabilize slopes by anchoring a weak soil mass to fractures in bedrock, by crossing zones of weakness to more stable soil, and by providing long fibrous binders within a weak soil mass. In deep soil, anchoring to bedrock becomes negligible and the other two conditions predominate. The reinforcement effect of plant roots intermixed with soil resembles soil cohesion (Endo and Tsuruta, 1969). The role of plant roots in the calculation of soil strength can be expressed as:

$$S = (C + r) + W \cos a \tan \phi \quad \ldots\ldots\ldots\ldots \quad (3)$$

where r is the relative root reinforcement or apparent cohesion due to roots.

The ability of roots to strengthen a soil mass is well known. The total force required to break a soil mass reinforced by linden (Tilia cordata) roots in a study in the U.S.S.R. was calculated to be about 137 tons. Of this force, 130 tons were required to break the roots and 7 tons to tear the sandy loam soil mass from a bank of the Moscow River. Breaking the linden roots took 95% 0f the total force, although the total cross-sectional area of all the roots comprised less than 0.5 percent of the wall area of the bank collapse (Turmanina, 1963).

The root network accounted for 71% of the shear strength at saturation Of glacial till soils on 35° slopes in British Columbia, Canada (O'Loughlin, 1972). An imposed load may be 70% greater before soil rupture in soils with a root network than in soils without roots (Bjorkhem, et al., 1975).

The strength of forest soil is difficult to measure directly. Evaluating the effect of roots on soil strength increases that difficulty. The weight of small alder (Alnus glutinosa) roots in a study in Japan explained 53% of the variation in measured soil strength (Endo and Tsuruta, 1969). The contribution to soil strength by roots of a-mixed old-growth forest of Douglas-fir (Pseudotsuga menziesii), western redcedar (Thuja plicata), and western hemlock (Tsuga heterophylla) growing on glacial till subsoils was studied in British Columbia (O'Loughlin, 1972). The weight of roots in the soil sample was the most significant of-seven variables tested, accounting for 56% of the variation in-measured soil strength. The strength of the soil-root fabric under a mature shore pine (Pinus contorta) forest growing on coastal sands was measured in northern California (Ziemer, 1981). The dry weight of the live roots less than 17 mm in diameter was the best variable predicting soil shear strength among 32 soil and vegetative variables tested.

Individual roots become stronger as they become larger. The logarithm of root shear strength is closely related to that of the root diameter (Ziemer and Swanston, 1977). The strenqth of roots also varies between species. Small Dougias-fir roots were, for example, about 10% stronger than western redcedar roots (O'Loughlin,, 1972). Poplar (Populus deltoides) roots were strongest, followed by birch (Betula pendula), oak (Quercus robur), linden (Tilia cordata), and spruce (Picea abies) (Turmanina, 1965). Poplar roots were about 40% stronqer than spruce roots. Tree roots were estimated to be one and one-half to three times stronger than the roots of grassy plants of the same diameter. The roots of brush, such as Ceanothus velutinus, were about twice as strong as those of conifer trees, such as Pinus ponderosa (Ziemer, 1981).

Slope stability problems will likely develop after timber cutting on steep slopes where most of the soil strength is provided by the binding action of roots. As roots decay after clearcutting, the value for their relative reinforcement (r in Eq. 3) declines (Fig. 1A). In the hypothetical example illustrated, about 50% of the original root reinforcement is lost within 2 years after clearcutting and 90% is gone within 9 years. If the tree sprouts after cutting, root decay and regrowth will be more complicated than the pattern described.

The rate of strength loss varies according to species, root size, and the activity of decay organisms. Small roots will decay most rapidly, while large decay-resistant roots may remain in the soil for decades. For

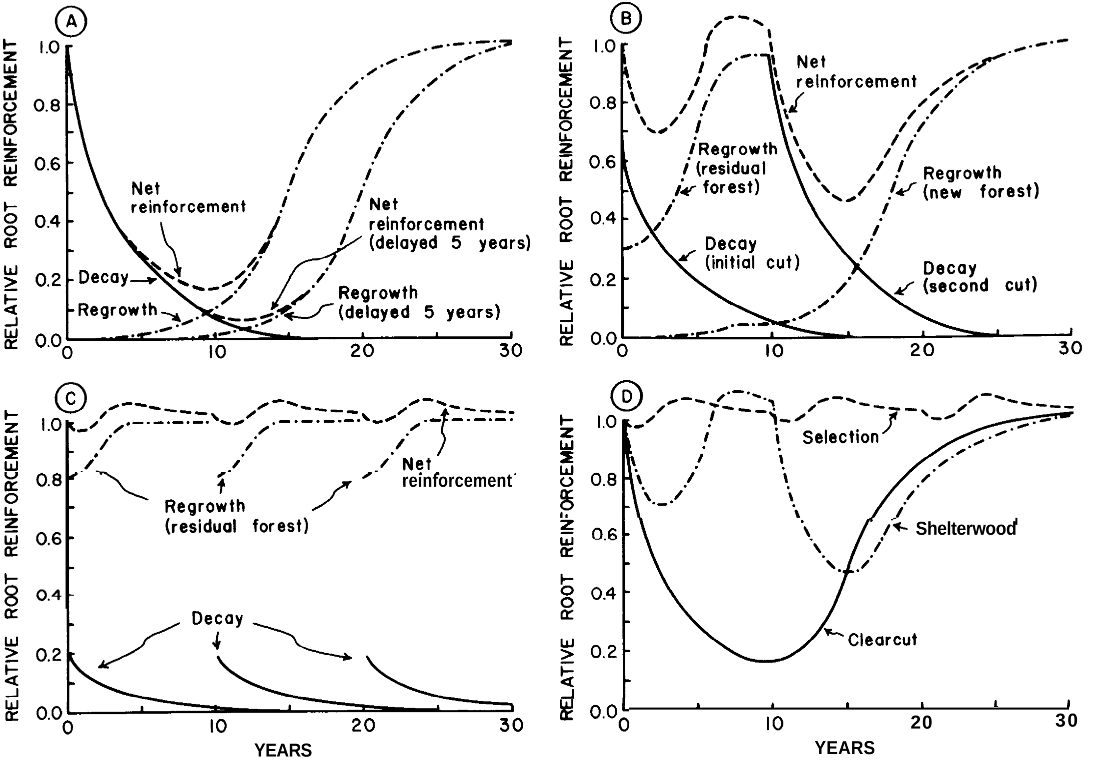

Figure 1. Conceptual model. of changes in relative root reinforcement after harvest due to root decay and regrowth of residual and new roots for (A) clearcut, (B) shelterwood, (C) selection harvests. Net reinforcement is the sum of reinforcement by decaying, residual, and new roots. These three silvicultural methods are compared (D).

example, intact roots greater than 15 cm in diameter were found on western redcedar trees which had been cut 50 years earlier. However, redcedar roots 1 cm in diameter had lost about 50% of their tensile strength within 5 years after cutting. Douglas-fir roots decay more rapidly than redcedar roots, and the rate of decay is related to geographic location. The strength of l-cm Douglas-fir roots had decreased by about 50% within 3 years after cutting in coastal British Columbia (O'Loughlin, 1972). About 50% of the Douglas-fir roots 1 cm in diameter had decayed within 1 l/2 years in the Rocky Mountains and the same proportion was gone within 1 year in coastal Oregon (Burroughs and Thomas, 1977). About 90% of the Rocky Mountain roots had decayed in 12 years, whereas 90% of the Oregon roots were gone in less than 5 years. Roots of Pinus radiata decay rapidly in New Zealand; nearly all roots less than 3 cm in diameter had completely decayed within about 3 years after cutting. And many roots larger than 5 cm in diameter consisted of only empty bark sheaths (O'Loughlin and Watson, 1979).

As vegetation reoccupies the harvested area, new roots begin to progressively reinforce the soil. It may take about 15 years until the new forest provides 50% of the root reinforcement supplied by the original forest before cutting and 26 years until the soil in the harvested area returns to the strength of that in the uncut forest (Fig. 1A). The actual rate of soil strength recovery can vary, and depends on many more environmental variables than does the rate of strength loss through decay. In severe sites, the recovery of root reinforcement can be lengthy. In logged mixed conifer forests in northwestern California, calculated root reinforcement in areas logged 25 years earlier was only about 40% of that in adjacent uncut areas (Ziemer, 1981).

The net reinforcement of the soil by roots is the sum of reinforcement by residual decaying roots of the cut trees and by new roots of the regenerating forest. In a promptly regenerated forest, net reinforcement reaches a minimum about 9 years after harvest, when it is about 18% of that in the uncut forest (Fig. 1A). It becomes greater after 9 years, as the roots of the new forest continue to develop in the cut areas.

If regeneration is delayed by 5 years, decay of the residual root system of the cut forest will continue for 5 years before the new root system begins to add strength (Fig. 1A). The net soil reinforcement will then reach a minimum that is substantially lower than in areas where regeneration is prompt. In the illustrated example, the minimum net reinforcement with a 5-year delay in revegetation occurs 12 years after logging and is only about 7% of that in the uncut forest.

If a shelterwood system is appropriate and 70% of the original stand is cut, followed by removal of the remaining trees 10 years later, several additional strength relationships must be considered (Fig. 1B). The dead roots from the 70% cut stand are expected to decay at a rate proportional to that in a clearcut area. The live root systems from the 30% remaining trees may begin to expand to occupy the soil previously occupied by the now dead root systems of the uncut trees. In the example (Fig. lB), root expansion is assumed to be accomplished within 8 years. Growing space would be available for the establishment of seedlings immediately after the initial cutting, when adequate moisture and nutrients should be available. However, as the root systems and foliage of the residual trees expand, competition will increase and growth of the regeneration would begin to stagnate. When the residual mature trees are cut 10 years after the first cut, their root systems will, in turn, begin to decay. The seedlings will now be released and resume nomal growth.

Net root reinforcement is the sum of reinforcement by (1) root decay from the initial cut, (2) root expansion and subsequent root decay of the residual trees, and (3) root expansion by the new seedlings. If the root decay rate of cut trees is slower than the root growth rate of the residual trees, net root reinforcement in the cut area might be greater, for a time, than that in the uncut forest. In the example (Fig. lB), net reinforcement drops to 70% of that in the uncut forest 2 years after the first cut, then rises to 10% greater net reinforcement than that in the uncut forest about 7 years after cutting. Ten years after the first cut, the residual forest is cut and minimum net reinforcement occurs about 15 years later, when reinforcement is about 50% of that in the uncut forest. By comparison, minimum net reinforcement in the clearcut example (Fig. 1A) reached about 20% of the uncut forest 9 years after cutting.

If a selection system is appropriate in which 20% of the trees are cut every 10 years, a root reinforcement pattern similar to that illustrated (Fig. 1C) might be anticipated. The dead roots from each cutting will decay at rates proportional to those in the previous examples. The live roots from the remaining 80% of the stand will reoccupy the soil relatively rapidly because the average spacing of the live trees would be affected little by such a light cutting. If the rate of root decay exceeds the rate of root recovery, net reinforcement will decrease. Conversely, if the recovery rate exceeds the decay rate, net reinforcement will increase. In the example, net reinforcement decreases 3% for the first 2 years after cutting, then increases to about 7% above that of the uncut area, then slowly decreases as root decay progresses. The pattern repeats following subsequent cuttings.

Engineering stability analyses have been applied to slopes with and without roots (Wu, et al., 1979). A safety factor -- defined as the ratio of the available shear strength to the shear stress -- provides an index of the relative stability of slopes. A slope with a safety factor of less than 1.0 cannot remain stable and must fail.

Consider a case where all factors in Eq. 3 are held constant except for r, the relative root reinforcement. Assume the safety factor equals 1.0 if the relative root reinforcement falls to 15% of that in the uncut forest. If prompt regeneration follows harvest the net reinforcement (Fig. 1D) always remains above 0.18 and the slope would not fail. If, however, regeneration is delayed 5 years (Fig. lA), the net reinforcement would fall below 0.15 from 8 years until 16 years after harvest, and the slope would fail 8 years after cutting.

If the safety factor were 1.0 when relative root reinforcement dropped to 60% of that in the uncut forest, promptly regenerated clearcut areas would be unstable from 2 years until 16 years after cutting, delayed regeneration clearcut areas from 2 years until 21 years after cutting, and shelterwood harvested areas from 12 years until 17 years after cutting. Only the selection harvested areas would not experience slope failures related to loss of root reinforcement.

In practice, a number of unknown factors must be evaluated to allow construction of the appropriate curves illustrated in Fig. 1. They include the influence of live roots of differing species, size, and distribution on soil strength; the rate of strength loss following timber cutting; the rate of strength gain as the new forest is regenerated; and the rate of strength gain as existing root systems expand following partial cutting. Other important slope stability considerations may overshadow the influence of root reinforcement.

SOIL WATER

The occurrence of a major storm and mass erosion is closely correlated. Excess soil water is generally accepted to be the principal factor causing slope failures. Pore water pressure produced by the head of water in a saturated soil can reduce shear strength. Rising pore water pressures can reduce the effective weiqht of the soil mass by producing an uplift force. The modified soil strength equation (Eq. 3) considering pore water pressure (ρ) becomes:

$$s = (C + r) + (W \cos \alpha - \rho) \tan \phi \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

Active pore water pressures can reduce soil shear strength by as much as 60% (Swanston, 1969). Increased soil water may also decrease cohesion (C) **of** some soils through leaching and eluviation.

The interaction between seasonal pore water pressure and the loss and recovery of root reinforcement in the context of changes in safety factor can be illustrated (Fig. 2). The slope would not fail because of either

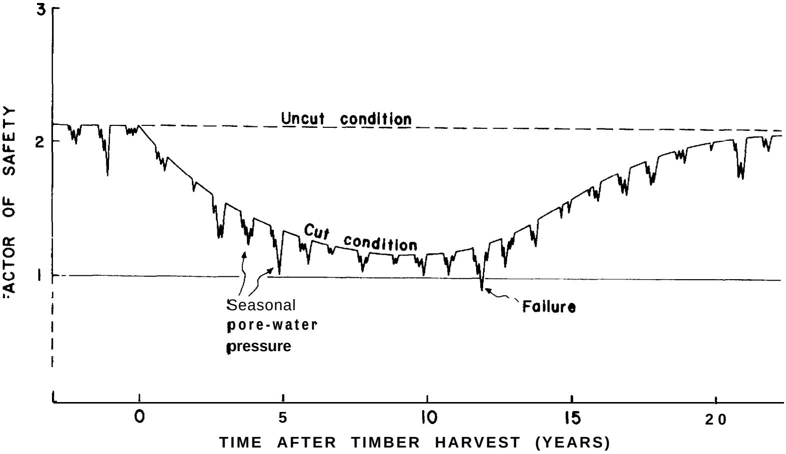

Figure 2. Interaction between seasonal pore water pressure and the loss and recovery of root reinforcement and the effect on safety factor, by years after timber harvesting.

changes in seasonal pore water pressure or loss of root reinforcement alone. When both factors are considered together, the loss of root strength following timber harvest lowers the safety factor to a level where a moderate storm and associated rise in pore water pressure can result in slope failure -- even though root reinforcement is past the minimum and is increasing. Had the same storm occurred a few years later, no slope failures would have resulted from this timber harvest.

Seepage forces resulting from frictional drag of water flowing downslope through the soil may add to the tangential component of shear stress (Swanston, 1974). The safety factor for a saturated cohesionless soil mantle with seepage parallel to the slope, but without a network of roots, is about half that for a similar soil mantle in an unsaturated condition with no downslope seepage (O'Loughlin, 1974).

Forests can remove considerable quantities of soil moisture by evapotranspiration. Resultant negative pore water pressure or capillary tension in unsaturated soil increases intergranular pressure and thereby increases soil strength. After a summer of evapotranspiration a dramatic pattern of residual soil moisture (Fig. 3A,B) was produced by an isolated mature sugar pine (Pinus lambertiana) in the California Sierra Nevada, USA (Ziemer, 1978). Most soil moisture depletion occurred at a depth between 2.4 and 4.0 m beneath the tree and extended to a distance of about 6 m from the tree. Beyond about 12 m from the tree, soil moisture content remained relatively uniform with depth. Surface evaporation was evident within the surface 0.6 m of soil.

After the isolated tree was cut, soil moisture depletion from the bare plot was measured for an additional year (Fig. 3C). The zone of active depletion 2.4 to 4.0 m under the tree disappeared and the soil moisture content remained rather uniform below a depth of 0.6 m. The eccentric pattern of low soil moisture adjacent to the tree was no longer evident after cutting.

There was a linear relationship between distance from the isolated tree and relative soil moisture content at the end of summer (Fig. 4). Relative soil moisture was obtained by subtracting the measured total soil moisture content within a radius of 12 m from the isolated tree from the total soil moisture in the area 12 to 18 m from the tree and then adjusting to equalize soil moisture throughout the 18-m radius plot after the isolated tree was cut. As distance from the tree increases, the relative soil moisture content decreases, that is, the soil moisture "savings" obtained by removing the tree decreased as distance from the tree increased. During a dry year the slope of the curve was greater than that during a wet year, that is, the soil moisture content closer to the tree was lower in a dry year than in a wet year relative to the soil moisture content in the area outside the influence of the tree. The explained variance, r^2, for each curve is greater than 0.99. The regression suggests that the influence of the tree extended to a distance of 11.6 to 12.8 m from the base of the tree. For the two years of measurement the isolated tree depleted 63.6 and 73.8 m^3 more soil water than the area beyond 12 m from the tree.

This isolated tree study demonstrates the inadequacy of understanding soil-vegetation-water interrelationships. Root distribution and biomass studies consistently show that roots are concentrated in the surface meter of soil. Many of these roots have a structural function, others have an

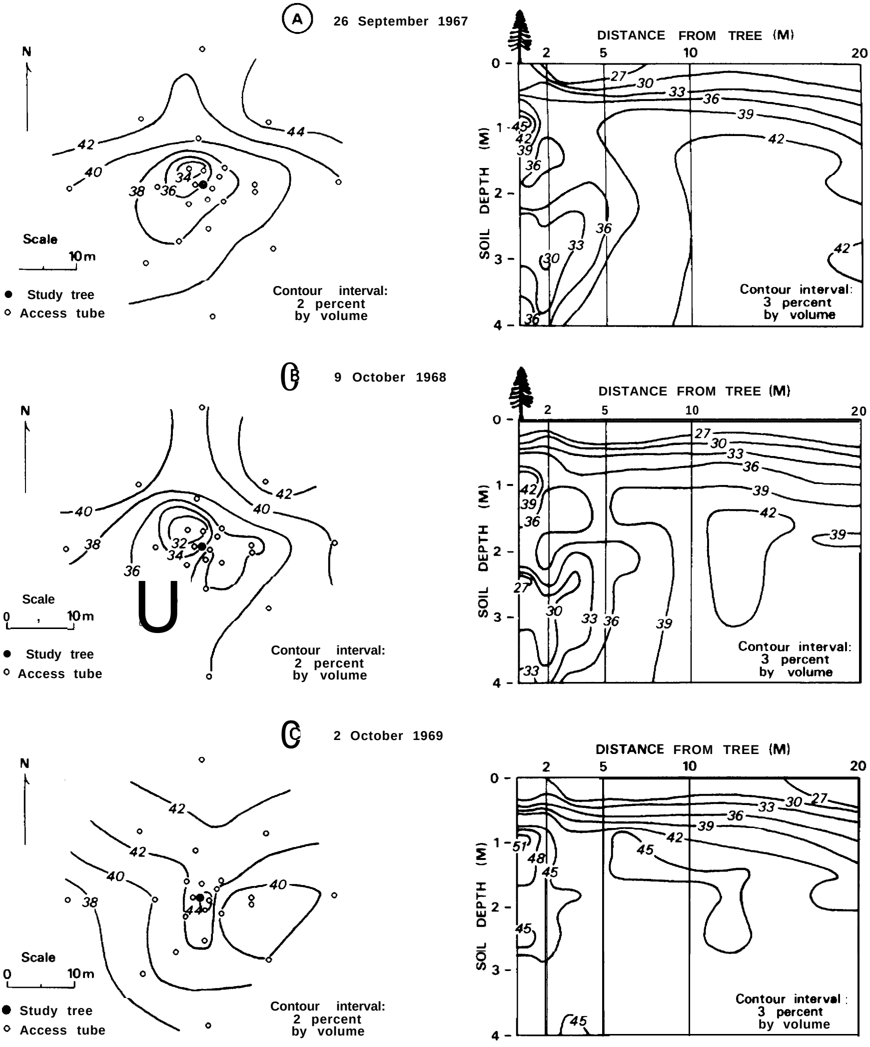

Figure 3. Isopleths of average soil moisture within the surface 4.6 m of soil (left) and average soil moisture by depth and distance from an isolated tree (right) at the end of three summer depletion seasons, (A) (B), and after the tree was cut (C) (Ziemer, 1978).

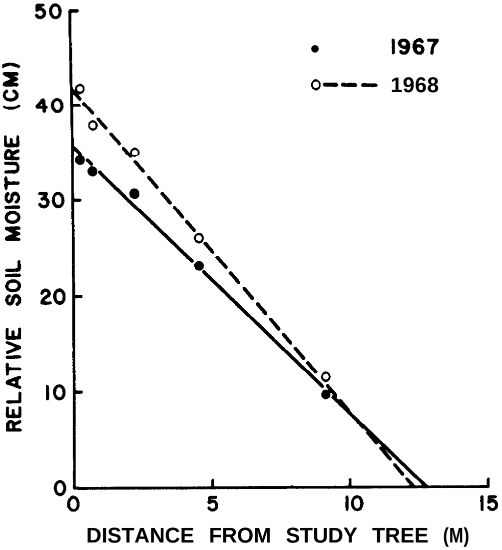

Figure 4. Distance from the isolated tree and relative soil moisture at the end of two summer depletion seasons (Ziemer, 1978).

absorption function. The most dynamic depletion of soil moisture by the isolated study tree occurred at a depth of 2.4 to 4.0 m; far deeper than the principal root biomass. Better understanding is needed of the interrelationships between root numbers, biomass, size, and distribution and soil moisture depletion. Only limited information is available concerning how the pattern of soil moisture depletion varies by tree size and species.

The role of forest transpiration in preventing landslides is unclear. Once rainfall satisfies the soil moisture deficit and the soil becomes saturated, tension-induced intergranular pressures disappear. Gray (1970) argues that forested slopes can tolerate a larger storm before a critical saturated condition develops. The importance of evapotranspiration in slope stability considerations is related to the climate and storm patterns. Using the isolated tree study as an example and assuming a forest with trees about 5 m apart, the forest would deplete about 30 cm more soil moisture than an equivalent clearcut area. In an arid environment receiving 60 cm of annual precipitation, half of the precipitation would be required to simply satisfy the soil moisture differences between the forested and cut area. In a region of high rainfall where precipitation greatly exceeds evapotranspiration, however, the critical time during which forested slopes are drier than cut slopes may be insignificantly short.

As a new forest regenerates, soil moisture differences due to logging will quickly lessen. In general, soil moisture differences between cut and forested areas are greatest the first year after cutting and recovery usually follows a negative exponential rate. In humid climates, differences in soil moisture depletion between cut and uncut forests are often negligible within 3 to 5 years after cutting (Hallin, 1967; Ziemer, 1964).

CONCLUSIONS

Vegetation helps stabilize steep forested slopes chiefly by reinforcing the soil through tree roots and by changing the soil water regime. Most slope failures occur during major storms when the soil is saturated. Pore water pressures within the soil change seasonally in response to precipitation. Soil moisture in areas where the forest has been recently cut is usually greater than in uncut areas. Also following cutting, the tree root system begins to decay, and the soil-root fabric progressively weakens. Eventually soil moisture depletion and the strength of the soil-root fabric will return to that of uncut forests as roots from the new forest reoccupy the soil.

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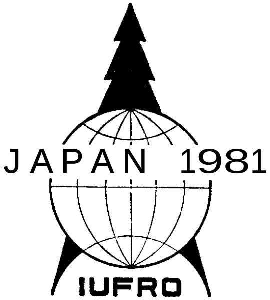

PROCEEDINGS-REFERATE-EXPOSES

DIVISION 1