Effect of Tree Roots on Shallow-Seated Landslides[1]

Kazutoki Abe and Robert R. Ziemer[2]

Abstract: Forest vegetation, especially tree roots, helps stabilize hillslopes by reinforcing soil shear strength. To evaluate the effect of tree roots on slope stability, information about the amount of roots and their strength should be known. A simulation model for the root distribution of _Cryptomeria japonica_ was proposed where the number of roots in each 0.5.cm diameter class can be calculated at arbitrary depths. The pull-out strength of roots was used to analyze the stability of four different types of forested slopes. Root reinforcement is important on slopes where roots can extend into joints and fractures in bedrock or into a weathered transitional layer between the soil and bedrock. Root reinforcement of soil increases quickly after afforestation for about the first 20 years, then remains about constant thereafter.

Sediment disasters by debris flows, mud flows, and landslides occur almost every year during the rainy July to October Typhoon season in Japan. In July 1982, a heavy rainfall of 488 mm in a day, with a maximum intensity of 127.5 mm per hour, caused 4300 debris flows in Nagasaki prefecture, Kyushu Island. This storm destroyed 2200 houses and killed 299 people. During July 1983, intensive rainfall initiated many debris flows and 199 people were killed in Shimane prefecture, along Japan Sea on western Honshu Island.

[1]Presented at the Subject Group S1.04 Technical Session on Geomorphic Hazards in Managed Forests, XIX World Congress, International Union of Forestry Research Organizations, August 5-11, 1990, Montreal, Canada.

[2]Research Scientist, Forestry and Forest Products Research Institute, Tsukuba, Ibaraki, 305 Japan; and Principal Research Hydrologist, Pacific Southwest Research Station, Forest Service, United States Department of Agriculture, Arcata, CA. U.S.A. 95521

The cause of so much destruction and death might be unprecedented intensive rainfall. In addition, expansion of cities, resorts, and roads onto hillslopes and mountain areas has been also thought to be a primary cause. In response, national and local governments have adopted a program of aggressively constructing many erosion control works at great expense. But, even so, it is impossible for such construction to protect all mountain hillslopes from debris flows.

An important cause of increased frequency of debris flows is the removal of forests to accommodate urbanization and road construction in mountainous areas. In monsoon areas, like Japan, where steep mountains are covered with forests, mass wasting is the prevailing type of erosion. There is a fragile balance of stability on such steep hillslopes where the forest cover interacts with soil moisture, soil strength, geological condition, historical rainfall, and other factors to stabilize the regolith on a slope. From a viewpoint of soil mechanics, on many hillslopes the factor of safety of a slope (FS) approaches 1.0 during a rainfall event that occurs once every several years. Under conditions of such delicate balance, removal of the trees by logging may result in a reduction in soil strength sufficient to cause landslides.

The influence of forests on slope stability has been one of the most important subjects of study--especially, the role of tree roots on reinforcing soil shear strength. To evaluate the mechanical effect of roots in strengthening soil, however, the quantity and distribution of roots in subsurface soil layers must be quantified.

In this paper, a simulation model for the distribution and stabilizing effect of roots is investigated using an infinite slope stability analysis model.

ROOT DISTRIBUTION

Field Sampling

A stability analysis of forest slopes can be made by adding the soil shear strength and a reinforcing component provided by the strength of roots (Endo and Tsuruta 1969; Gray and Ohashi 1983). This reinforcing strength is generally shown by equation [1] (Waldron 1977; Wu 1976).

$$Cr = \sum tr_i \ (\sin \theta + \cos \theta * \tan \alpha), \quad [1]$$

where Cr : Reinforcing strength provided by roots
tr_i: Root tensile stress generated in root i at the landslide shear plane
θ : Slope gradient
α : Angle of internal friction of the soil.

The tensile stress for various species has been reported to be a function of root diameter (Ziemer and Swanston 1977; Burroughs and Thomas 1977; O'Loughlin and Ziemer 1982; Abe and Iwamoto 1986). Thus, to model the influence of trees on slope stability, the number and diameter of roots at specific depths must be obtained.

To develop the root model and to understand the influence of different environmental conditions on root distribution, roots of about 16 trees of Cryptomeria japonica, the most popular species planted in Japan, were sampled in five different fields. The sampling was done as follows:

1. The study tree was cut down and its entire root system was carefully excavated.
2. All roots were cut along planes at 10-cm depth intervals below the ground and parallel to the surface (fig. 1).

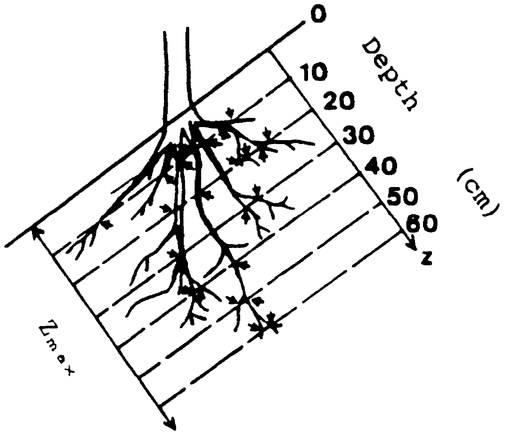

Fig. 1. Method of sampling for root distribution. All roots were cut along planes at 10-cm intervals below the ground surface and diameters of both ends and the lengths of cut roots were measured in each 10-cm thick layer. Z_{max} is a maximum root penetrating depth, ↗ point where diameter is measured.

3. The diameter at both ends and the length of cut roots larger than 0.5 mm in diameter were measured in each 10-cm-thick layer.
4. The number, volume, and total length of roots were then calculated for each layer.

Characteristics of the Root Distribution

Root volume in 10-cm-thick layers (V(z))

About 85 to 90 percent of the total root volume of a tree was found in the upper half of the rooting depth. Root volume decreases exponentially with depth.

To investigate the pattern of root distribution by depth, V(z), the accumulated root volume ratio, F(z), was calculated (eq. [2]).

$$F(z) = \sum_{z=0}^{z} V(z) / Vr * 100 \quad [2]$$

$$Vr = \sum_{z=0}^{z_{max}} V(z)$$

where, Vr: entire root volume of one tree
$\sum V(z)$: accumulated root volume from the ground surface to the depth "z"
Z_{max}: maximum depth of root growth.

The relationship between F(z) and depth "z" could be approximated by the probability function of the Weibull-distribution (fig. 2). The solid line in figure 2 is the Weibull probability function, f(z), calculated from equation [3] (Makabe 1966).

$$f(z) = m*(z-1)^{m-1} / \alpha * EXP[-(z-\gamma)^{m}/\alpha] \quad [3]$$

There are three parameters that must be estimated: α, γ, and m. "γ" is a location parameter that determines a beginning point of the curve. In the root distribution case, "γ" is 0, because the ground surface (z=0) is the initial point. "m" is a shape parameter. It can be read off the Weibull-graph as a gradient of the line, and also calculated by equation [4] with "Z_{max}" and "X0".

$$m = 2.0/(\log Z_{max} - \log X0) \quad [4]$$

X0 is an intersecting point of Fn(z)=0 and the solid line (fig. 2).

From our data, it appeared that if Z_{max} is deeper, the gradient of "m" may be steeper (fig. 2). A regression between Z_{max} and X0 resulted in equation [5].

$$X0 = 0.3522*Z_{max} - 10.799 \quad [5]$$

Substituting equation [5] into equation [4], "m" can be estimated by equation [6].

$$m = 2.0/\{\log Z_{max} - \log(0.3522 * Z_{max} - 10.799)\} \qquad [6]$$

"α" is a scale parameter and can be defined as a dependent variable of Z_{max} by equation [7].

$$\alpha = X0^{m} = (0.3522 * Z_{max} - 10.799)^{m} \qquad [7]$$

Accordingly, the root volume in each 10-cm-thick layer V(z) is obtained by equation [8].

$$V(z) = \{\int_{z}^{z+10} f(z)\,dz\} * Vr \qquad [8]$$

Root Number

In general, the most roots are found 20 to 50 cm deep. The number of roots then gradually decreases with depth. Sixty to 85 percent of the routs are smaller than 0.5 cm in diameter.

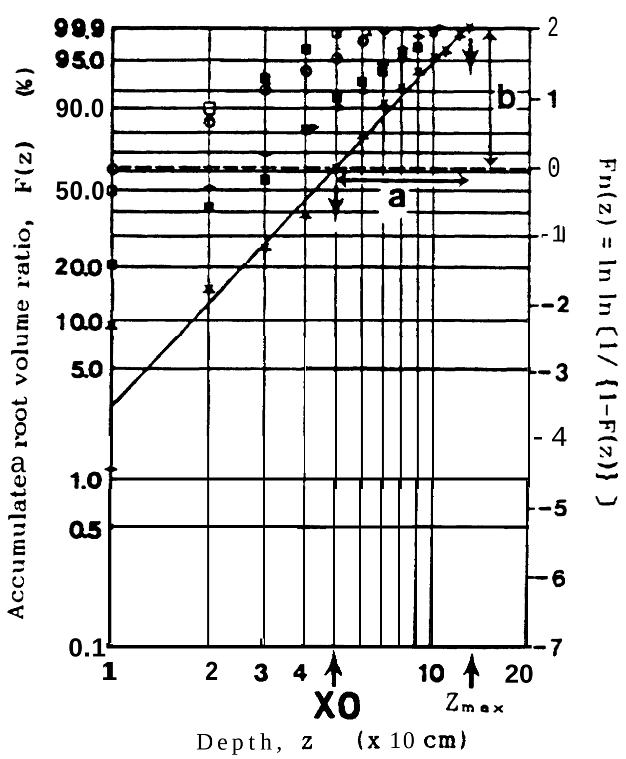

Fig. 2. Relationship between depth (z) and accumulated root volume ratio (F(z)) in the Weibull graph. Weibull coefficient "m" is the gradient of a regression line, obtained by "b/a", "a", and "b".
■ :Tree 1 in Minakami,
○ :Tree 3 in Minakami,
□ :Tree 5 in Komatubara,
◆ :Tree 9 in Misugi,
★ :Tree 10 in Ksukuba.

Table l--Root number ratios (Y(i)) in four field sites

Site	Top zone	Middle zone	Bottom zone
Minakami	$7.91\ i^{-1.47}$	$4.91\ i^{-2.11}$	$5.95\ i^{-1.91}$
Komatsubara	$6.01\ i^{-1.76}$	$2.97\ i^{-2.34}$	$0.62\ i^{-3.66}$
Misugi	$3.29\ i^{-2.03}$	$1.98\ i^{-2.65}$	$1.13\ i^{-3.20}$
Tsukuba	$6.43\ i^{-1.53}$	$4.73\ i^{-1.86}$	$6.04\ i^{-1.81}$

To compare root distribution between each field site, the total rooting depth was divided into three zones: top, middle, and bottom. In the top zone, there are many lateral roots that vary widely in diameter. In the bottom zone, most roots grow vertically and there are few roots greater than 1.0 cm in diameter. In the middle zone, many roots develop vertically and diagonally, but there are few lateral roots. Even though the depth zones do not coincide with soil horizons and the thickness of the zones varies between sites, each respective depth zone has similar root distributions. Root distribution was estimated as the root number ratio, obtained by regression between the proportion of the number of roots in each 0.5-cm diameter class, Y(i), and the diameter class, i (table 1).

Mean volume of a root in each diameter class (Vm(i))

There was no difference in the mean volume of a root in each diameter class, Vm(i), among the three depth zones. Consequently, regressions were calculated for each field site (table 2).

Maximum root depth (Z_{max})

It is important to note the depth of root penetration when estimating the effect of roots in stabilizing slopes. The more roots that penetrate a potential shear plane, the greater is the chance that vegetation will increase slope stability. Some of the factors restricting Z_{max} are existence of bedrock, soil porosity, soil moisture, soil structure, soil consistency, and soil fertility. Morimoto (1982) and Ikemoto and Takeshita (1987) reported that Z_{max} could be estimated as the depth where the soil hardness, using a cone penetrometer, is 27 mm, or the N value (number of falls per 10-cm penetration) in the sounding test is 5. However, much more data on this subject is needed.

Table 2- Mean root volume, Vm(i), of the four field sites

Site	Mean root volume Vm(i)	Coefficient of determination	Sample number
Minakami	$7.62\ i^{2.12}$	0.96	51
Komatsubara	$7.04\ i^{2.32}$	0.94	24
Misugi	$6.07\ i^{2.29}$	0.96	59
Tsukuba	$7.81\ i^{2.14}$	0.97	53

MODEL

Figure 3 is a flow chart of the root distribution simulation model. The input factors are field measurements of height (H), diameter (DBH), and Z_{max} of the object tree. The model output is the number of roots in each 10-cm layer and each root diameter class. Yt(i), Ym(i), Yb(i), and Vm(i) are used in the model as variables, so they must be measured for each region having different environmental conditions.

The model was composed as follows:

(1) Input DBH, H, and Z_{max}.

(2) Calculate whole root weight, Wr, in g.

Wr can be calculated by an allometric formula, equation [9] (Karizumi 1977).

$$\log Wr = 0.8216*\log(DBH^2*H)-0.3085 \qquad [9]$$

(number of trees = 79; corr. coef. = 0.99).

(3) Calculate whole root volume, Vr, in cm^3.

$$Vr = Wr/Gs \qquad [10]$$

(4) Calculate root volume in each 10-cm layer, V(z).

V(z) can be calculated by equation [8], where f(z) is obtained from equation [3] by substituting Z_{max} into equations

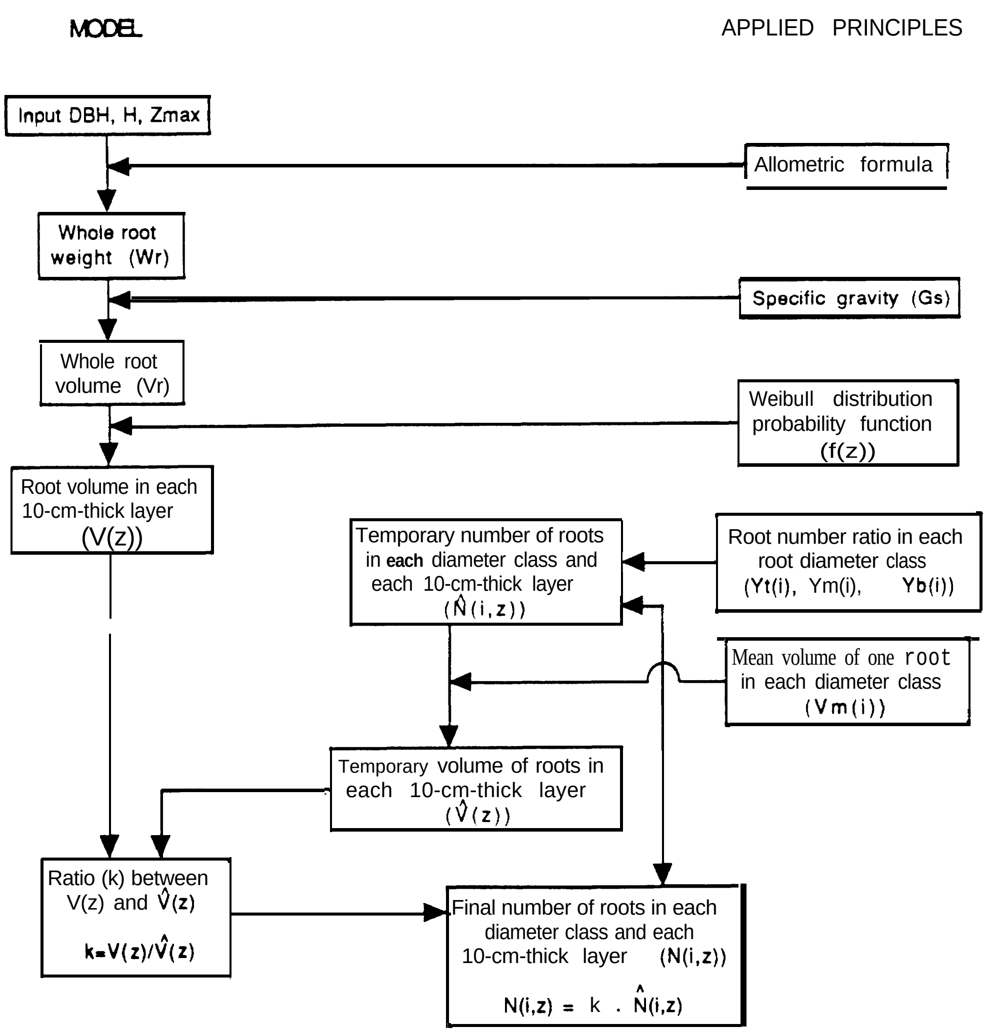

Fig. 3. Flow chart of the root distribution simulation model.

[6] and [7].

(5) Set up the temporary root number in each diameter class and each 10-cm-thick soil layer, $\hat{N}(i,z)$.
The maximum root diameter (i_{max}) should be determined, and $\hat{N}(i,z)$ in each diameter class (0.5-cm intervals in this paper) up to i_{max} in each zone is set up in proportion to the root number ratios Yt(i), Ym(i), and Yb(i). All 10-cm layers that belong to one zone have the same initial value of $\hat{N}(i,z)$.

(6) Calculate temporary root volume in 10-cm layer, V(z).

$$\hat{V}(z) = S\{\hat{N}(i,z) * Vm(i)\} \quad [11]$$

(7) Calculate the ratio between V(z) and V(z), k.

$$k = V(z)/\hat{V}(z) \quad [12]$$

(8) Determine the number of roots in each root diameter class and each 10-cm layer, N(i,z).

$$N(i,z) = k * \hat{N}(i,z) \quad [13]$$

Even fine roots have a strong influence in preventing landslides (Burroughs and Thomas 1977; Abe and Iwamoto 1986). Thus, the model must be able to estimate the number of such fine roots. Also, the landslide shear plane has a tendency to occur near the limit of rooting depth where there are few roots on the shear plane (Abe and others 1985). This model can estimate the number of roots in each diameter class in the deeper layers. Furthermore, it is important that root distribution under different conditions can be expressed by one model.

ROOT STRENGTH

The contribution of roots to increasing soil shear strength has been mainly estimated by four kinds of experiments: tensile test, pull-out test, <u>in-situ</u> shear test, and laboratory shear test.

Many tensile strength tests of roots have been performed. A segment of a root specimen is usually loaded in tension and the maximum value at failure is measured (O'Loughlin 1974; Burroughs and Thomas 1977; Ziemer and Swanston 1977; Nakane and others 1983; Abe and others 1986). From these tests, the tensile strength of live roots and its decline after the roots die have been measured for many of the important tree species.

The pull-out test measures the maximum resistance when a root is pulled out of the soil (fig. 4). Tsukamoto (1987) and Abe and Iwamoto (1986) reported pull-out strength could be predicted by root diameter and was independent of slope conditions and root type, such as lateral, tap, or sinker root. Pull-out strength was composed of tangential friction between soil and roots, and was influenced by root bending, branching, root hairs, and the tensile strength at breakages.

Data from <u>in-situ</u> shear tests (Endo and Tsuruta 1969; Ziemer 1981; O'Loughlin and others 1982; Abe and Iwamoto 1987) are important for evaluating the appropriateness of theoretical concepts. But, it is difficult to perform such tests on steep rocky hillslopes.

Laboratory shear tests have been performed to reveal the mechanism of the root reinforcing effect (Waldron 1977; Wu 1976; Waldron and Dakessian 1981; Gray and Ohashi 1983; Shewbridge 1985). We conducted direct shear tests using sand that contained roots and modified the reinforcement model proposed by Waldron (1977) and Wu (1976).

$$\Delta S=[\{(1+B^2b^2e^{-2bx})^{1/2}-1\} *E*a_r](\cos\theta \tan\phi + \sin 8) + E*I*b^3*B \quad [14]$$

where,
- E: Young modulus
- a_r: cross sectional area of the roots
- B: one half of a shear displacement
- I: modulus of section
- θ: root angle at the origin
- φ: internal friction angle of sand.

From observations of shallow landslide sites, there were only a few fine roots on the bottom shear planes (Abe and others 1985). And, for fallen trees, most of the roots were broken near their tips where the

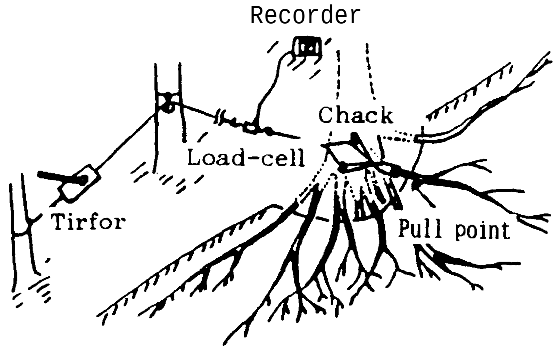

Fig. 4. Diagram of the root pull-out test.

diameter was less than 1 to 2 cm. This suggests that most roots were pulled out. Burroughs and Thomas (1977) reported that the width of the shear zone ranged from 7 to 25 cm and the majority of tree roots had failed in tension. Studies of slope failure in soil over glacial till in Alaska indicated that the expected width of the soil shear zone ranged from 7.5 to 30 cm, and that the expected mode of root failure is in tension (Wu, 1976). We assume that the roots crossing a shear zone generate tensile strength, are elongated in tension, and break at the tips, not in the shear zone. Thus, the mode of root failure is similar to that during a pull-out test. Abe and Iwamoto (1986) conducted tests on *Cryptomeria japonica* and measured both the pull-out resistance and the tensile strength at the point of breakage (fig. 4). The results were quite different. The pull-out resistance includes the tensile strength at breakage, plus the tangential friction between roots and soil and the mechanical strength caused by pulling bent parts of the root through the soil. Consequently, it is not appropriate to use the maximum tensile strength to represent root reinforcing strength. Although the relationship between pull-out resistance and the theoretical reinforced soil strength is not fully understood, we postulate that both are about equal.

Stability of a forested slope was simulated using the pull-out resistance (PO), obtained by a regression analysis (eq. [15]) of the root diameter (D) at pull points (fig. 4).

$$PO = 126.39D^{1.03}, \quad \text{(kgf)} \qquad [15]$$

SLOPE STABILITY ANALYSIS

Slope classification

Geology, soil mechanics, and soil moisture affect slope stability and also affect the distribution of tree roots, especially tap roots. Tsukamoto (1987) classified slopes into four types.

A type--Regolith is thin and underlain by bedrock with few cracks and joints. The roots cannot penetrate the bedrock and are densely distributed in the regolith. Tap roots are not important. Soil water cannot permeate the bedrock, and pore water pressure is easily generated on the bedrock surface. Thus, this type of slope is rather unstable and mostly found on dipping slopes in tertiary parent materials.

B type--Regolith is thin and underlain by bedrock having many joints and cracks. Roots are able to penetrate into bedrock and contribute to stability. Pore water pressure is seldom generated because of high permeability. Accordingly, this type of slope is quite stable and is found in areas with mesozoic and paleozoic parent material.

C type--Regolith is thin and there is a transitional (weathered) layer between the regolith and bedrock. Root growth may be affected by soil density and hardness of this transitional layer. Soil moisture does not easily permeate the transitional layer, because of its high density, and pore water pressure is easily generated. Roots are most effective on this type of slope. As root strength declines after logging, many debris flows would be expected. This type is frequently found in granite mountains.

D type--Regolith is thick and roots can grow without restriction by soil layers. This type of slope is usually found at the base of hillslopes and have a gentle angle. Debris flows never occur on this type of slope.

Stability analysis

The stability of these four types of slope was investigated by assuming reasonable values of important soil and slope characteristics (table 3).

The A-type slope has 80 cm of regolith thickness underlain by bedrock without cracks and the roots can not penetrate more than 80 cm deep. The B-type slope also has 80 cm of regolith, but bedrock is fractured and roots can invade the cracks up to 100 cm deep. The C-type slope also has 80 cm of regolith, plus a 40-cm-thick transitional layer underlain by bedrock. The D-type slope has 150 cm of regolith and a 40-cm-thick transitional layer underlain by bedrock. The stability calculations assumed that the ground water reached the ground surface. Forests of *Cryptomeria japonica* aged 10, 20, 30, and 40 years were assumed to be growing on each slope. The

Table 3--Characteristics of the four slopes

	Slope type			
	A	B	C	D
Slope angle (°)	32	32	32	15
Thickness of regolith (cm)	80	80	80	150
Transitional zone (cm)	0	0	40	40
Cohesion of soil (ton/m^2)	0.2	0.2	0.2	0.2
Internal angle of soil (°)	30	30	30	30
Cohesion of bedrock (ton/m^2)	20	20	20	20
Internal angle of bedrock (°)	40	40	40	40
Ground water table depth (cm)	0	0	0	0
Density of soil (g/cc)	1.3	1.3	1.3	1.3
Density of bedrock (g/cc)	2.5	2.5	2.5	2.5
Z_{max} (cm)	80	100	100	170

size of trees in each forest was obtained from yield tables. Root distributions (number of roots in each 10-cm-thick soil layer for each 0.5-cm diameter class) were simulated using the model (fig. 3). The reinforcing strength (ΔS) in each 10-cm-thick layer was calculated using equation [16].

$$\Delta S(z) = \sum_{i=1}^{m} N(z,i)*PO(i) \qquad [16]$$

where, $\Delta S(z)$: reinforcing strength at depth z cm
$N(z,i)$: number of roots of diameter i cm at depth z cm
$PO(i)$: pull-out strength of a root with diameter i cm.

The simulation results of the four slope types are shown in figure 5. Soil shear strength, Ss, shows an abrupt increase at the boundary between soil and bedrock of the A-type and B-type slopes, but on the C-type slope that has a transitional soil layer, soil shear strength gradually increases. Shear stress, Ps, exceeds the soil shear strength at a depth of 40 to 80 cm on type A, B, and C slopes. This indicates a potential shear zone at these depths leading to the possibility of a landslide. The reinforcing strength by roots (ΔS) was calculated by equation [16] and added to Ss (fig. 5).

On the A-type slope, the growth of tap roots is restricted by the bedrock so there is no reinforcing effect at the boundary (potential shear zone). ΔS is increased by the growing forest only to a depth of 70 cm. In other words, although the number of roots is increased as the forest becomes older, root reinforcement of the soil never develops at the boundary and Ps will exceed Ss at this depth when the ground water surface rises. This condition can lead to a debris flow.

On the B-type slope, however, roots penetrate the cracks in the bedrock, and root reinforcement develops at the soil-bedrock boundary. When the forest is older

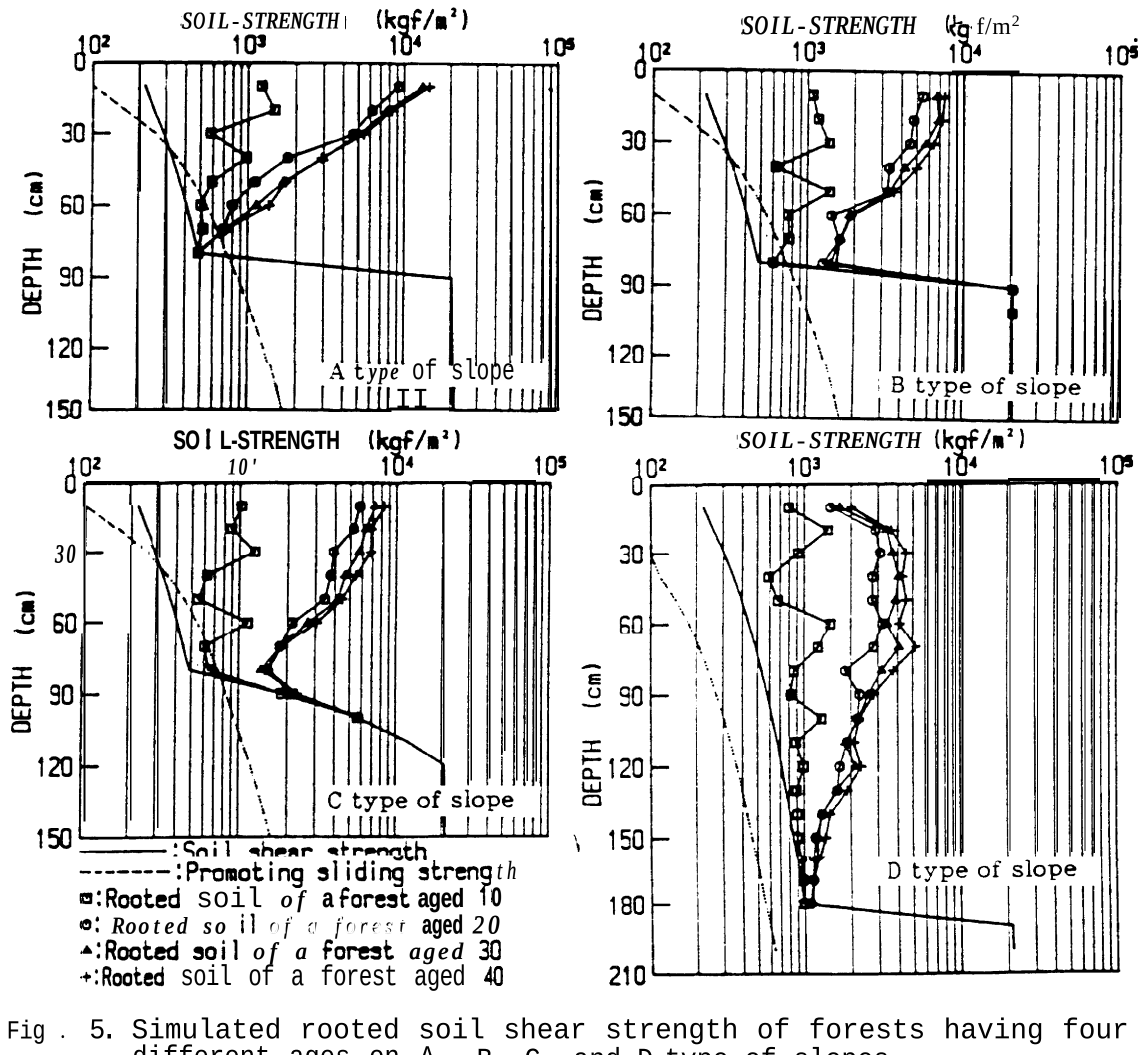

Fig. 5. Simulated rooted soil shear strength of forests having four different ages on A, B, C, and D type of slopes

than 20 years, ΔS becomes stronger than Ss, and Ps never exceeds shear strength of the rooted soil, Sr (fig. 5). But, for the 10-year-old forest, ΔS is not strong enough to prevent a debris flow on the slope.

The C-type slope is similar to the B-type. Roots invade and reinforce the transitional zone, and the probability of landslides decreases as the forest becomes older.

The D-type slope is always stable with or without a forest.

The factor of safety (FS) at the potential shear zone increases for type B and C slopes as the age of a forest increases, up to an age of 20 to 25 years, after which it remains about constant at about 2.0 (fig. 6). For these slope types, the FS of 10-year-old forests is under 1.0, indicating a high probability of landslides. The FS values were calculated for a condition where the ground water reaches the ground surface. For A-type slopes, FS does not change with increasing forest age because roots cannot reinforce the soil and bedrock interface. Type-D slopes remain stable at all ages of forest.

DISCUSSION

As forests grow, root systems develop to provide structural support to the trees and to absorb water and nutrients. Roots are important in stabilizing hillslopes. To quantify the amount of root reinforcement (ΔS), it is necessary to understand the relationship between root growth, slope structure, and depth of sliding surface. In this paper, root reinforcement was modelled for four types of slopes. Previous research has shown that there are high slope failure rates on granite, shattered Paleozoic and mesozoic, and tertiary slopes associated with young forests (Tsukamoto 1987). It is expected that there are differences in ΔS related to differences in geologically related slope structure. Thus, it is important to identify those factors that restrict the growth of roots and to quantify the number and size of roots that can penetrate into joints of bedrock or transitional soil layers and reinforce the potential shear zone.

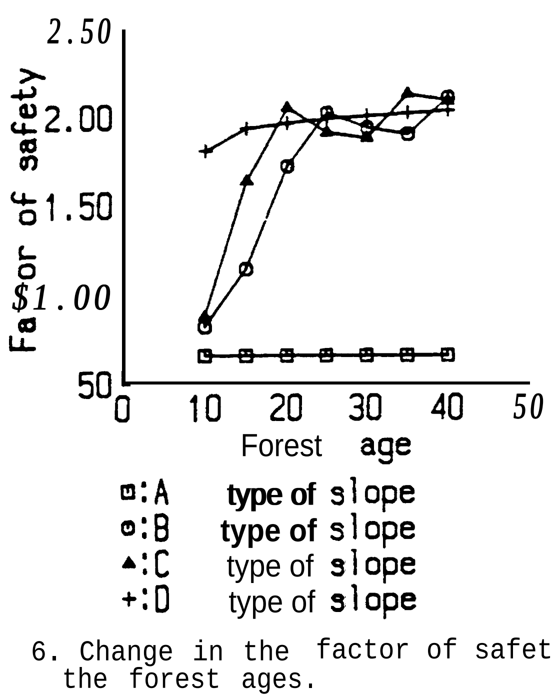

Fig. 6. Change in the factor of safety as the forest ages.

Logging can cause a large decrease in ΔS. As the roots decay, after a 40-year-old forest has been cut, the shear resistance of rooted soil in the potential shear zone will decrease to one third of that in the uncut forest (fig. 5), and the probability of slope failure will increase. Kitamura and Namba (1981) noted that the resistance of tree stumps to uprooting decreases rapidly as the root systems decay following timber harvest. They concluded, when considering the combined effect of root decay of the cut trees and root growth of the planted trees, that the forest soil would reach a minimum strength between 5 and 10 years after cutting and replanting. Ziemer and Swanston (1977) measured the changes in strength of roots remaining in the soil after logging and noted that even the largest roots lost appreciable strength.

In general, the influence of forest logging on debris flows are greatest in granitic and tertiary slopes (C-type). Paleozoic and mesozoic slopes (B-type) generally do not have an increased incidence of debris flow after forest removal. Tsukamoto (1987) explained that the reason for this is that the high permeability of the fractured bedrock prevents the build-up of lateral groundwater flow along the bedrock. Ohta (1986) suggested that roughness of the bedrock also makes this type of slope stable.

ΔS tends to increase as the forest becomes older, up to an age of about 20 years, after which ΔS remains about constant. The contribution of a single tree to ΔS continues to increase as the tree becomes older. However, the number of trees in the forest decreases with forest age (table 4) and the net effect is a constant ΔS after about 20 Years. Forty-year-old stands of *Cryptomeria japonica*

Table 4--Sizes of *Cryptomeria japonica*

	Tree age (yr)			
	10	20	30	40
DBH (cm)	5.0	13.8	20.0	24.3
Height (m)	5.4	12.l	15.8	18.1
Number (h^{-1})	3430	2265	1345	1030
Area (m^2)	2.9	4.4	7.4	9.7

have a high density--one tree per 3.1 x 3.1 m. For this stand density, it is acceptable to estimate ΔS on a unit area basis. However, for old-growth and scattered trees, it may not be proper to estimate the reinforced strength by unit area, because tap roots tend to concentrate below the widely-spaced tree trunks.

Most roots in the potential shear zone are less than 1.0 cm in diameter. In this paper, only the effect of roots within the shear zone were considered. However, soil reinforcement by lateral roots should also be considered. Burroughs and Thomas (1977) reported that zones of weakness developed between stumps that could lead to the initiation of slope failure.

CONCLUSIONS

Using a model of tree root distribution and the pull-out strength of roots to estimate the effect of roots upon slope stability, we conclude that:

(1) Root reinforcement could be expected on slopes where roots grow into joints of bedrock or weathered transitional layers. DS in a potential shear zone on such slopes had twice the shear strength of soil without roots.

(2) Most roots directly affecting slope stability are about 1.0 cm or less in diameter.

(3) After afforestation, DS would increase quickly for about 20 years, then remain nearly constant.

REFERENCES

Abe, K.; Iwamoto, M.; Yoshino, S.; Ishigaki, I.; Tarumi, H. 1985. Tree-root distribution on a landslide surface. Tran. 96th. Ann. Mtg. Jpn. For. Soc.: 639-642.

Abe, K.; Iwamoto, M. 1986. An evaluation of tree-root effect on slope stability by tree-root strength. J. Jpn. For. Soc. 68: 505-510.

Abe, K.; Iwamoto, M.; Sammori, T. 1986. Strength of binding soil by tree root. Trans. 38th. Ann. Mtg. Kanto Jpn. For. Soc.: 217-220.

Abe,K.; Iwamoto, M. 1987. Soil mechanical role of tree roots in preventing landslides. Proc. 5th International Conference and Field Workshop on Landslides; 1987; Christchurch, NZ; l-9.

Burroughs, E. J. Jr.; Thomas, B. R. 1977. Declining root strength in Douglas-fir after felling as a factor in slope stability. Research Paper INT-190. Ogden, UT: U.S. Department of Agriculture, Forest Service. 27 p.

Endo, T.; Tsuruta, T. 1969. The effect of the tree's root upon the shear strength of soil. 68 Ann. Rep. Hokkaido Br., For. Experiment Station: 167-182.

Gray, D.H.; Ohashi, H. 1983. Mechanics of fiber reinforcements in sand. J. Geotech. Div. ASCE 108(GT3): 335-353.

Ikemoto, N.; Takeshita, K. 1987. Effect of tree root on slopes stability. Trans. of Sabo Research Presentation Meeting: 262-265.

Karizumi, N. 1977. Root biomass. JIBPO Synthesis (Shidei, T.; Kira, T., ed.). University of Tokyo Press, Tokyo. 16: 45-52.

Kitamura, Y.; Namba, S. 1981. The function of tree roots upon landslide prevention presumed through the uprooting test. Bull. of For. and For. Prod. Res. Inst. 313: 175-208.

Makabe, H. 1966. Usage of Weibull probability graph. Nippon Kikaku Kyoukai. 81 p.

Morimoto, Y. 1982. Syamen Ryokka Kashima Syuppankai, Tokyo: 94-120.

Nakane, K.; Nakagawa, K.; Takahashi, F. 1983. Change in tensile strength of Japanese red pine roots after death by fire. J. Jpn. For. Soc. 65: 155-165.

Ohta, T. 1986. Forest effect on prevention of sediment disaster. Report of Forest Management Research Meeting. 298: 17-26.

O'Loughlin, C. L. 1974. A study of tree root strength deterioration following clearfelling Canadian J. of For. Research 4(l): 107-113.

O'Loughlin, C. L.; Rowe, L. K.; Pearce, A. J. 1982. Exceptional storm influences on slope erosion and sediment yields in small forest catchments, north Westland, New Zealand. Proc. of National Symposium of For. Hydrology, Melbourne, Australia.

O'Loughlin, C. L.; Ziemer, R. R. 1982. Importance of root strength and deterioration rates upon edaphic stability of steepland forests. Proceedings of IUFRO Workshop P.1.07-00 Ecology of Subalpine Ecosystems as a Key Management. 1982 August 2-3, Corvallis, OR. Corvallis, OR: Oregon State University; 70-78.

Shewbridge, S. 1985. The influence of reinforcement properties on the strength and deformation characteristics of a reinforced sand. Berkeley, CA: University of California; Dissertation
Tsukamoto, Y. 1987. Evaluation of the effect of tree roots on slope stability. Bull. of the Experiment Forests. Tokyo Univ. of Agric. and Technol. No. 23: 65-124.
Waldron, L. J. 1977. The shear resistance of root-permeated homogeneous and stratified soil. Soil Science Soc. of America J. 41: 843-849.
Waldron, L. J.; Dakessian, S. 1981. Soil reinforcement by root: calculation of increased soil shear resistance from root properties. Soil Science 136(6): 427-435.
Wu, T. H. 1976. Investigations of landslides on Prince of Wales Island, Alaska. Geotech. Eng. Rep 5, Columbus, OH: Dept. Civ. Eng,, Ohio State Univ. 94 p.
Ziemer, R. R. 1981. Roots and the stability of forested slopes. In: Davies, T. R. H.; Pearce, A. J., eds. Erosion and Sediment Transport in Pacific Rim Steeplands; 1981 January; Christchurch, NZ. IAHS/AISH Publ. No.132 Wallingford, UK: International Association of Hydrological Sciences; 343-361.
Ziemer, R. R.; Swanston, D. N. 1977. Root strength changes after logging in southeast Alaska. Research Note PNW-306. Portland, OR: U.S. Department of Agriculture, Forest Service. 10 p.