TREE ROOTS AND SLOPE STABILITY: A COMPARISON BETWEEN *PINUS RADIATA* AND KĀNUKA

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(Received for publication 13 January 1997; revision 24 September 1997, 10 February 1998)

ABSTRACT

Increasingly, in the East Coast region of the North Island of New Zealand stands of indigenous regenerating kānuka (*Kunzea ericoides* var. *ericoides* (A.Rich.) J.Thompson) are being felled and replanted with *Pinus radiata* D.Don. Conversion has occurred predominantly on erosion-prone hillslopes where storm-generated landsliding has been widespread and severe, but data on the relative effectiveness of these two forest species in enhancing slope stability are rare. For kānuka and *P. radiata*, shear stress-displacement curves for their corresponding potential shear planes were measured at two sites by *in situ* direct shear tests on soil with and without roots. The contribution of roots to soil strength was first estimated by calculating the difference between the maximum shear stress of the shear stress-displacement curves obtained for soil with and without roots. Results suggested that for individual trees the contribution from the roots to soil strength on a root cross-sectional area per unit shear area basis was independent of species for the two tree species tested. There were, however, significant differences in stand density between these two species. These results were then used to obtain relationships between shear stress and shear displacement at the peak of the shear stress-displacement curve, and between cross-sectional area of roots per unit shear area. Taking the shear strength of the combined soil-root system as the peak value of the shear stress-displacement curve produced from the *in situ* direct shear tests, a limit equilibrium slope stability analysis method was used to derive the safety factors. A simple model developed using the relationship between the shear strength of the soil-root system, the specific root cross-section area, and slope angle was then used to determine safety factors for typical stand densities of naturally regenerating kānuka for comparison with different *P. radiata* management regimes at equivalent stages of growth.

The model predicted that safety factors for stands of *P. radiata* in the first 8 years after establishment would be lower than for equivalent-aged stands of fully-stocked regenerating kānuka under similar conditions. However, after 16 years the safety factor for a stand of kānuka would be lower than that for *P. radiata* at final stocking densities typical of framing and biomass regimes.

In areas where vegetation plays a major role in soil conservation and erosion control, the model can be used to compare the stability of forested slopes with different species and stand densities. However, the model does not take into account the effect of buttressing by mature tree roots.

Keywords: tree roots; shear test slope stability; *Kunzea ericoides*; *Pinus radiata*.

INTRODUCTION

In 1988, a large cyclonic storm (Cyclone Bola) centred over the East Coast region of the North Island of New Zealand initiated widespread landsliding. The landsliding was particularly severe on steep terrain devoid of woody vegetation cover. Research undertaken subsequent to this storm has shown that areas of regenerating scrub, often dominated by the myrtaceous species kānuka (Connor & Edgar 1987), are four times more effective than pasture and young *P. radiata* (<6 years old) in preventing the initiation of shallow translational landslides during periods of extreme rainfall (Marden & Rowan 1993). Research has also shown that within 10–15 years of the establishment of regenerating indigenous scrub there is a substantial decrease in landslide susceptibility during such storms (Bergin *et al.* 1993). It would appear, therefore, that mature kānuka is an effective cover for improving slope stability in steep erosion-prone terrain and that areas currently in young and immature regenerating scrub should be retained for erosion control purposes. Increasingly, however, stands of kānuka are being felled and replanted with pine.

Although there are considerable scientific data in support of the effectiveness of *P. radiata* as protection against the initiation of shallow landslides and other forms of erosion (O'Loughlin 1984; O'Loughlin & Zhang 1986; Phillips *et al.* 1990; Marden *et al.* 1991; Marden & Rowan 1993) little comparative research has been undertaken on other species (exotic or indigenous) including kānuka. In recognition of this, a research programme was initiated to compare the performance of kānuka with *P. radiata* in stabilising erosion-prone hillslopes.

In this paper we compare the contribution of live roots of a naturally regenerating indigenous species (kānuka) with that of a planted and managed exotic species *(P. radiata)* to soil reinforcement using *in situ* direct shear tests. The relationships between shear strength of soil root system, root cross-section area per unit shear area, and slope angle were used to describe the significance of stand densities, typical of each tree species, on slope stability.

Tree Roots and Slope Stability—Background

Tree roots are considered to be a major contributor to soil strength and slope stability (O'Loughlin 1974; Gray 1974, 1978; Waldron 1977; Forest Research Institute 1981; O'Loughlin *et al.* 1982; O'Loughlin & Ziemer 1982; Wu 1984; Wu & Erb 1988; Terwilliger & Waldron 1990; Abe & Ziemer 1991; Sidle 1991; Lee 1996). The extent to which roots can improve the soil strength depends on the physical and chemical composition of the soil and the strength and morphology of the roots. However, experimental data about root contribution to soil strength also vary with the sample size and the test method used (Mulder 1991).

Stability analyses of vegetated hillslopes require special attention as the stress-strain behaviour of soil with roots is quite different to that of fallow soil (soil without roots). Past results of *in situ* direct shear box tests (O'Loughlin *et al.* 1982; Waldron 1977; Gray 1978;

Abe & Iwamoto 1986) show that soils with roots produce broader and flatter-peaked shear stress-displacement curves. Such soils have the ability to undergo more shear displacement before failure than fallow soils. The conventional limit equilibrium stability analysis method (Terzaghi & Peck 1967) assumes static equilibrium at failure where the shear displacement is assumed to be very small. This ignores the ability of the increased shear displacements of soil containing roots to improve the stability of vegetated hillslopes. Results from direct shear tests (Wu *et al.* 1979; O'Loughlin *et al.* 1982) suggest that there is considerable uncertainty in the choice of values for cohesion and the angle of internal friction for soil with roots. Therefore the strength of soil with roots may not be estimated from the traditional Mohr-type failure envelope and a suitable stability analysis method that takes into account the ability of soil with roots to withstand large shear displacements is thus required for vegetated hillslopes.

Because it is difficult to obtain a linear Mohr failure envelope for the combined soil root system, the strength of soil with roots is usually estimated by adding the contribution of roots to the strength value obtained for fallow soil (Wu *et al.* 1979; Terwilliger & Waldron 1990). A few researchers have attempted to approximate the roots' contribution to soil strength using theoretical and analytical models and models based on physiology and ecology (Wu *et al.* 1979; Waldron & Dakessian 1981; Gray & Leiser 1982; Gray & Ohashi 1983; Wu & Erb 1988; Lee 1996). These models were built using data from both laboratory and direct *in situ* shear box tests. Although these models were developed using different assumptions, all of them were based on a special situation of fibre-reinforced elasto-plastic material. Many of these models rely on knowing the structural deformation patterns of roots to estimate the strength increase. After carrying out 32 *in situ* shear box tests on field soil with roots and without roots we found it was impracticable to apply any of these models to predict the contribution of roots to soil strength. This was because of the large number of roots (10 to 30 with diameters of 2–15 mm) within the sheared soil mass, and the complex morphology of the root systems. It was therefore extremely difficult to determine the structural arrangement of roots before and after the test, and the mode and stage of failure of individual roots.

Another way of finding the contribution of roots to soil strength is by using *in situ* direct shear tests on field soils with and without roots to determine shear stress-displacement curves (O'Loughlin *et al.* 1982; Ziemer 1981; Wu *et al.* 1988; Tobias 1994). The root contribution to soil strength may be estimated as the maximum difference between the shear stress-displacement curves of fallow soil and soil with roots (Wu *et al.* 1979). However, the point where this maximum difference occurs varies with the actual shear displacement, which also depends on the root content at the shear plane.

These *in situ* shear box tests show that the maximum shear strengths of soils with roots are usually reached at larger shear displacements than for fallow soil (Waldron 1977; Gray 1978; O'Loughlin *et al.* 1982; Abe & Iwamoto 1986). These tests also show that soil with roots produces a broader peak resistance than the sharp peak resistance produced by fallow soil. Therefore, the total strength obtained by adding the root contribution to the strength of fallow soil does not necessarily equal the actual maximum strength of the combined soil-root system at failure. It is not only the increased peak resistance but also the increased shear displacement due to the elasticity of the roots that contributes to improved hillslope stability.

Theory

Stresses acting on an infinite* hillslope are represented in Fig. 1. According to Wu *et al.* (1979) the effect of vegetation roots on soil shear strength can be taken as part of the cohesive strength component of the soil-root system. Assuming that the phreatic surface is at the soil surface and the location of the potential shear plane is z distance below the soil surface, the safety factor (the minimum possible shear strength / the maximum possible shear stress) for a vegetated infinite slope is given by Eq. 1:

$$SF = \frac{[c' + \Delta c + (z \cos^2(\alpha)(\gamma_{sat} - \gamma_w) + w_t \cos\alpha) \tan\phi']}{[z\, \gamma_{sat} \cos\alpha \sin\alpha + w_t \sin\alpha]} \qquad \ldots 1$$

where c′ and φ′ are the effective soil strength parameters, Δc is the increased cohesion due to tree roots, α is the slope angle, w_t is the vegetation surcharge (weight /unit area), γ_{sat} is the saturated unit weight of soil, γ_w is the unit weight of water.

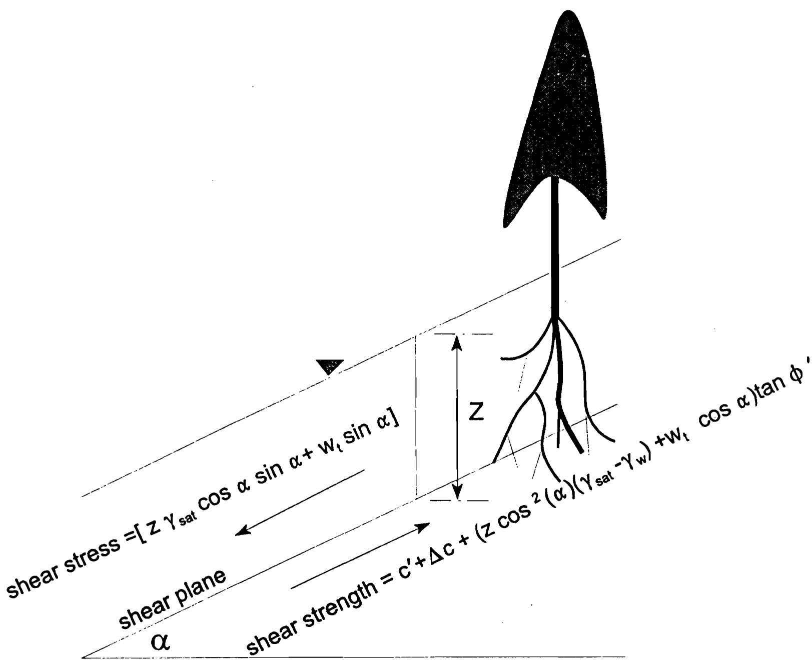

FIG. 1–Schematic of infinite slope stability analysis for a planar failure. c′ and φ′ are the effective soil strength parameters, Δc is the increased cohesion due to tree roots, α is the slope angle, w_t is the vegetation surcharge (weight /unit area), γ_{sat} is the saturated unit weight of soil, γ_w is the unit weight of water.

In conventional limit equilibrium slope stability analysis the shear strength (numerator of Eq.1) is usually estimated using the soil strength parameters c′ and φ′ with the estimated effective normal stress on the potential shear plane under the given pore-water pressure condition. In order to predict the landslide threshold conditions these soil strength parameters are estimated from the Mohr-Coulomb failure envelope derived from the peak values of a

* The thickness of the moving unstable material is small compared to the length of the slope.

series of shear stress-displacement curves performed under different normal stresses. Therefore, the total shear strength of the soil root system may be taken as the peak value of the shear stress-displacement curve obtained from the individual *in situ* direct shear tests performed corresponding to the potential shear planes. Such *in situ* direct shear tests must be performed under the maximum possible pore-water pressure conditions in order to estimate the total shear strength of the combined soil-root system. However, much evidence exists to show that shallow landslides on forested hillslopes are more likely to be triggered under near saturation conditions even before the pore-water pressure begins to build up at the shear plane (Rahardjo *et al.* 1996; Fourie 1996). Therefore *in situ* direct shear tests performed under submerged conditions can approximate the shear strength under saturated conditions and such an approach is thus adequate for comparing the contribution of different tree roots to slope stability. Since this procedure requires knowledge of the potential shear plane location to simulate the direct shear test under the required normal stress, this approach is limited to infinite hillslopes where the potential shear plane is clearly defined. The shear stress is given by the denominator of Eq. 1 which can be estimated if the saturated bulk density of soil, vegetation surcharge, and the slope angle are known. For young vegetation the surcharge is negligible compared to the weight of the overburden soil.

The safety factor can now be written as

$$SF = \frac{\tau_{RP}}{\tau_S} \qquad \ldots 2$$

where τ_{RP} is the peak stress of the shear stress-displacement curve obtained from the direct shear test performed on the soil root system and corresponds to the potential shear plane under submerged conditions, and τ_S is the maximum possible shear stress on the potential shear plane. τ_S can be estimated from the denominator of Eq. 1 if the slope angle, unit weight of saturated soil, vegetation surcharge, and the location of the shear plane are known.

STUDY SITES

The two study sites, Waimata and Kanakanaia, were located in the East Coast region of the North Island of New Zealand (Fig. 2). On late Tertiary sedimentary terrain, shallow (0.1–3.0 m) storm-generated soil slides and debris avalanches (Varnes 1978) predominate. The depth of landslide failure is largely a function of the thickness of the soil and colluvium overlying mudstone and sandstone lithologies, with the formation of a shear plane being coincidental with the bedrock interface (Marden *et al.* 1991).

Soils were shallow (< 3 m), and varied from Orthic Recent Soils and their intergrades to Brown Soils (on well-drained sites) and to Gley Soils (on poorly drained sites). They were typical of land that is being eroded or has received sediment mainly as a result of slope processes (Hewitt 1992), and correlated with the Inceptisols of Soil Taxonomy (Soil Survey Staff 1992). Soil at the Waimata site was a silty clay with 19% clay content and soil at the Kanakanaia site was classed as a poorly graded sandy-clay with 28% clay content. The vegetation at Waimata consisted of a stand of mature, closed-canopy kānuka in which individual trees varied in age from 16 to 40 years. Smaller diameter (16-year-old) trees were selected for testing. The dimension of the shear box limited the size of trees that could be tested. At the Kanakanaia site pasture had recently been replanted with *P. radiata*. At the time of this study trees were 2 years old. Both study sites were considered representative of erosion-prone terrain being converted from pasture to exotic pines or cleared of kānuka for

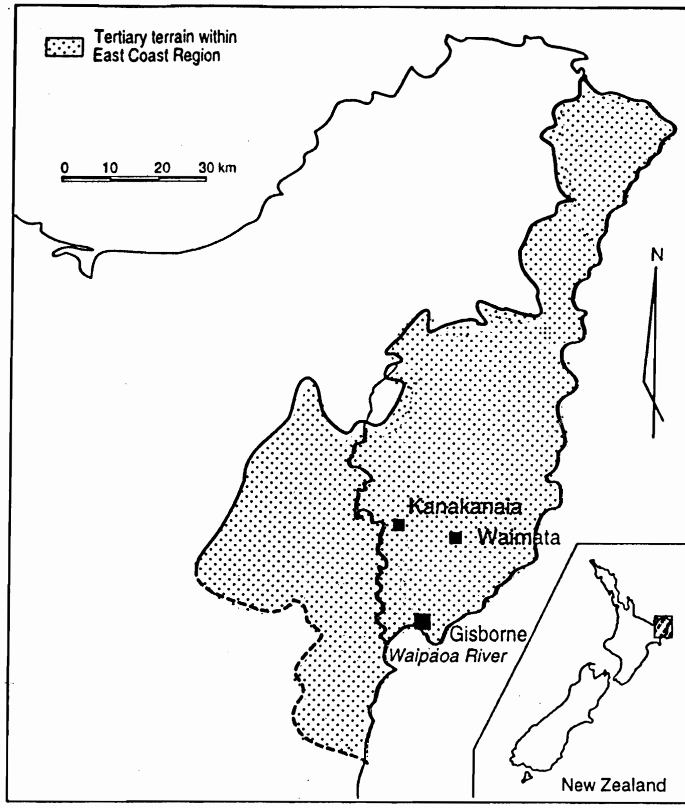

FIG. 2–Location map of the study sites.

exotic forest establishment. As a large quantity of water was requirėd to saturate the soil blocks before testing, water availability was one of the major site selection factors.

Experimental Procedure

All the tests were carried out on midslope sites near a source of water (dam or stream). While 49 tests were attempted, only 23 with roots were completed (12 *P. radiata* and 11 kānuka). In addition, nine tests wsere completed on soils without roots (four at the *P. radiata* site and five at the kānuka site). Incomplete tests were caused by problems with misalignment of the shear box during the tests. The stems were initially cut close to the ground surface and test blocks approximating the internal dimensions of the shear box were prepared so that the stems were centred within the test blocks (Fig. 3). Pits either side of the test blocks were excavated to about 50 cm depth and the test soil block and stem were then trimmed to ensure a neat fit with the shear box (Fig. 3).For each soil block the initial moisture content was measured using a Time Domain Reflectometer (TDR). Pits were then repeatedly filled with water to submerge the test block which was left until it reached saturation. The average volumetric moisture content of the soil blocks at the Waimata site increased from 33% before the tests to 46% at saturation. The Kanakanaia site was initially dryer than the Waimata site

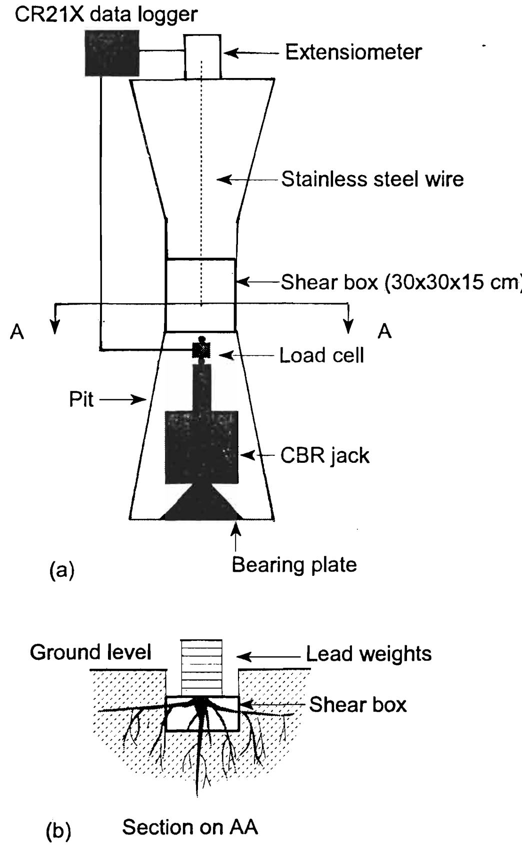

FIG. 3–The field set-up used to perform *in situ* shear tests on soil with and without roots. (a) Plan view. (b) Cross-section on A-A.

and the average volumetric moisture content increased from 29% before wetting to 42% after saturation.

When saturation point was reached, water was bailed from both pits, instruments were installed, and the pits were refilled with water. A high-strength aluminium-alloy shear box (30×30×15 cm—O'Loughlin *et al.* 1982) with a manually driven, two speed, 45-kN CBR (California Bearing Ratio) jack was used to shear test the soil blocks (Fig. 3). A comprehensive data acquisition system was used to measure and record the shear force and displacement. This included:

- A TDR to measure the moisture content of the soil block.
- A load cell with a resolution of 0.01 kN to measure the shear force.
- An extensiometer made by converting an old Belfort water level recorder and gearing a 10-K potentiometer to 0.5-mm resolution to measure the shear displacement.
- A Campbell Scientific Data Logger (CR21X) to measure the force-displacement with time and record shear force at every 2-mm shear displacement.

All shear tests were carried out with the test block submerged and under a normal load of 148 kg equivalent to an overburden pressure at the potential shear plane of a 1-m-thick soil.

Strain was applied at a constant rate to give an approximate shear displacement rate of 1 cm/ min. Soil blocks were sheared close to the maximum displacement capacity of the jack which was approximately 90 mm. After each test, the average moisture content of the soil block was remeasured and the numbers and diameters of roots crossing the basal and both lateral shear planes were recorded.

RESULTS AND DISCUSSION

The shear test results show that soils with roots undergo larger shear displacement than fallow soils prior to total failure (Fig.4). An ellipse (Eq. 3) defined in $x_{RP} > x > 0$ and $\tau_{RP} > \tau > 0$ can be used to approximate the shear stress-displacement curve $\tau_R(x)$ up to the peak shear stress τ_{RP} to an acceptable accuracy (*see* Table 1 and Fig.5).

$$\tau_R(x) = \tau_{RP}(1 - (\frac{x}{x_{RP}} - 1)^2)^{0.5} \quad \ldots 3$$

Eq. 3 can therefore be used to obtain the shear stress-displacement curve up to the peak stress if the shear stress and the displacement at the peak stress are known. The suitability of Eq. 3 to describe the shear stress-displacement curves was tested by approximating 32 stress-displacement curves. The results are given in Table 1 and three examples are shown in Fig.5. The current shear stress at the shear plane after the landslide was triggered can be found from the shear stress-displacement curve given by Eq. 3. The safety factor $(SF)_c$, at a known shear displacement x, can be estimated from Eq.(4). It must be pointed out that the safety factor estimated using Eq. 4 for a measured shear displacement, x, is larger than the safety factor estimated using Eq. 2. This is because τ_S in Eq. 2 is the maximum possible shear stress expected in the hillslope. τ_R in Eq. 4 is the actual shear stress at the shear plane which is in equilibrium with the mobilized shear strength at the shear displacement, x.

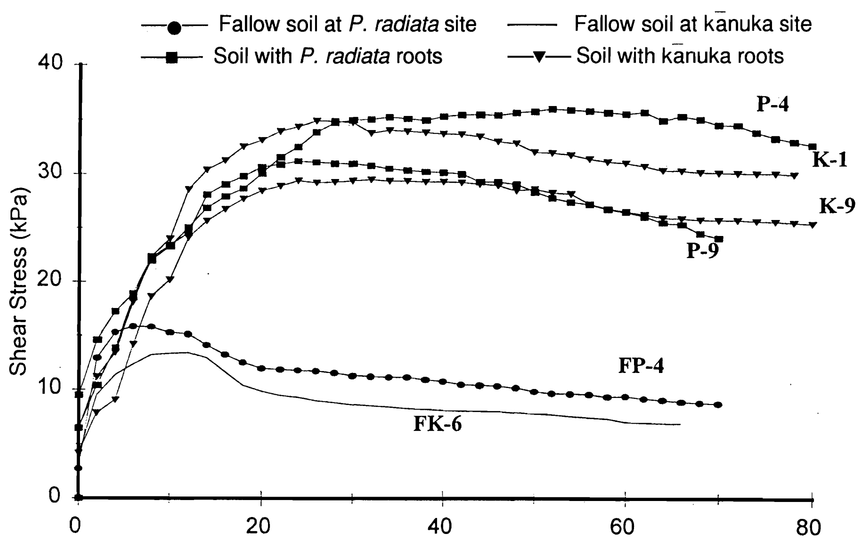

FIG. 4—Shear stress-displacement curves obtained for soil with 2-year-old *P. radiata* roots P-4, P-9; for soil with 8-year-old kānuka roots K-9, K-12; and for fallow soil at the pine site FP-4 and the kānuka site FK-6.

TABLE 1–Results of testing the ability of Eq.3 to approximate the *in situ* direct shear test data of stress-displacement and energy spent in the shear zone up to the peak during the shearing processes of soil with roots and without roots. Soil with roots: P = *P. radiata*, K = kānuka; soil without roots: FP and FK.

Tree and block No.	Shear displacement at peak (measured) x_p (mm)	Shear stress at peak (measured) τ_P (kPa)	Shear stress at peak (best fit Eq.6) (kPa)	Regression coefficient (r^2)	Root cross-sectional area per shear area (cm^2/m^2)
P-1	22	25.9	27.9	0.89	8.35
P-2	26	33.7	33.9	0.93	22.10
P-3	24	34.2	34.1	0.96	26.80
P-4	52	36.0	37.4	0.97	35.20
P-5	22	29.6	32.2	0.85	14.70
P-6	32	29.1	30.4	0.96	26.67
P-7	26	31.1	30.9	0.94	16.11
P-8	28	28.2	30.7	0.9	21.67
P-9	24	31.2	30.5	0.9	17.22
P-10	26	27.1	28.8	0.95	11.67
P-11	32	31.5	33.8	0.89	24.60
P-13	48	33.4	36.2	0.83	38.33
K-1	18	35.2	35.5	0.86	13.89
K-2	22	19.1	20.3	0.92	5.00
K-3	22	27.7	29.7	0.92	10.00
K-4	24	26.4	28.3	0.93	14.44
K-6	24	26.4	28.3	0.93	18.33
K-7	34	36.4	36.1	0.95	35.00
K-8	26	30.1	30.9	0.96	22.78
K-9	36	29.4	30.3	0.96	25.56
K-10	30	33.3	32.0	0.76	23.89
K-12	28	34.9	34.0	0.95	21.67
K-13	48	33.4	36.2	0.83	41.67
FP-1	20	13.3	13.6	0.95	
FP-2	16	15.1	14.7	0.88	
FP-3	14	17.3	17.9	0.67	
FP-4	6	15.9	16.3	0.96	
FK-1	10	14.1	14.4	0.98	
FK-2	16	16.4	15.7	0.96	
FK-3	12	13.4	14.2	0.88	
FK-4	10	10.2	9.9	0.9	
FK-5	14	15.8	15.0	0.94	

$$SF_c(x) = \frac{\tau_{RP}}{\tau_R} = \frac{x_{RP}}{(x^2_{RP} - (x - x_{RP})^2)^{0.5}} \quad \ldots 4$$

The actual safety factor, which indicates the current stability condition of an active hillslope if the slope movement has been monitored since its initiation, is estimated in Eq. 4. Ironically the safety factor derived from Eq. 4 is independent of the slope angle. This is because the shear stress τ_R used in Eq. 4 is not the maximum possible shear stress (τ_S) as given in Eq. 2, but equal to the actual mobilized shear strength at the current shear displacement. The safety factor given by Eq. 4 is, therefore, not an indication of the absolute stability conditions of the hillslope. Because SF_c varies from a minimum of 0 to the maximum of 1

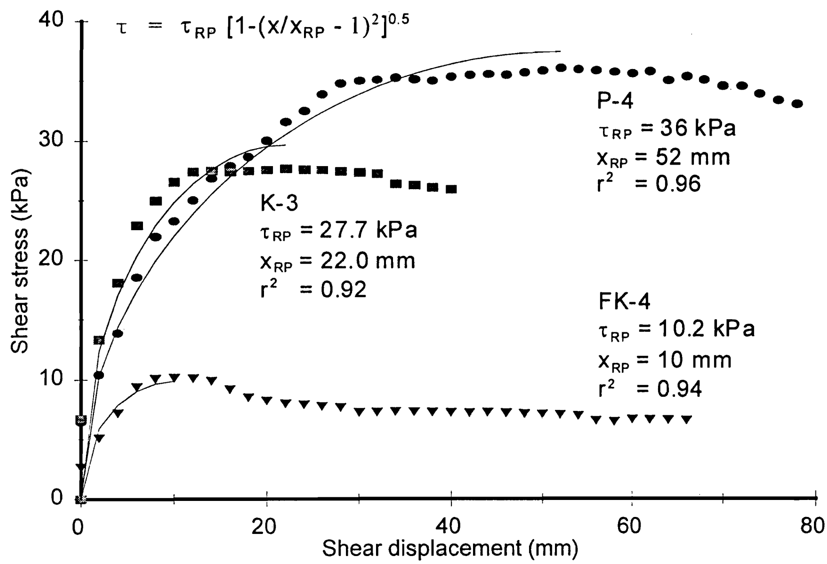

FIG. 5—Fitting of Eq.3 (fine solid lines) to shear stress-displacement curves obtained for soil containing 2-year-old *P. radiata* roots (P-4), 8-year-old kānuka roots (K-3), and fallow soil at the kānuka site (FK-4).

at the ultimate failure, it indicates how far the hillslope is from its final failure stage. Thereafter the hillslope may face a total collapse or begin to slide continuously against the residual shear strength.

In order to compare the present experimental results with published results, the contribution of roots was determined as the maximum difference in shear stress between stress displacement curves for soil with and without roots (Fig. 6). Results from previous studies indicated that the relationship between increasing shear resistance and increasing root cross-sectional area per unit shear area (specific root cross-sectional area), was generally linear for most soil fibre systems (Waldron 1977; Gray 1978). However, the slopes of these lines varied with different species. Both kānuka and *P. radiata* showed a linear relationship between increasing shear stress and increasing root cross-sectional area per unit shear area but correlation coefficients were low. The wide scatter in the data could be due to the high natural spatial variability of the soil because of the high stone content and physical weathering of these soils.

Results (Fig. 6) suggest that there was no significant difference in root contribution between the two species as far as the root cross-sectional area per shear area is concerned. The general equations which describe the relationship of the root cross-sectional area per shear area (A_R/A_S) to shear stress (τ_{RP}) and displacement (x_{RP}) at the peak for both species are approximated by Eq. 5 and 6 (Fig.7).

$$\tau_{RP} = 0.32 \frac{A_R}{A_S} + 24.34 \qquad r^2 = 0.66 \qquad \ldots 5$$

$$x_{RP} = 0.72 \frac{A_R}{A_S} + 13.3 \qquad r^2 = 0.75 \qquad \ldots 6$$

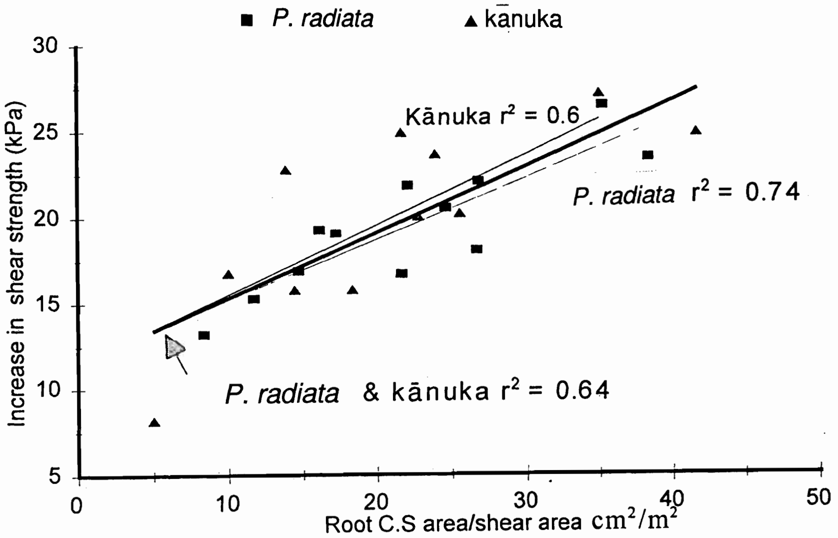

FIG. 6–Root contribution evaluated as the maximum difference in shear stresses between the shear stress-displacement curves for different root cross-sectional areas of *P. radiata* and kānuka.

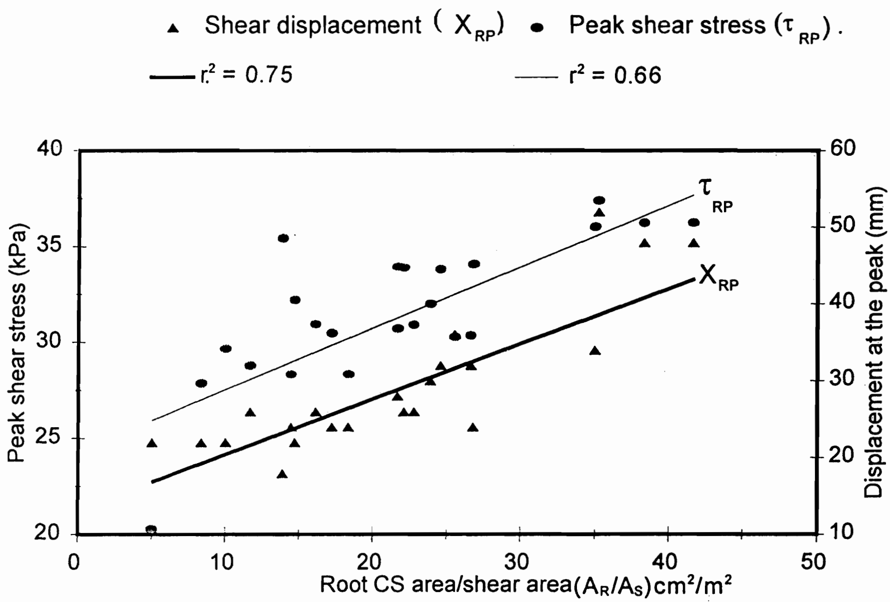

FIG. 7–Shear stress τ_P and shear displacement x_P at the peaks of the shear stress-displacement curves for soil with *P. radiata* and kānuka roots for different root cross-sectional areas.

The peak shear stress τ_{RP} given in Eq. 5 can be used in Eq. 2 to derive SFs for a range of measured root cross-sectional areas for known slope angles. This safety factor is related to the worst conditions where the shear stress is estimated assuming the phreatic surface is at the soil surface.

The following example describes how this model can be used to evaluate and compare the safety factors for different planting densities of *P. radiata* and kānuka and to estimate the current stability conditions of an active hillslope at a given stage. This computation is valid only if Eq. 5 and 6 are obtained from direct shear tests performed on the corresponding potential shear planes of the vegetated hillslopes considered.

The procedure is as follows:

(1) For a known specific root cross-sectional area (root cross-sectional area per unit shear area estimated from the plant density) at the assumed potential shear plane, first determine the peak shear stress (τ_{RP}) and the shear displacement (x_{RP}) at the peak of the shear stress-displacement curve from Eq. 5 and 6.

(2) Estimate the shear stress (τ_S) at the shear plane from the saturated bulk density, slope angle, vegetation surcharge as given in the denominator of Eq. 1.

(3) Estimated τ_{RP} and τ_S can then be used in Eq. 2 to determine the absolute safety factor.

(4) If the slope movement has been monitored since its triggering point, Eq. 4 can then be used to evaluate the current safety factor for the measured shear displacement (x).

Using steps (1) to (3), safety factors were determined for four different forest management regimes for *P. radiata* and compared with those for natural stands of regenerating kānuka at ages 8 and 16 years (Fig. 8 and 9). The calculation of safety factors was for 35° and 45° slopes with an average potential shear plane depth of 1 m, typical of landslide failures on erosion-

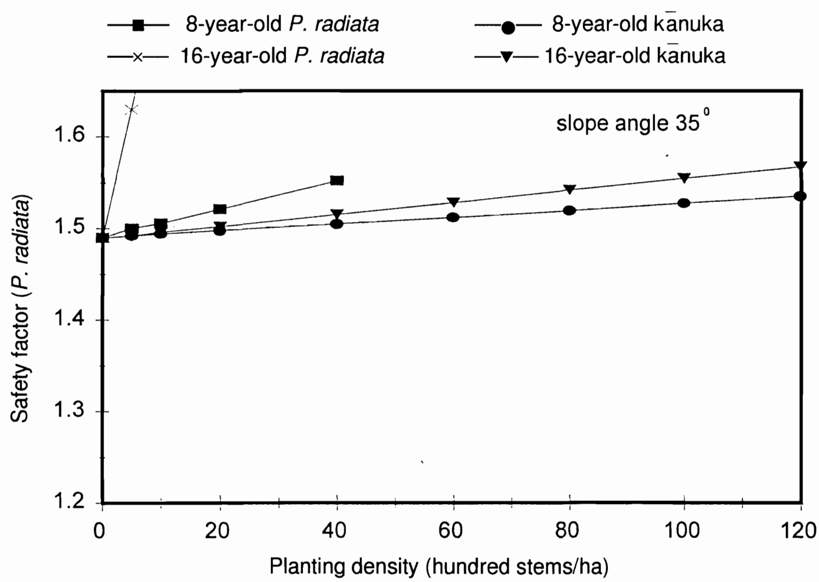

FIG. 8—Safety factors derived from Eq.2 for 8- and 16-year-old *P. radiata* and 8- and 16-year-old kānuka. The potential shear plane is assumed to be at 1 m depth on a slope angle 35°. Root cross-sectional area of 8-year-old *P. radiata* is 7.9 cm^2/stem and 8-year-old kānuka is 1.9 cm^2/stem at 1 m depth. Root cross-sectional area of 16-year-old pine is 149.2 cm^2/stem and 16-year-old kānuka is 3.27 cm^2/stem at 1 m depth.

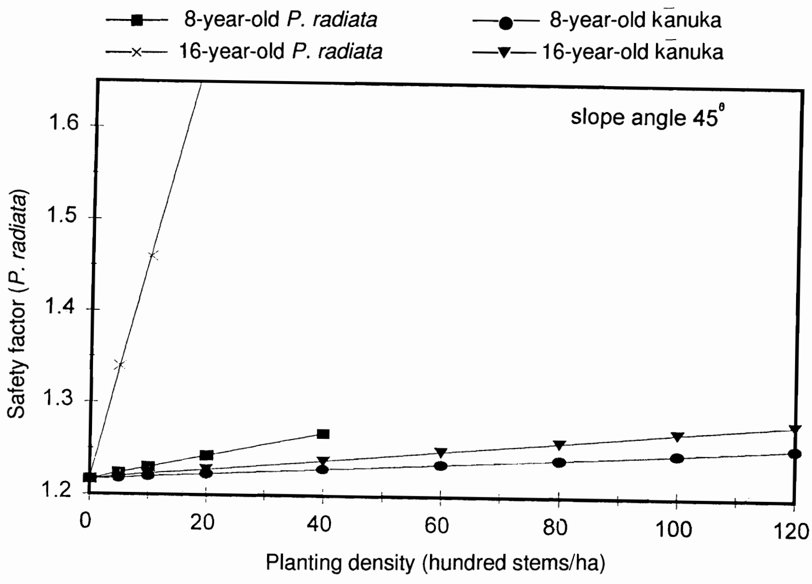

FIG. 9—Safety factors derived from Eq.2 for 8- and 16-year-old *P. radiata* and 8- and 16-year-old kānuka. The potential shear plane is assumed to be at 1 m depth on a slope angle 45°. Root cross-sectional area of 8-year-old *P. radiata* is 7.9 cm^2/stem and 8-year-old kānuka is 1.9 cm^2/stem at 1 m depth. Root cross-sectional area of 16-year-old pine is 149.2 cm^2/stem and 16-year-old kānuka is 3.27 cm^2/stem at 1 m depth.

prone Tertiary hill country in this region. Saturated bulk density of the slope material was taken as 19 kN/m^3. The typical root cross-sectional area at 1-m depth was as follows: for 8-year-old *P. radiata* 7.9 cm^2/stem, for 16-year-old *P. radiata* 149.2 cm^2/stem (from Watson & O'Loughlin 1990), for 8-year-old kānuka 1.9 cm^2/stem, and for 16-year-old kānuka 3.27 cm^2/stem (from unpubl. data). The safety factors derived for each of the different stand densities are given in Table 2.

For a typical stand of intensively managed *P. radiata* on a 35° slope with a final stocking density of 300 stems/ha at 8 years, the model estimates a safety factor of 1.495 (Fig. 8). Compared with alternative *P. radiata* regimes that retain 350 stems/ha or 600 stems/ha (frame regime) at final stocking, the difference in safety factor would be imperceptible at this age (Table 2). A regime where final stocking is held at 1250 stems/ha (biomass/fibre regime) would, after 8 years of growth, result in a small improvement in safety factor to 1.509 (Table 2).

To achieve a safety factor of 1.509 on the same hillslope with equivalent-aged kānuka, a minimum of 5260 stems/ha would be required. Previous work has shown that typical stands of naturally regenerating 8-year-old kānuka, unless heavily grazed by stock or modified by man, average 25 000 stems/ha (range 15 000 to 40 000) (Bergin *et al.* 1995). For these stand densities, safety factors averaging 1.583 (range 1.546 to 1.639) can be calculated with the model (Table 2). That is, 8-year-old fully-stocked stands, and indeed many slightly understocked-stands, of kānuka would achieve a higher safety factor than would stands of *P. radiata* at age 8 under most forest management regimes.

TABLE 2–Safety factors derived from Eq.2 for 8- and 16-year-old pine and kānuka for different stand densities for slope angles 35° and 45° which are common in the area studied.

Species	Age (years)	Stand density (stems/ha)	Safety factor	
			Slope 35°	Slope 45°
Pinus radiata	8	300	1.495	1.221
		350	1.496	1.222
	16	300	1.578	1.289
		350	1.592	1.301
– framing regime	8	600	1.499	1.225
	16	600	1.666	1.362
– biomass regime	8	1 250	1.509	1.233
	16	1 250	1.857	1.517
kānuka	8	15 000	1.546	1.263
		25 000	1.583	1.293
		≥40 000	1.639	1.339
	16	9 000	1.547	1.264
		13 000	1.573	1.285
		20 000	1.618	1.322

The model predicts that between years 8 and 16 there should be a marked improvement in the safety factor for slopes in *P. radiata* but that little change is likely for slopes in kānuka. After 16 years of growth the two intensively managed regimes of *P. radiata* with final stockings of 300 stems/ha and 350 stems/ha would have safety factors of 1.578 and 1.592, respectively. To achieve equivalent safety factors for regenerating kānuka the stand densities would have to be in excess of 14 000 stems/ha. From previous research it is known that the average stand density for fully-stocked stands of 16-year-old kānuka is 13 000 stems/ha (range 9000–20 000) (Bergin *et al.* 1995). For these stand densities the model estimates safety factors of 1.573 (range 1.547 to 1.618) (Table 2), comparable to those for intensively managed stands of *P. radiata* at the same age.

The most notable improvements in safety factor between 8 and 16 years occurred in stands of *P. radiata* managed for framing timber and biomass (fibre) production. The model shows that safety factors attained by these regimes were 1.666 for framing and 1.857 for biomass and exceeded those possible for stands of naturally regenerating kānuka at this age and on similar slopes. The excavation of root systems of both species revealed that although the roots of individual kānuka were smaller than for *P. radiata* at all stages of growth, the difference was more than compensated for by the significantly higher stand densities associated with kānuka. The annual rate of root production of kānuka (2.2 tonnes/ha) exceeds that of a managed stand of *P. radiata* (1.1 tonnes/ha) for the first 9 years of growth (Watson *et al.* 1995), but kānuka is a shallow-rooting species with 95% of the root mass lying above the potential shear plane for most shallow landslides. The tap root and vertical sinker roots do not appear to penetrate to depths below the shear plane until the sixth year of growth (Watson *et al.* 1995). Consequently, the root cross-sectional area of an 8-year-old kānuka at 1-m depth is only 25% of that for an 8-year-old pine. The significantly higher stand density of kānuka explains why the safety factor for most stands of regenerating kānuka would exceed that achieved by the regimes for *P. radiata* considered in this paper, at least for the first 9 years after establishment.

Parity in safety factor between these two species is brought about by the sixteenth year of growth as a consequence of an increase in the rate of root biomass production in *P. radiata* to 7 to 8 tonnes/ha/year while that of kānuka remains relatively constant at 2 tonnes/ha/year (Watson *et al.* 1995). In addition, *P. radiata* exhibits a period of strong vertical root development with both the tap root and vertical sinkers growing to depths of 2.1 m at age 8 years and to 2.6 m at age 16 years (Watson & O'Loughlin 1990). Thus, rapid root biomass production and strong vertical root development in pines results in a 45-fold increase in root cross-sectional area at 1-m depth. In contrast, kānuka stands undergo natural thinning, largely as a consequence of suppression, during which stand density declines by 50% and root cross-sectional area less than doubles.

Safety factors for *P. radiata* and kānuka older than 16 years could not be predicted with reasonable accuracy using the present method as the effect of buttressing by mature tree roots was not taken into account. Nonetheless, data on root biomass and stand dynamics can be used to predict likely trends in safety factor beyond the 16-year time frame. Root biomass production in *P. radiata* between 16 and 25 years old is at a slightly increased rate of 9–10 tonnes/ha/year, with vertical root development increasing to a depth of 3.1 m by the twenty-fifth year (Watson & O'Loughlin 1990). Although root cross-sectional data for 25-year-old *P. radiata* are not available, the corresponding safety factor would be expected to remain high throughout the latter part of the rotation until harvesting at 27 to 30 years of age. In contrast, it is likely that the safety factor for kānuka would decline with increasing age, albeit slowly, as stands undergo natural self-thinning at a time when tree root biomass production remains relatively static (Watson *et al.* 1995). Safety factors for old-age kānuka stands would nonetheless remain high, at least until stands reach senescence.

The vulnerability of slopes to landsliding during extreme rainfall events is greatly reduced in *P. radiata* forests about 8 years after planting (Phillips *et al.* 1990; Marden *et al.* 1991) and in fully-stocked stands of regenerating kānuka about 8–10 years after establishment. Under-stocked stands of kānuka at the same age gave a lower but still significant level of protection (Bergin *et al.* 1995). These documented improvements in slope stability coincide with safety factors ranging from 1.495 to 1.509 for *P. radiata* irrespective of the forest regime, and from 1.546 to 1.639 for kānuka. These safety factors could therefore represent threshold values above which there is a reduced incidence of widespread shallow landsliding during severe storm events.

The present method for predicting slope stability safety factors for vegetated hillslopes assumes that the soil is fully saturated and that the phreatic surface is at the shear plane. Safety factors are based primarily on the ratio of root cross-sectional area to shear area and the slope angle. Thus the limitations of this model are twofold. Firstly, the contribution to slope stability by buttressing and anchorage by large structural roots has not been taken into account. These processes would likely make an important contribution to slope stability when trees are aged 10 years and older. Secondly, stands with closed canopies significantly influence the soil moisture regime so that saturated soil conditions may occur only rarely. The model may therefore grossly under-estimate the safety factor in stands 10 years and older. In order to include the effects of large piezometric pressures and root anchorage on the estimation of safety factors, τ_p and x_p would have to be obtained from a direct *in situ* shear test on a shear plane that corresponded with the potential shear plane. This would require simulated testing in the laboratory and would be difficult to do.

CONCLUSION

The total shear strength of the combined soil-root system is taken as the peak of the shear stress-displacement curve obtained from the *in situ* direct shear test performed on the corresponding potential shear plane. Therefore, the method described here indirectly takes into account the ability of soil to undergo large shear displacement and provides a realistic way to compare the contribution of roots to soil strength for different species.

Although individual kānuka trees have less root cross-sectional area per shear area than individual *P. radiata* at a similar age, kānuka stands initially have higher total cross-sectional area per shear area than *P. radiata* stands. From the scenarios discussed in this paper we conclude that for the first 8 years stands of fully-stocked regenerating kānuka would provide a better level of protection against the initiation of shallow landslides than stands of planted and managed *P. radiata*. In addition, slopes planted in very young *P. radiata* are clearly "at risk" of damage by landsliding, particularly during heavy rainfall events that on average frequent this region at 6-yearly intervals (Kelliher *et al.* 1995). The model indicates that increasing the initial planting density of *P. radiata* does little to alleviate the likelihood of storm-related damage during these formative years, at least until root systems penetrate below the potential shear zone.

Sixteen-year-old *P. radiata* managed for framing and biomass production would afford a level of protection superior to that of both intensively managed *P. radiata* and stands of regenerating kānuka of equivalent age. In still later years (16 to 25 years after establishment) and irrespective of differences in silvicultural practices, *P. radiata* would be expected to afford a high level of slope stability. For similar-aged kānuka, safety factors would likely show a gradual decline with increasing age, though changes would be small and unlikely to affect the overall stability of kānuka-covered slopes unless stands were severely damaged or in the longer term had reached senescence. Published reports confirm that very few incidences of storm-generated landsliding occur in stands of mature *P. radiata* or indigenous forest vegetation (Marden *et al.* 1991; Bergin *et al.* 1993; Marden & Rowan 1993).

In areas where vegetation plays a major role in soil conservation and erosion control, and for resolving issues involving vegetation conversion or clearance on steep erosion-prone hill country, the present model provides a simple and an improved method for calculating the safety factors of forested and scrub-covered slopes. The model does not, however, take into account the effect of buttressing by mature tree roots or anchorage by roots penetrating the substrata. The applicability of this method is limited to vegetated infinite hillslopes where the location and the orientation of the shear plane are well defined, such as on much of the erosion-prone, steep, ash-covered Tertiary hill country of the eastern North Island.

ACKNOWLEDGMENTS

This study was funded by the Foundation for Research Science and Technology (C09517). The authors thank Jim and Sharon Hall and Forest Enterprises Ltd for access to their properties. We also thank Dr Chris Phillips for reviewing an earlier draft of this paper and Dr Megan Ogle-Mannering for editorial assistance.

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