The protective role of trees in soil conservation

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Abstract

The impacts on slope stability of Cyclone Bola in 1988 and the February storms in Wanganui-Manawatu in February 2004 provided strong evidence that treeless steepland is very vulnerable to mass wasting during large cyclonic storms whereas forested slopes are relatively resistant to failure. The evidence from numerous studies indicates it is the tree root systems which provide most of the additional resistance.

This paper briefly reviews the influence of trees on shallow landslides with most of the emphasis on radiata pine. The relatively rapid development of radiata pine root systems enables this species to provide good soil reinforcement after about 10 years of growth but within a few years after harvesting, most of the root reinforcement is lost. The various approaches that can be adopted to manage forests for soil protection, and identify where the most landslide-vulnerable slopes or parts of slopes are located, are outlined. Modern computer models, in combination with GIS, provide very useful predictions of instability.

Introduction

For many foresters it may seem unnecessary and superfluous to once again emphasise the protective function of trees and forests. In New Zealand this topic has been addressed in general by McKelvey (1995), Maclaren (1996), and in detail by Sidle *et al.* (1985), O'Loughlin (1974, 1995), Pearce *et al.* (1987), Phillips & Watson (1994), Phillips *et al.* (1990) and Marden (2004) to mention only a few of the numerous key publications which have examined the protection role of forests.

However, in many steep hill country areas of New Zealand it appears that the ability of trees and forests to stabilise the soil mantle and counter erosion processes continues to be accorded less importance than it deserves. Large tracts of essentially treeless steep-land, mainly covered in pasture, light scrub or tussock, remain vulnerable to landslides and other forms of erosion in many regions of New Zealand.

The devastating consequences of Cyclone Bola on the East Coast in 1988 (Marden 2004) and the February 2004 storms in the Manawatu / Wanganui region (Hancox & Wright 2004; Hocking 2004) provided grim reminders of this vulnerability. With the benefit of hindsight it is highly probable that the impacts of these two events on the stability of the soil mantle would have been moderated significantly if critically sensitive areas which occupied perhaps as little as 20 to 30 percent of the total productive landscape in the badly affected areas, had been forested.

The susceptibility of slopes to serious erosion is certainly not confined to pastoral lands but also extends onto production forest steep-land after harvesting or road building or when the forest is in its early years of development. However, the experience in New Zealand and in other countries has shown that, under similar climate and geomorphic conditions, forest covered lands generally produce less sediment to streams and rivers than other vegetation covers.

This paper attempts to summarise some of the knowledge about the protective function of forests and, in particular, how trees strengthen soils and increase the resistance of slopes against failure and soil loss during storms. Most of the emphasis is on shallow debris slides and debris avalanches (which may transform into debris flows on lower slopes) which are often the most common failure types on steep slopes during cyclonic storms. The paper also summarises the approaches that can be used to identify individual slopes or areas of steep land which have a high susceptibility for failure and in most need of slope protection (forest cover). The paper does not address large deep seated landslides including large earthflows which often appear to be less influenced by vegetation cover and are often triggered by long periods of above-normal antecedent precipitation or by earth tremors.

Understanding why slopes fail

In simple terms, slopes fail when the gravitational and seepage forces operating on the regolith are greater than the forces resisting failure. The shear strength of the soil or regolith which provides the resistance to failure can be expressed by the Mohr-Coulomb equation (Terzaghi 1950):

$$S = C + [\sigma - u] \tan \phi \qquad \text{-------(1)}$$

Where S = soil shear strength (kPa)
C = effective soil cohesion (kPa)
σ = normal stress (kPa)
u = soil pore water pressure (kPa)
ϕ = effective soil internal friction angle (degrees)

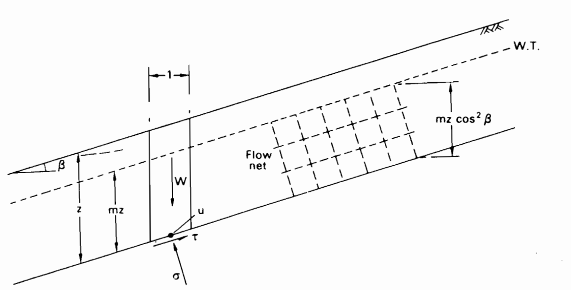
The cohesion C is the result of cementation, weak electrical bonding of clays and organic colloids and capillary tension; the frictional component ϕ is an expression of the frictional interaction of individual soil particles which, in sandy or stoney soils with little clay, contributes to most of the soil strength; the normal stress σ results from the weight of the soil, soil water and vegetation cover above a potential failure surface; the soil pore water pressure u reduces the normal stress by buoyancy. Root systems contribute to soil strength. This strength enhancement is considered to behave as an additional cohesion (Gray & Megahan 1981; O'Loughlin & Ziemer 1982; Sidle *et al.* 1985; Tsukamoto & Minematsu 1987). For forest soils with a dense root network equation (1) can be rewritten:

$$S = [C + Cr] + [\sigma - u] \tan \phi \qquad \text{------(2)}$$

Where Cr = additional soil cohesion caused by binding action of roots (kPa)

A slope susceptible to shallow debris slides and debris avalanches typical of the failures common on pasture hill country in New Zealand after heavy storms, can be represented by an infinite slope model where the failure plane is planar and parallel to the slope surface and at a depth which is small compared to the length of the slope (Fig. 1). The downslope shear stress is denoted by τ.
The expressions for σ, τ and u are:

Fig. 1: An infinite slope showing potential failure plane, water table (WT) and the various forces acting on the slope.



$$\sigma = \{(1-m)\gamma + m\gamma_{sat}\}\, z \cos^2\beta$$
$$\tau = \{(1-m)\gamma + m\gamma_{sat}\}\, z \sin B \cos\beta$$
$$u = mz\gamma_w \cos^2\beta$$

where γ_{sat} = saturated unit weight of soil
γ = unit weight of soil
γ_w = unit weight of water
β = slope
z = soil depth
m = water table as proportion of soil depth

The infinite slope model can be used to calculate the slope factor of safety FS which is the ratio of the forces resisting failure (soil strength) and the downslope shear stress.

$$FS = S / \tau \qquad \text{--------(3)}$$

A factor of safety > 1 implies a stable slope but a factor of safety < 1 indicates imminent failure.

A large array of slope stability analyses have been developed in soil and rock mechanics, most being more complex than the simple infinite slope example outlined above. However, the application of such analyses is fraught with uncertainties because of the heterogeneous soil, soil water, vegetation and geological conditions that prevail on natural slopes. Furthermore, it is often difficult to obtain reliable measures of the soil strength parameters on natural slopes. Estimates of C, Cr and ϕ can be obtained from field shear strength testing of carefully prepared soil blocks using strain-controlled direct shearing equipment (O'Loughlin 1974; Wu *et al.* 1988; Phillips & Watson 1994). Field piezometric studies can provide estimates of u (Sidle *et al.* 1985).

Slope stability analyses can provide useful first approximations of the likelihood of failure of slopes under various vegetation covers and they help indicate which slope and soil strength parameters are most important for continuing stability. The factor of safety is sensitive to changes in C, Cr, *z*, *b* and u but relatively insensitive to changes in the weight of any vegetation and ϕ. As explained below, the establishment or removal of trees or forests have major effects on Cr and on u.

During heavy rainfall when the soil mantle saturates, the pore water pressure u increases thus diminishing the frictional strength component of soil strength. Under saturated conditions steepland coarse grained forest soils often depend upon the cohesive strength provided by the root network (Cr) to provide stability. Deterioration of the tree root system after forest removal can place the soil mantle in a vulnerable condition when, under saturated or near fully saturated conditions, the slope factor of safety is reduced to 1.0 or less.

In addition to heavy rainfall, earthquakes also provide an episodic trigger for serious and extensive slope instability in New Zealand. They reduce stability in complex ways by increasing the shear stress τ and reducing the shear strength S. An outstanding example was the 1929 Murchison earthquake (magnitude M 7.7) which caused thousands of individual landslides ranging from large deep-seated types to small shallow soil failures, particularly in the mountainous Mokihinui and Matiri river catchments north of the Buller River (Pearce & O'Loughlin 1985).

The influence of trees on slope stability

Trees or forests affect the stability of slopes in a number of ways:

- They modify soil moisture conditions and pore water pressures. Forests can deplete soil moisture to considerable depth through evapotranspiration (Helvey *et al.* 1972; Jackson & Rowe 1997; Mitchell & Correll 1987) and lower ground water levels (Bell *et al.* 1990). Evapotranspiration by forests may delay soil saturation during storms but during large landslide-causing storms when usually more than 150mm of precipitation falls in less than 36 hours, it is likely that there is ample water to fill all available soil and vegetation storages.
- They provide a protective permeable organic forest floor layer and may increase soil conductivity thus enhancing soil drainage. The accumulation of a forest floor consisting of accumulated litter, humus and tree roots, protects the underlying soil from raindrop impact and surface wash. Furthermore, thick forest floors have a high moisture holding ability and help release water to the soil in a controlled manner. Permeable forest floors may also help maintain high soil conductivities in the upper soil horizons while tree roots, especially decayed roots, can provide pathways for rapid transmittance of water through the soil profile (Beasley 1976; Mosley 1979).
- They increase the surcharge on a sloping soil mantle. Calculations by Bishop & Stevens (1964), O'Loughlin (1974) and Wu *et al* (1979), show that in most temperate forest ecosystems the weight of the forest crop is small compared to the weight of the soil mantle above a potential failure plane. The vertical stresses on the upper soil mantle resulting from the tree crop surcharge range between 1 and 5 kPa and average about 2 kPa. In some soils this additional surcharge has been calculated to increase downslope soil creep rates.
- They are subject to windthrowing and root wedging. Strong winds can overturn trees on exposed slopes causing soil disturbance and initiating landslides. Schweinfurth (1967) and White (1949) revealed that tree toppling is a common landslide initiation process in the mountains of Fiordland, New Zealand and in the volcanic mountains of Hawaii respectively. However, the beneficial effects of trees to slope stability greatly outweigh the adverse effects.
- They mechanically reinforce the soil with tree roots. This is the over-riding influence of forests on soil stability. A range of studies in the USA, Canada, Japan and New Zealand indicates that roots stabilise soils by:

1. Bonding unstable upper soil layers to more stable substrata or sub-soils when roots penetrate into such stable layers.
2. Creating a laterally strong covering soil-root mantle within the top 50 to 100 cm which helps hold the underlying soil in place.
3. Providing localised centres of great reinforcement in the close vicinity of individual trees where the root stump and large structural roots act as reinforcing buttresses.

The relative importance of these three root stabilising mechanisms varies according to the slope and soil conditions. Studies in Japan (Tsukamoto & Minematsu 1987), USA (Gray & Megahan 1981) and New Zealand (Phillips & Watson 1994) suggest that mechanisms 2 and 3 are most important. Mechanism 3 appears to be very important for large trees with massive root systems including radiata pine plantation trees over 15 years of age. Many studies have shown that, on slopes over 32 degrees in steepness, forest soils depend on the root reinforcement factor (Cr) to maintain stability when they are saturated or near saturation. Using slope stability models it is possible to estimate the value of Cr required to maintain stability by making Cr the dependent variable and setting the factor of safety at 1.0.

Radiata pine tree root morphology and root deterioration after harvesting

This section concentrates on *Pinus radiata* D. Don. which is often the tree of choice for afforestation of hill country in New Zealand. Many analyses of slopes show that it is the tree roots which provide the last line of defence against failure when the soils become saturated. The few radiata pine tree root morphology studies that have been reported reveal that tree root systems vary greatly depending on the depth of the soil, its texture, drainage conditions as well as the age and species and density of trees.

In New Zealand, Watson & O'Loughlin (1990) used a hydraulic excavation approach to expose the root systems of 8, 16 and 25 year old radiata pine trees at Mangatu forest near Gisborne. At 8 years the lateral tree roots were confined to the upper 40 cm of soil and vertical roots were concentrated near the bole and showed strong vertical development down to 1.0-1.5 m. Total root biomass was 8.8 tonnes/ha and roots appeared to occupy about one third to half the soil volume.

Twenty five year old tree root systems were dominated by shallow lateral roots which extended over 10 m from the root bole. The larger vertical roots penetrated to depths of over 3 m. Roots <2 cm diameter contributed only 8 percent of the total root biomass but accounted for 80 percent of the total root length. Total root biomass was 151 tonnes/ha. On steep slopes there appeared to be a tendency for lateral roots to grow predominantly across slope and downslope. Vertical root development was limited by water table levels and high stone content in the subsoil and bedrock. At 25 years and 250 stems/ha, the soil volume appeared to be fully occupied by tree roots.

Other studies of radiata pine tree root systems are reported by Phillips & Watson (1994). In comparison to the 16 year old radiata pine root system, the root system of a 15 year old Douglas fir tree growing nearby at Mangatu forest was less developed and smaller in size. However, as the

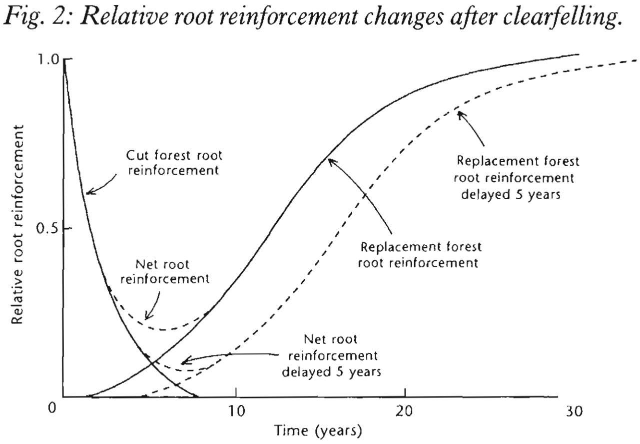
Douglas fir root system matured it would no doubt be as massive or more massive than a mature radiata pine root system as indicated by studies in Canada (McMinn 1963; Eis 1974).

After harvesting, the tree root system tends to shrink from the outer extremities towards the central bole. Studies of the deterioration the tensile strength of radiata pine roots <1.0 cm in diameter (O'Loughlin & Watson 1979) indicated that about half the strength was lost 15 months after harvesting and 3 years after harvesting larger roots >5 cm diameter were in an advanced state of decay. In other words, the reinforcement provided by the tree roots had largely disappeared 3 years after harvesting.

In broad terms, radiata pine provides advantages for stabilising slopes compared to many other species because of its early rapid growth and ability to provide good root reinforcement by age 8 to 10 years. However, radiata pine also presents some challenges if the primary intent of forest management is to preserve soil stability. The traditional approach to managing radiata pine plantations involving clearfelling at age 25 –30 years is not ideal for continued long term soil stability on sensitive slopes. Other approaches to managing radiata pine stands involving small coupe felling, continuous canopy systems involving selection felling, staging logging on individual slopes so that no large areas are left vulnerable and without tree cover at any time and increasing the rotation length to, say, 45 years or more, may need to be considered on highly hazardous slopes. The conversion of radiata pine forest to indigenous forest while retaining some degree of forest cover through the transition period, may be a possibility and would provide a very good solution for long term soil protection on sensitive slopes.

The information provided from the root biomass and root morphology development studies combined with the results of post-harvest root strength deterioration studies, has enabled the development of a generalised model of the relative reinforcement provided by radiata pine through a harvesting period and subsequent rotation of growth (Fig. 2).

Fig. 2: Relative root reinforcement changes after clearfelling.



Post storm assessments of the damage to slopes caused by Cyclone Bola and other large storms in the Gisborne area and in the Wanganui-Manawatu region have revealed that young plantations of radiata pine less than 7 or 8 years old did not have a marked influence on the incidence of landsliding compared to pasture, light scrub or tussock covered land (Marden & Rowan 1993; Marden 2004). On land covered by plantations older than 10 years, landslide frequencies were generally low compared to frequencies in young plantations and on pasture land. These responses are explained by the studies of root morphology mentioned above. Trees younger than 10 years have root systems which are not very extensive and only occupy part of the total soil volume, mainly in the top 0.5 m of soil whereas trees older than 10 years have root systems which extend more than 5 metres from the root bole and interlace with adjacent trees. By age 16 tree roots are occupying most of the soil volume in the upper 1-2 m of soil and have a well developed vertical and lateral root system thus providing good soil reinforcement.

Fig. 3 illustrates the vulnerability of recently deforested steep slopes in the Wanganui hill country. Many of the shallow landslides originated on the upper and mid slopes between the remaining stumps of felled radiata pine trees (Graham Hancox, pers. comm.). This suggests that the large structural roots near the root bole continued to provide protection at the time of the intense landslide-causing storms in February 2004, about two years after the harvesting of pine forest.

The evapotranspiration effects of mature forest cover in protecting slopes from failure during very large cyclonic storms is unclear. The additional water use by forests which creates dryer soils may induce a slower build up in the pore water pressures during storms and the tree root systems may enhance soil water transmissibility and drainage during storms.

Fig. 3: Severe landslide activity on steep slopes in the lower Whangaehu valley near Wanganui. The radiata pine which covered these slopes had been harvested two years before the February 2004 storms which caused the erosion. Forested slopes in the middle background suffered only minor damage. Photo by G.T. Hancox, GNS, Lower Hutt, February 2004.

Managing production forests on hill country to protect soils

The establishment of a forest cover on steep country does not guarantee continuing soil stability. Recently harvested steep slopes and slopes traversed by tracks and roads are usually the parts of the productive forest estate which are most vulnerable to landslides and or accelerated surface erosion (Fig. 3). On steep harvested sites the potential risk of slope failure is highest during the period 2 to 8 years after harvesting when the original root systems are in an advanced state of decay and the replacement root systems of the young crop of trees have not developed sufficiently to provide good soil reinforcement (Fig. 2).

Recently constructed roads and tracks, where cut and fill slopes remain unvegetated, are generally more likely to be the initiation sites of failures than older established roads and tracks where cut and fill slopes have had time to consolidate and are well vegetated. Where landslides are not a major problem, overseas and New Zealand studies consistently show that the major source of sediment supply to streams after harvesting are roads, tracks and landings (Sidle *et al* 1985; Grace 2000).

Adopting best forest management practices as outlined in the Forest Code of Practice (Vaughan 1993) and Forest Roading Manual (Larcombe 1999) is likely to substantially reduce the risks of slope failures and accelerated erosion. The application of forest management standards aimed at minimising environmental impacts during forest operations, should also help lessen erosion risks. Locating roads on ridge tops, terraces and benches and avoiding obviously unstable and poorly drained areas is always preferable. Catering for good road drainage, avoiding extensive side casting on steep slopes and vegetating new cut and fill slopes are also important actions to lessen impacts of roads on slope stability.

Forest road side slopes are a major source of sediment. Stabilizing side slopes using modern bio-degradable erosion mat covers seeded with grass species has been shown in the USA to reduce sediment production from roads by over 90 percent compared to non-treated roads (Grace 2000). Limiting the size of clear-felled areas on steep sensitive slopes subject to periodic high intensity storms, particularly in parts of the eastern North Island, Coromandel Peninsula, the Wanganui region, Motueka region and the Marlborough Sounds and staging harvesting on individual slopes so that only parts of a slope are devoid of trees at any one time, can also lessen the risk of landslides.

Identifying where slope hazards are high and protection measures may be required

Large scale changes in landuse to improve soil conservation, such as a change from pastoralism to forestry, are not likely to occur without a great deal of careful planning involving benefit – cost analyses of such schemes, analyses of the long term risks of soil degradation under various types of land cover and assessments or predictions of the potential risks of landsliding and other accelerated erosion forms. Even at the farm scale, land owners who see a need to improve the stability of the soils on their farm, should also undertake such analyses, even if they use only very rudimentary analyses, before embarking on afforestation schemes. The most complex, difficult and important issue is predicting where landslides might occur in the future at an individual slope scale, a catchment or farm scale or at a regional scale.

Predictions based on a knowledge of where landslides have occurred in the past

At a general level, assessments of landslide occurrences after major storms provide an insight into where landslides might occur in the future. Many studies show that landslides tend to initiate in slope hollows or depressions where subsurface drainage converges to produce high soil pore water pressures during heavy rainfall (Sidle *et al* 1985).

On variable topography, shallow failures are often concentrated on slopes above a threshold slope value. For instance, on hill country at Whangapoua, Coromandel Peninsula a large storm in 1971 triggered many shallow landslides on non-forested slopes over 32 degrees of steepness but very few on slopes less than 28 degrees (O'Loughlin, Unpublished NZ Forest Service Report 1973). On slopes which are concave (upwards) failures often tend to concentrate on the upper steeper slopes. On a larger regional scale, Hocking (2004) reports that the hill country underlain by soft Tertiary sandstones and mudstones in the Taranaki-Manawatu region are much more susceptible to shallow landsliding than slopes underlain by older greywacke rock. In the Wairarapa, Crozier *et al.* (1980) found that landslides caused by an extended wet period in 1977, were most common on northern aspects and on upper slopes where soil strength was low.

These general indicators of landslide occurrence can be used to plan where in the landscape it is most important to provide slope protection. The reliability of this approach can be reduced if land use or vegetation cover changes over time.

Predictions based on storm rainfall information

Studies of shallow landslides which occurred during measured rainfall events have been used to develop threshold relationships using rainfall intensity and duration as the main predictor parameters. For instance Caine (1980) used information from 73 storms to predict if and when during a storm landslides will probably occur. His relationship [$I = 14.82(\text{duration in hours})^{-0.39}$] indicates the rainfall intensity threshold when landslides are likely to occur.

Where the frequency of regional rainfall intensity-duration is known, this information can be used in combination with threshold relationships to identify return periods for landslide-causing events. Areas with more frequent return periods may need to be given higher priority for slope protection measures. Other similar rainfall threshold approaches are discussed by Crozier *et al.* (1980) and Sidle *et al* (1985).

Predictions based on terrain assessment approaches

Terrain assessments provide an approach to landslide prediction which is similar but more sophisticated than simply using a knowledge of where landslides have occurred in the past. Terrain assessments involve the mapping of a range of geological, topographic, vegetation cover, slope hydrologic factors and the locations of past landslides to provide a spatial depiction of the changing slope stability conditions across the landscape.

In New Zealand multiple factor terrain assessments have been carried out by Gage & Black (1979) for the upper Waipaoa river catchment on the East Coast of the North Island, Phillips & Pearce (1984) for the Tokomaru Forest area on the East Coast and Pearce (1977) for Waimea Forest in north Westland. A general multiple factor approach specifically designed for evaluating the hazards associated with forest road building and harvesting on steep terrain is outlined by Hicks & Smith (1981).

Predictions based on applications of slope stability models in combination with the use of GIS and other computer tools

The ability to apply slope stability models in a spatial sense across catchments or regions was simplified with the advent of GIS and other computer tools in the late 1980s and 1990s. One of the best approaches was developed by Pack *et al* (1999) specifically for shallow debris slides and debris avalanches. Known as SINMAP (Stability Index Mapping), this GIS-based approach utilises the infinite slope model with wetness (soil pore water pressure) obtained from a topographically based steady state model of slope hydrology. Digital elevation model methods are used to obtain key input information such as slope and catchment area. These and other soil strength and soil wetness parameters are delineated on a numerical grid over the study area. The SINMAP model calculates a stability index at each grid location in a study area. The stability index ranges in numerical value from 0 (most unstable) to 1 (least unstable). The final output of most SINMAP studies is maps that can be used to define areas of potential slope instability. Pack *et al* (1999) provide a very comprehensive theoretical background of the SINMAP model, a clear guide for its application and a set of case studies in landslide-prone areas of British Columbia, Canada.

The SINMAP approach was recently applied by Zaitchik & van Es (2003) in Honduras to predict zones of instability. They found that SINMAP provided a very useful tool for rapid characterisation of landslide susceptibility over large land areas. Forest managers operating on steep landslide-susceptible country would be well advised to familiarise themselves with SINMAP or similar landslide prediction approaches.

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