Stabilising-Parameters of Vegetation: A Critical Look Down-Under

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ABSTRACT

There has been a long held belief that erosion control performance by vegetation relates to the additional strength provided by vegetation roots to the soil as well as the ability of the above-ground parts to intercept and transpire water. While the latter has received considerable attention and the processes are well documented and quantified for a range of vegetative covers, the former has not.

The research team has two decades of experience investigating the hidden talents of plants and the contribution they make to reducing erosion in New Zealand's landscapes. This paper presents some of the critical-success parameters of the below-ground components of plant species in terms of their contribution to the performance of a vegetation cover. Parameters such as canopy occupancy, root occupancy, root depth, root biomass, and root cross-sectional area per shear area, are discussed and compared for two woody tree species. A modelling framework that allows the evaluation of a slope's stability is discussed.

INTRODUCTION

The role played by vegetation in improving slope stability and preventing soil erosion is well recognised (e.g., Greenway 1987; Marden & Rowan 1993; Phillips & Watson 1994; Morgan & Rickson 1995; Gray & Sotir 1996). Surprisingly, the international literature of below-ground root data for grasses and woody tree species used in erosion control is limited. As restoration projects, particular those associated with waterway enhancement, increase in popularity, there is a need to quantify the cost and benefits in terms of effectiveness or performance of vegetation strategy to control erosion.

In general terms, the mechanisms by which vegetation influences slope stability may be broadly classified as either hydrological or mechanical in nature. Hydrological factors include interception of rainfall by the foliage and transpiration of water from the soil. Mechanical factors arise from interactions of either the foliage or root system with the slope. Roots, due to their tensile strength and frictional properties, reinforce the soil. Large roots may penetrate deeply and become anchored in firm strata, forming a support (buttress) to the soil upslope of the tree. Hydrological mechanisms leading to lower pore-water pressures are beneficial, while those that increase pore pressures are adverse. Mechanisms that increase shear resistance in the slope are beneficial, while those that increase shear stress are adverse. All factors are not applicable to all slopes and the relative importance of each varies from site to site.

In this paper, data are presented to demonstrate the effectiveness of woody tree species in the prevention of natural slope failure. We focus on storm events, which in New Zealand account for the majority of natural landslides. A new modelling framework that allows evaluation of a slope's stability by considering the energy that plant roots absorb during soil failure is also presented.

Parameters useful in assessing vegetation performance for erosion control in New Zealand's hill country are compared for two woody tree species – *Pinus radiata* (radiata pine) the most widely planted commercial tree species in New Zealand, and *Kunzea ericoides* (kanuka) a native scrub species that rapidly colonises abandoned pastoral farmland. (Note: we focus on structural roots, i.e., those that are 2 mm or greater in diameter).

STABILISING PARAMETERS

Canopy site occupancy

The rate a site is occupied by a tree canopy depends on the growth rate and planting density. Canopy site occupancy equals 1 when a circle representing the canopy is projected onto the ground and touches circles from adjacent trees (Kelliher et al. 1992). Canopies of individual trees, i.e., circles, are grown at the selected planting density, increasing their diameter over time until canopy closure is attained (Figure 1). *<insert Figure 1 here>*

Stands of naturally regenerating kanuka have the potential to reach 100% canopy closure in 3 years (Figure 2 and Table 1). Radiata pine and other exotic species planted at typical plantation densities reach canopy closure at about 5 years.

<insert Figure 2 and Table 1 here>

Treatment options that promote the quickest canopy closure are likely to be the most effective in terms of reducing sediment generation. Canopy closure is a useful surrogate for "erosion control effectiveness", particularly when no other data are available, as it intrinsically takes account of lateral root spread, which we have found precedes canopy spread.

Root morphology

As trees grow, their contribution to a site's stability increases as a function of the speed and ease at which roots "colonise" the soil. This depends on the root content, the roots' material properties, and the morphology or architecture. Root morphology and architecture may be genetically controlled or modified by environmental and edaphic factors.

Studies of 8-, 16-, and 25-year-old radiata pine root systems (e.g., Watson & O'Loughlin 1990) indicated root system and root morphology were determined by the physical soil conditions, particularly stoniness, drainage conditions, and depth to water-table, bedrock or impermeable substrata. On most steep slopes, shallow soils over bedrock cause root systems to be plate-like, and roots seldom penetrate beyond 2.5 m depth.

Studies of 6-, 16-, and 32-year-old kanuka root systems (e.g. Ekanayake et al. 1997; Watson et al. 1999) indicated that lateral roots of most of the trees were distributed asymmetrically around the stump, growing predominantly, up and across the slope. Approximately 97%, 90%, and 90% of the mass of the 6-, 16-, and 32-year-old root systems, respectively, were within 1 m of the stump and about 95% of the root mass of all the age classes were confined to the top 1.0 m of soil.

Root biomass

Root biomass is the total weight (dry weight) of roots present in the soil. Usually work on root biomass centres on production rates of the fine root fractions to understand nutrient uptake and carbon cycling. Structural root biomass has been done only in a limited number of New Zealand studies.

Mean individual tree root biomass, including the root bole, for radiata pine and kanuka is listed in Table 1. A high percentage of the root mass for both species is confined to within a metre of the ground surface; 97% for kanuka at age 6 years and 84% for pine at age 4 years, and probably has little effect at the critical failure depth.

Treatment options that promote greatest root biomass, particularly in the early years following establishment, are likely to be the most effective in terms of reducing sediment production. For sediment reduction effectiveness, however, root biomass *alone* is a poor predictor of effectiveness.

Lateral root site occupancy

Site occupancy is related to plant density and lateral root growth rates. Root site occupancy occurs when root systems of adjacent plants overlap, and is taken as a theoretical starting point for slope stability contribution. The concept projects the root system onto the ground as a circle, in the same manner as for canopy occupancy.

The faster the site is occupied by roots, the greater the reinforcement to the soil. Kanuka reaches 100% lateral root occupancy within about 2 years (Figure 3). Radiata pine on good sites can also approach this value. Although 100% lateral root occupancy is achieved for both k~nuka and radiata pine within 3 years, the occurrence of landsliding on slopes with young vegetation arises because most roots are confined to shallow depths and have no

influence on the critical failure surface. Lateral root site occupancy is, therefore, not in itself a foolproof indicator of "effectiveness".

<insert Figure 3>

Root depth

Root depth is the maximum depth a root of 2-mm diameter reaches. How well roots grow in the vertical plane largely reflects the site environmental conditions and any impediments to vertical root growth. Thus effectiveness is a function of the roots ability to anchor soil to bedrock or to layers within the regolith that might be prone to failure.

Radiata are deeper rooted than most other exotic plantation species we have studied. Indigenous species, including k-nuka, are in general, very shallow rooted. On its own, this parameter does not give a strong indication of the expected performance but it can be indicative of the potential for effective control if enough data from the same species across a range of site conditions is obtained.

Root strength

A traditional method for assessing how roots contribute to stability is to determine the strength of individual tree roots. Most studies measure tensile strength of individual roots, usually in a laboratory. A sizeable amount of data has been gathered for a number of species.

Root tensile strength varies with growing environment (Phillips & Watson 1994). Mean tensile strength of radiata roots ranges from 13.36–17.62 MPa (range 4.18–42.75 MPa, N=387) and for kanuka is 32.34 MPa (range 15.54–79.98 MPa, N=64) (Figure 4).

Root strength on its own is not a good predictor of the effectiveness of a particular species for erosion control.

Root cross-section area per shear area (RAR)

This parameter is defined as the combined area of roots at depth that cross a potential shear plane parallel to the ground surface. Others have used the term root area ratio (RAR), though this is usually determined by trenching or profiling a vertical section through the soil and roots and assuming this to be uniform in all directions.

Maximum effectiveness is gained for the treatment that has the largest root cross-sectional area at the depth at which failure is most likely to occur. For New Zealand hill country, many landslides triggered by rainstorms fail at depths around 0.75–1.0 m. There are more radiata roots, or roots of a greater diameter, that collectively have a greater cross-sectional area at a depth of 0.8–1.0 m than kanuka roots (Figure 5). Hence, for an 8-year-old stand we regard radiata as being more effective than kanuka based on this parameter alone. Deep-rooted species planted at high stand densities will be more effective than shallow-rooted species planted at lower densities. Species with fibrous root systems or those that tend to be shallow rooted will rank poorly using this criteria *alone*. *<insert Figure 5 here>*

STABILITY MODEL

Models based on physiology and ecology have been developed to approximate the tree roots' contribution to slope stability (Wu et al. 1979; Gray & Ohashi 1983; Wu & Erb 1988). Although these models are useful to estimate and compare the strength contribution from tree roots between different species, none are available to estimate the actual thresholds for the initiation of landslides. Many such approaches relate the tensile strength differences between species as a surrogate for the additional cohesion factor in a stability analysis (Montgomery et al 2000).

A new stability analysis approach has been developed that incorporates the ability of a soil-root system to withstand strain (Ekanayake & Phillips 1999b). It is based on a consideration of the energy consumed during the shearing process of the soil-root system. The method uses characteristics of the shear stress — displacement curve of a soil-root system obtained from *in situ* direct shear tests under simulated overburden pressure and pore-water pressure conditions. The model is well suited to the conditions found in New Zealand soft-rock hill country where shallow landslides are frequent and share common features such as similar shear surface depth, rainfall conditions, and soil characteristics. While the method is currently limited to vegetated hillslopes where the stability analysis can be approximated by a simplified infinite slope model, it is currently being extended to account for circular slip

surfaces more typical of river bank collapse and offers an alternative approach to that Abernethy & Rutherfurd (1999).

The approach has been coupled with a shallow landslide initiation model (Ekanayake & Phillips 1999a) to produce a composite model that allows the determination of landslide thresholds for combinations of vegetation, slope, and rainfall characteristics (Ekanayake & Phillips submitted). Using this model we can determine the effectiveness of various vegetation treatments in terms of reducing or shifting the landslide thresholds.

Vegetation has the effect of increasing the critical shear plane depths for landslide initiation as well as increasing the critical rainfall duration. The results show the contribution of plant roots to slope stability is greater for steeper slopes than for less steep slopes — more or less what our intuition and observations would suggest.

On a 40E slope, 16-year-old kanuka forest increased the critical shear plane depth by 75% while 16-year-old radiata pine on the same slope changed the critical shear plane depth by 50% (Figure 6). The higher plant density of indigenous kanuka forest is the main reason for the difference.

On the same hillslope at 50% initial saturation, the critical rainfall duration without trees at an average rainfall intensity of 10 mm/h is 25 h (Figure 7a). An 8-year-old radiata pine forest with 600 stems/ha will increase the critical time duration for the same rain intensity by 40%. At 16 years old, this pine forest will increase the critical time duration by 80% (Figure 7b). In comparison, an undisturbed 16-year-old indigenous kanuka forest with 30 000 stems/ha will increase the thresholds by 120% (Figure 7c).

We can use these figures to choose different combinations of species and plant densities to suit the landscape and climatic conditions of the area we might be interested in. The generalised method for stability analysis described may be used as a simple tool to compare and select the most appropriate species and densities to increase the stability of a given hillslope.

CONCLUSIONS

Various vegetation parameters that contribute to a slope's stability have been presented. Each parameter on its own may not be a significant predictor of a vegetation's effectiveness in controlling erosion. However, in the absence of "complete" knowledge of the species under consideration, these parameters can assist in determining the relative performance of a vegetation treatment option for sediment control.

In strict engineering terms, it is necessary to have quantitative data on root characteristics of plants if these data are going to be incorporated into any stability or cost–benefit analysis aimed at determining the safety factor or risk of a particular proposal. In New Zealand we can use the parameter values for the two species in our composite model to allow us to predict how vegetation changes the landslide-initiation thresholds for a range of sites.

The problem that ground bio-engineers, in general, are faced with is a virtual lack of data for the common species used in rehabilitation or restoration projects. There is, however, a growing international interest in using plant materials in engineering projects, and it is likely there will be renewed efforts to begin to collect these fundamental, down-under data for our plants.

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Table 1Vegetation parameters for radiata pine and kanuka. Figures in parentheses represent the standard
error of means (From Watson et al. 1999).

| Mean age (yrs) | Radiata pine | | | K~nuka | | |
|--|--------------|--------------|---------------|--------------|--------------|---------------|
| | 8 (0) | 16 (0) | 25 (0) | 6 (0.7) | 16 (1.4) | 32 (2.7) |
| Stand density ^(a) Stems/ba | 240 | 250 | 270 | 16000 | 12800 | 3900 |
| No. trees | 5 | 5 | 3 | 5 | 5 | 5 |
| Mean tree ht. (m) | 9.5 (-) | 21.1 (-) | 30.4 (-) | 6.1 (0.5) | 6.7 (0.3) | 13.6 (0.3) |
| Mean dbh(b) (mm) | 170 (10.7) | 400 (25.9) | 550 (27.7) | 45 (4.4) | 66 (7.2) | 127 (15.3) |
| Mean max. root length (m) | 3.5 (0.3) | 4.2 (0.5) | 9.1 (1.0) | 1.5 (0.2) | 3.0 (0.4) | 3.6 (0.7) |
| Max. root length (m) | 4.7 | 6.4 | 10.4 | 1.9 | 4.5 | 6.1 |
| Mean max root depth (m) | 1.8 (0.1) | 2.4 (0.1) | 2.9 (0.1) | 1.3 (0.3) | 1.6 (0.2) | 1.3 (0.1) |
| Max. root depth (m) | 2.1 | 2.6 | 3.1 | 2.2 | 2.1 | 1.5 |
| Time to canopy occupancy at normal density (Years) | 3–5 | | | 2 | | |
| Root biomass (t/ha) | 37 | 174 | 560 | 13 | 29 | 78 |
| Root strength (MPa) | Min 4.18 | Max 42.75 | Mean 15.16 | Min 15.54 | Max 79.98 | Mean 32.45 |
| Root cross-section area per shear area at depth 0.8 m for 8-year-old trees (cm2/m2) | 11.23 | | | 3.0 | | |

dbh = Diameter at breast height (height measured to 1.4 m on uphill side of tree).



Figure 1 (a) Concept of canopy occupancy for radiata pine at age 5, 1250 stems/ha.(b) Effect of planting density and spacing on canopy occupancy for radiata pine age 5.



Figure 2 Generalised canopy occupancy for radiata pine (1250 stems/ha) and kanuka (natural stand densities). Note: silvicultural treatments not taken into account.



Figure 3 Generalised lateral root-site-occupancy for radiata pine – 1250 stems/ha and kanuka – natural stand densities.



Figure 4 Mean maximum root strength for New Zealand tree species.



Figure 5 Root cross-section area per shear area for radiata pine and kanuka. Hashed area represents typical depths for shallow landslides in New Zealand hill country (data consolidated from various sources).



Figure 6 Safety factors estimated for a range of plant densities on a 40 degree slope and various shear plane depths (the critical shear plane is found when the safety factor = 1) (after Ekanayake & Phillips submitted).

- (a) 16-year-old radiata pine
- (b) 16-year-old kanuka.



Figure 7 Landslide threshold combinations (critical rainfall duration and intensity) for 30 and 40 degree slopes (after Ekanayake & Phillips submitted).

- (a) 8-year-old pine at 600 stems/ha
- (b) 16-year-old pine at 600 stems/ha
- (c) 16-year-old kanuka at 30000 stems/ha.