Soil Fixation by Tree Roots: Changes in Root Reinforcement Parameters with Age in *Cryptomeria Japonica* D. Don. Plantations

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Abstract The number of catastrophic incidents due to slope instability problems in China is a major problem, with > 2400 major events occurring in recent years, resulting in the destruction of urban and rural environments and the loss of human life. Cost-effective and ecologically friendly methods can be used to avoid certain potential catastrophes. Such techniques involve the use of vegetation to stabilize a slope or arrest erosion, but can also include for example, the management of protection forests against avalanches and landslides.

Shallow landslides can be avoided by planting species which improve soil cohesion, either through having an increased Root Area Ratio (RAR), a high root tensile strength, or a combination of both. A large number of species, both woody and non-woody, have been identified as useful in improving soil cohesion. However, with regard to tree species, it is not known whether tree age affects soil cohesion through differences in either RAR or root mechanical properties. Therefore, we carried out a study on root distribution and mechanical properties of trees at different ages, growing in plantation forests in Sichuan province, China.

Soil cores (150×450 mm) were extracted at different distances around trees of Japanese cedar (*Cryptomeria japonica* D. Don) growing in plantations aged 9, 20 and 30 years old. All plantations were close together on the same type of soil and the same slope angle. Each soil core was divided into three different depth classes and roots < 10 mm in diameter were removed from each class. Root tensile strength was then determined on > 150 roots using a tensile testing machine. Initial results suggest that young trees provide greater soil cohesion than in older plantations through increased RAR. The increase in RAR of young trees may be due to a higher planting density. In older plantations, RAR was extremely low at distances of > 1.0 m from the tree stem, therefore soil cohesion is highly heterogeneous in older plantations, thus leading to an increased likelihood of soil slippage. It was also observed that removal of trees through thinning can also decrease soil cohesion temporarily, as roots of harvested trees die and remaining trees have not yet had time to exploit the newly available space.

Keywords: landslides, slope stability, Japanese cedar, Root Area Ratio, root biomass, tensile strength.

Introduction

Water contamination and land degradation through erosion and landslides have been listed as China's top environmental priorities. Since 1991, it has been prohibited to cultivate crops on reclaimed slopes > 25° (http://www.ec.com.cn/pubnews/2003_02_16/200594/1000429.jsp), and the planting of trees is strongly encouraged. However, the choice of tree species and the management of even-aged, monospecific forest stands should be carefully considered when planting on steep slopes. In some cases, mature stands may even result in surcharge on a slope, whereby the weight of the stand contributes to slope instability (Dhakal and Sidle 2003). Therefore, studies on soil fixation by trees on steep slopes, and how this fixation is influenced by stand characteristics is of utmost importance in China, where two-thirds of the country is made up of rugged plateaux, hills and mountains.

The use of vegetation in the form of ground bio- and eco-engineering (Stokes et al 2004) techniques is now becoming standard engineering practice to reinforce soil on natural and man-made slopes (Coppin and Richards 1990, Greenway 1987, Roering et al. 2003, Schiechtl 1980, Schmidt et al. 2001). Certain species of plants, and in particular woody shrubs and trees (Schmidt et al. 2001, Wu 2006), can reinforce the soil matrix, as their root systems increase soil shear strength (Anderson and Richards 1987, Coppin and Richards 1990, Operstein and Frydman 2000). The presence of plant roots results in an increase in apparent cohesion via root fiber reinforcement, which usually augments superficial slope stability (Schmidt et al. 2001, van Beek et al 2005). The root-soil reinforcement model developed by Wu (1976), and elaborated upon by Waldron (1977),

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is widely used to express additional cohesion due to the presence of roots in the soil matrix (Bischetti et al. 2005, Gray and Sotir 1996, Roering et al. 2003). This model states that the shear strength of soil reinforced by roots $s_s r$ is calculated by the Mohr-Coulomb equation:

$$s_{sr} = c'_s + c_r + \sigma' \tan\phi \tag{1}$$

where c'_s is the soil cohesion, c_r is the apparent cohesion provided by roots, σ' is the effective normal stress on the shear plane and ϕ' is the soil friction angle. Shear forces developed in the soil when the soil layer moves are translated into tensile force in roots. The mobilization of this tensile resistance in the roots can then be translated into tangential and normal components. Assuming that roots are elastic, oriented perpendicularly to the slip plane, fully mobilized in tension and that the effective internal friction angle is unaffected by root reinforcement, the additional root cohesion can be defined as:

$$c_r = t_r(\sin\delta + \cos\delta\tan\phi') \tag{2}$$

where δ is the angle of root deformation in shear zone and t_r is the average mobilized tensile strength of roots per unit area of soil. t_r can be expressed as the product of Tr the average tensile strength of roots and $\frac{A_r}{a}$ the fraction of soil occupied by roots called the Root Area Ratio (RAR). The values of $(\sin\delta + \cos\delta\tan\phi'$ can be approximated as 1.2 (Wu et al. 1979) and so equation 3 can be rewritten as:

$$c_r = 1.2T_r(A_r/A) \tag{3}$$

Additional cohesion due to the presence of roots can thus be evaluated by two major characteristics of root systems: Tr and RAR. Such characteristics are determined by genetic and environmental factors and have a high degree of variability. Both RAR and Tr are influenced by species and site factors e.g. local climate, soil type, land use management, season, root type and size, as well as orientation of roots in the soil (Genet et al. 2005, Gray and Sotir 1996, Operstein and Frydman 2000, Lindstrom and Rune 1999, Turmania 1965). However, RAR can be difficult to measure in the field, as large trenches need to be dug and root diameter measured by hand.

Compared to measurements of RAR in the field, estimating root biomass is relatively simple. Soil cores can be extracted from several sites within the chosen study area, and fresh or dry root biomass determined from roots present within the core (Bohm 1979). Therefore, if RAR could be determined from root biomass data, a larger number of samples could be measured, thus reducing variability. Variations in root biomass may nevertheless occur within sites, e.g. John et al. (2001) found that seasonal variations of root mass in stands of Khasi pine (*Pinus kesiya* Royle ex. Gordon) existed, with maximal values occurring during the rainy season. Schmid et al. (2002) observed that the total fine root biomass was greater in mixed stands of spruce (*Picea abies* L.) and beech (*Fagus sylvatica* L.) compared to the respective pure stand. Root biomass also changes with tree age. Some studies have shown that fine root biomass peaks at an early age in stand development and is maintained relatively constant thereafter (John et al. 2001). However, other studies demonstrated a marked increase in fine root biomass with an increase in age (Vogt et al. 1981). Nevertheless, modifications in root biomass will also be reflected in RAR, and should therefore be taken into account when developing models of root-soil reinforcement for a given species. In particular, how root biomass or RAR evolves with tree age should provide a useful indicator of changes in additional soil cohesion in a stand over time.

To determine how additional cohesion evolves over time, it would also be necessary to examine changes in Tr with age. Few data exist concerning temporal changes in Tr. Operstein and Frydman (2000) found that Tr was unaffected by the age of woody shrubs roots but only plants < 10 months were studied. Genet et al (2005) determined that Tr was highly dependent on root diameter and cellulose content. Thinner roots were relatively more resistant in tension than thicker roots and had greater amounts of cellulose. Therefore, it seems possible that changes in Tr may well occur with tree age.

Root biomass and Tr in Japanese cedar (*Cryptomeria japonica* D. Don) stands of different ages in the Sichuan province of China were measured to determine if changes in these parameters occurred over time.

Materials and Methods

Site description

Study sites were located north-west of Chongzhou City, on the eastern limits of the Tibet-Qinghai plateau, Sichuan province, China. The three sites were all situated in the same valley (30°48′4104′N, 103°24′732′E), which belongs to the middle segment of Longmen Mountain, the south-east offshoot of Qionglai Mountain. The

Table 1. Stand characteristics of plots.

Plot	Age (years)	Mean DBH (mm)	Mean height (m)	Number of samples
Young plantation	9	94.4 ± 0.37	7	136
Middle plantation	20	193.1 ± 0.71	12	201
Old plantation	30	278.9 ± 1.04	15	252

topography of the area is mountainous and characterized by gorges, steep hills and valleys, ranging from 960–3868 m in altitude.

Sites are situated in the moist monsoon zone and the climate is subtropical. Annual average temperature is 12.3 °C with minimum temperatures of 6°C in January and a maximum of 32.7°C in July and August. Average annual precipitation is 1300–1450 mm with 70% of the annual average amount in June to September and only 5% from November to January. Climate is characterized by long, misty days, high humidity (annual average relative humidity 86%), little sunshine (average annual sunshine = 641.6h), and low wind speeds (annual average wind speed = 1.4 m/s). Soil parent material is mainly constituted of lime rock, sandstone, and granite stone. The major soil type is a yellow soil accompanied with brown forest soil in mountainous regions. The general soil thickness is 0.5–1.3 m with a humus layer of 0.01–0.03 m.

Three even-aged plantations of Japanese cedar (*Cryptomeria japonica* D. Don) aged 9, 20 and 30 year old were selected. All plantations were close together on the same type of soil, slope orientation and angle (35°) and were located at approximately the same altitude (1110m, 1080m and 1240m, respectively). Stand characteristics of the three plantations were measured (Table 1) and ten trees from each plantation were selected randomly to study root biomass and root tensile strength.

Root sampling

Root samples were collected in July 2005. The samples were harvested using the soil core method (Bohm 1979, John et al. 2001, Sudmeyer et al. 2004). Cylinders contained 17 dm^3 of root-soil matrix (0.19 m diameter * 0.15 m long). Cores were collected around each tree in four directions along the slope (upslope, downslope and perpendicular to the slope direction). In the 30 year old plantation, the distance between cores was 0.75 m and three cores were taken in every direction. However, in the younger plantations, tree density was higher, therefore, cores were taken every 0.50 m and only two distances from the tree base could be sampled in the 9 year old stand. Samples were extracted every 0.15 m to a total depth of 0.60 m. Several samples could not be extracted due to the presence of stones. In total, 135 samples were obtained for the 9 year old stand, 200 for the 20 year old stand and 253 for the 30 year old stand. Roots were separated manually from soil core using a sieve. Only live roots of Japanese cedar were retained because dead roots will have a negligible influence on slope stability (Schmidt et al. 2001). Live roots of Japanese cedar could be identified easily because of their woody texture, plasticity and reddish colour (Schmidt et al. 2001). Roots were then washed, dried in the open air and stored in a dry place for three days, after which biomass was measured.

Root biomass

Roots from each core sample were separated into four diameter classes : < 1 mm, 1–2 mm, 2–5 mm, 5–10 mm, < 10 mm (Drexhage and Gruber 1997, Köstler et al. 1968, Sudmeyer et al. 2004). The number of roots in each class was counted and each group of roots was then weighed using a balance with a precision > 0.001 mg. Root biomass was determined according to the volume of the auger and expressed as g m^{-2}.

Model to predict Root Area Ratio with root biomass

The Root Area Ratio can be found by dividing root biomass by the unit weight of the root fiber (Gray and Sotir 1996, Leuschner et al. 2004). A model for determining the unit weight of roots per stand was established by measuring the diameter, length and weight of a selection of roots.

Root tensile tests

Tensile strength was measured on 100 tree roots per plantation. Roots were collected randomly from the above samples, but ensuring that each diameter class was represented, along with each distance from the tree trunk, depth and slope direction. Roots were soaked in water for one night so that all roots had the same moisture content. The diameter of roots tested varied between 0.3 mm and 4.3 mm. The length of each sample was at least 15 times its diameter. Mechanical tests were performed with a Universal Testing Machine (ADAMEL Lhomargy, France). A load cell with a maximal capacity of 1.0 kN was used and crosshead speed was kept constant at 10 mm/min. Self clamping jaws were used to avoid damaging the roots. Only samples which broke approximately in the middle of the root were considered successful, so that root rupture was due to the force applied in tension and not induced by root structural damage. Root diameter was measured using an electronic slide gauge with 1/50 mm accuracy. Tensile strength at rupture was calculated as the maximal force required to cause failure in the root, divided by the root cross-sectional area at the point of breakage.

Statistical analysis

Biomass data were analyzed using analysis of variance (ANOVA) and analysis of covariance (ANCOVA) to detect differences between the three plantations and biomass, according to depth, distance from the tree or orientation along the slope in each plantation. Power regressions were carried out to determine the relationship between root tensile strength and diameter. ANOVA and ANCOVA were used to evaluate root tensile strength differences between the three Japanese cedar plantations. Data were analyzed with Minitab version 13.

Results

Root biomass

Mean root biomass differed significantly between the three plantations ($F = 37.26$, $p < 0.001$, ANOVA, Table 2). When roots of all diameters to a depth of 0.6 m were considered together, mean root biomass was greatest in the young plantation (75.57 ± 5.33 g m^{-2}) compared to the middle (24.33 ± 3.62 g m^{-2}) and old plantations (40.47 ± 3.20 g m^{-2}) (Table 2, Figure 1). Mean total root biomass decreased significantly with increasing depth in the three plantations (Figure 1). Root biomass declined significantly from 135 g m^{-2} to 34 g m^{-2} ($F = 38.62$, $p < 0.001$) in the young plantation, from 52 g m^{-2} to 12 g m^{-2} in the middle plantation ($F = 7.05$, $p < 0.001$) and from 66 g m^{-2} to 22 g m^{-2} in the old plantation ($F = 10.73$, $p < 0.001$).

In the 9 year old stand 60% of the total root mass was present in the top 0.15 m of soil, sharply decreasing to 9% at depths of 0.45 and 0.60 m. In the 20- and 30- year old stands, 55% and 49% of the total root mass, respectively, was located in the upper 0–0.15 m of soil and only 11% was present at a depth of 0.45–0.60 m.

Root biomass was significantly different between the three plantations at each depth (Figure 1) and for all root diameter classes except those in the 5–10 mm diameter class (Table 2). Biomass decreased significantly with distance from the tree in the old ($F = 5.23$, $p = 0.024$, ANOVA) and the middle plantations ($F = 6.44$, $p = 0.012$, ANOVA) but not in the young plantation. No significant differences in biomass were found around trees with regard to slope direction in any of the plantations.

Table 2. Mean tree root biomass (g m^{-2}) in the three plantations of Japanese cedar per diameter root class.

Age of plantation (years)	Root diameter classes				
	<1 mm	1-2 mm	2-5 mm	5-10 mm	All diameters
9	10.49 ± 0.83*	24.69 ± 1.83*	29.36 ± 2.18*	35.53 ± 4.05	75.57 ± 5.33*
20	1.83 ± 0.13*	4.49 ± 0.41*	11.30 ± 1.13*	36.91 ± 6.02	24.33 ± 3.62*
30	4.02 ± 0.31*	10.93 ± 0.61*	16.20 ± 1.06*	35.76 ± 3.72	40.47 ± 3.20*

*Indicates a significant difference in tree root biomass between the three plantations at p < 0.001 level using ANOVA.

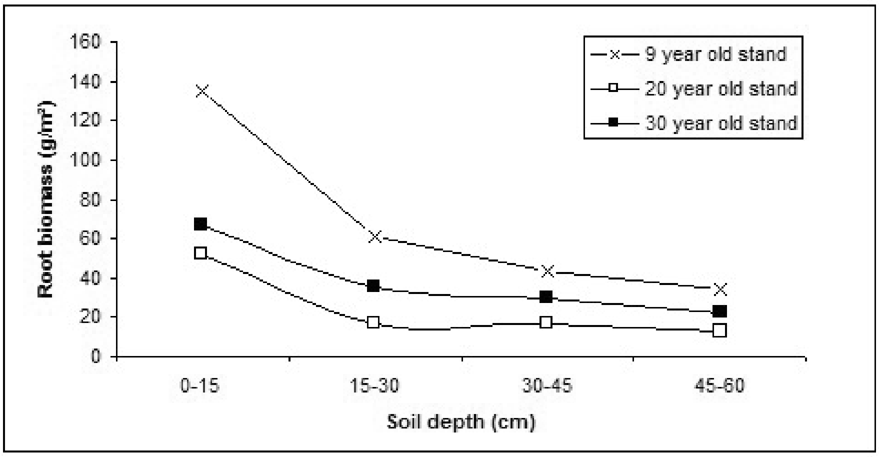

Fig. 1. Vertical distribution of mean root biomass (g m^{-2}) according to age in Japanese cedar is significantly different between the three plantations at each depth ($p < 0.001$).

Table 3. Relationship between root weight x (g) and root surface area y (cm^2).

Age of plantation (years)	Regression	R^2	p
9	y 6.8x 0.05	0.90	< 0.001
20	y 4.69x 0.42	0.82	< 0.001
30	y 11.1x 0.93	0.97	< 0.001

Root biomass to Root Area Ratio

A highly significant linear relationship between root weight x (g) and root surface area y (cm^2) was found for each plantation (Table 3).

Root tensile tests

Mean tensile root strength was 22.59 ± 0.76 MPa for the young stand, 24.18 ± 0.64 MPa for the middle stand and 31.71 ± 0.57 MPa for the old stand. The diameter of roots tested varied between 0.25 mm and 3.50 mm for the young plantation, 0.45 mm and 4.20 mm for the middle plantation and between 0.30 mm and 4.30 mm for the oldest plantation. A power regression between tensile strength and diameter was significant for roots in all three plantations (Figure 2 for the young and old stand; $y = 25.72x^{-0.22}, R^2 = 0.15$, $p < 0.001$ for the middle stand). Tensile strength was significantly greater in roots from the old plantation compared to those from the middle and young plantations ($F = 21.88$, $p < 0.001$, ANCOVA) with regard to root diameter ($F = 37.12$, $p < 0.001$, ANCOVA).

Discussion

Results from the tensile tests confirm the power law relationship between root strength and diameter obtained in previous studies (Bischetti et al. 2005, Burroughs and Thomas 1977, Genet et al. 2005, Gray and Sotir 1996, Mattia et al. 2005, Nilaweera and Nutalaya 1999, Operstein and Frydman 2000). Root tensile strength decreased significantly with increasing diameter. The smallest roots were the most resistant in tension, which could be explained by differences in cellulose content (Commandeur and Pyles 1991, Genet et al. 2005, Turmanina 1965).

Tree roots in the oldest stand were the most resistant in tension compared to roots growing in the middle and young stands for the same diameter range. The root tensile strength differences observed between

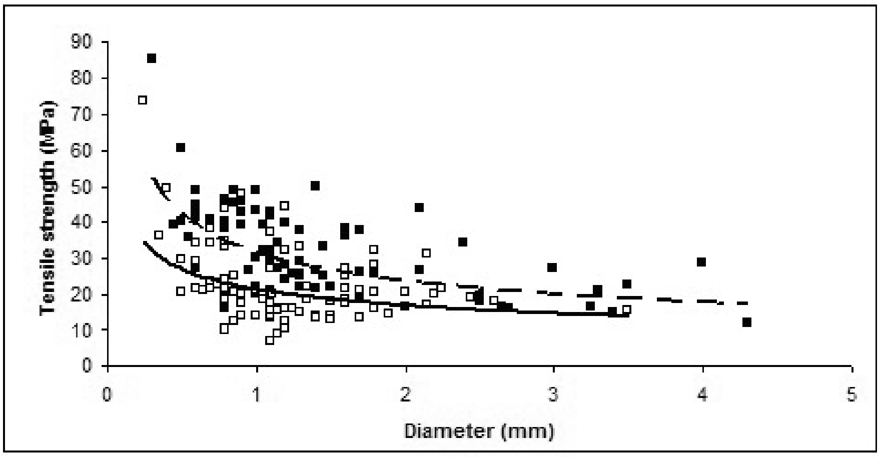

Fig. 2. Tensile strength increased significantly with decreasing diameter in roots of Japanese cedar growing in both the young plantation (white squares and solid line, $y = 21.59x^{-0.34}$, $R^2 = 0.15$, p < 0.001) and the old plantation (black squares and dashed line, $y = 31.9x^{-0.41}4$, $R^2 = 0.36$, p < 0.001).

plantations could be explained by differences in root structure, as older trees may possess higher quantities of cellulose. Therefore, it would be of interest to analyse cellulose content in roots from the three plantations.

Root biomass was highest in the youngest plantation. This increase in biomass may be due to a higher planting density as well as a higher production of fine roots in young trees. John et al. (2001) explained the decrease of fine roots with increasing age in Khasi pine, by showing that a high production of fine roots occurred in the initial stages of stand development. These fine roots rapidly absorb water and nutrients but are coverted into into coarse roots with time, thus providing better structural support to adult trees. Root biomass in the 20 year old plantation was lower than that in the older plantation. In the plantation measured, thinning was carried out several months before root sampling. Removal of trees through thinning can decrease soil cohesion temporarily, as roots of harvested trees die and the remaining trees have not yet had time to exploit the newly available space (Roering et al. 2001). Claus and George (2001) also observed that there was rapid increase in fine-root biomass after thinning, but which decreased and stabilised in mature stands.

Root biomass decreased significantly with depth and most biomass was found in the upper 0.15 m of soil. In general, the fine roots of Japanese cedar are distributed in the surface soil rather than in deeper soil (Karizumi 1976). Greater fine root concentration in the surface soil layer can be explained by a high nutrient level and better aeration and moisture content (John et al. 2001). A decrease in root biomass in lower soil layers can be attributed to the deterioration in nutrient status and biological conditions. Coarse roots are typically involved in tree mechanical support and not in nutrient absorption, thus they can be found in deeper soil. Few roots grow beyond depths of 0.6 m (Drexhage and Gruber 1997, Nilaweera and Nutalaya 1999, Schmid and Kazada 2002, Sudmeyer et al. 2004). The ultimate depth is determined by interactions among root phenology, soil structure, presence of satured soil zones, rainfall and competition from understory species (Sudmeyer et al. 2004).

Root biomass decreased with distance from the tree stem in the old and middle plantations. However, in the young plantation, biomass was more homogenous in the horizontal direction due to higher tree density. The root network is strongly dependent on crown radius or diameter at breast height according to a power-law relationship (McMinn 1963, Roering et al. 2003). In our study, most tree roots occurred within a maximum distance of 2 m distance from the stem root base.

Several studies have shown that trees growing on slopes develop a specific type of root system architecture (Chiatante et al. 2003, Khuder et al 2006, Scippa et al. 2005, Shrestha et al. 2000). However no significant differences with regard to root biomass between directions or along the slope were found in our study. The high density of the plantations along with the fact that fine roots only were measured, not structural roots responsible for anchorage, may explain the lack of asymmetric root biomass.

Young trees have greater root biomass but roots are less resistant in tension than roots of old trees. Additional root cohesion should be analyzed to determine soil cohesion in the three plantations. Initial results suggest that young trees provide greater soil cohesion than in older plantations through increased RAR. In older plantations, RAR was extremely low at distances of > 1.0 m from the tree stem, therefore soil cohesion is highly heterogeneous in older plantations, thus leading to an increased likelihood of soil slippage. Roering et al. (2003) also observed that landslides tend to occur in areas of reduced root strength. Abe and Ziemer (1991) also explained that root reinforcement of soil in Japonica cedar plantation increases quickly after afforestation for about the first 20 years, then remains about constant thereafter.

Future research should focus on the calculation of additional cohesion and also the Factor Safety (Greenwood 2006) within plantations of different ages. Therefore, measurements of soil mechanical properties need to be carried out and data added to the types of root reinforcement models developed by Wu (1976) and Greenwood (2006).

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