Detachment characteristics of root-permeated soils from laboratory jet erosion tests

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ABSTRACT

The influence of vegetation on flow and sediment dynamics at various spatial and temporal scales has been well documented. Vegetation may be one of the most effective measures in streambank stabilization. Traditionally, research on the influence of vegetation roots on streambank stabilization has focused on mechanical reinforcement and reduced applied shear stress due to above ground biomass. Few studies have investigated the effect of roots on fluvial detachment of sediment. This study conducted 36 mini-jet erosion tests (mini-JETs) on bare soil samples and 29 mini-JETs on root-permeated soil samples (average root diameters of 0.5 to 1.7 mm) to determine the role of roots in erosion resistance. The research also estimated parameters of the linear excess shear stress model (erodibility coefficient, k_d, and critical shear stress, τ_c) and a nonlinear detachment model called the Wilson Model (b_0 and b_1) and investigated the correlations between parameters of the two models and root characteristics. Root-permeated soil samples were more erosion resistant at higher shear stress as the τ_c and b_1 parameters were on average higher for the vegetated samples than the bare soil samples. As root diameter increased in the soil samples, erosion rates at high shear stress decreased. The erodibility coefficient parameters (b_0 and k_d) of both the linear and nonlinear detachment models were negatively and significantly correlated to root diameter through power functions. No significant correlation was detected between critical shear stress or b_1 and root parameters which supports conclusions of previous studies. Significant correlations were observed among the parameters of the excess shear stress model and the nonlinear detachment model; especially high correlation was observed between τ_c and b_1 for the vegetated samples. In conclusion, root-permeated soils exhibited lower erosion rates primarily through increasing the required shear stress before detachment.

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1. Introduction

A delicate feedback exists between riparian vegetation and fluvial systems which determines the form and function of the fluvial environment (Reinhardt et al., 2010; Darby, 2010; Gurnell, 2013). The influence of vegetation on flow and sediment dynamics at various spatial and temporal scales has been well documented (Curran and Hession, 2013), and determines the stability of the banks and supply of sediment load in the river (Lawler 2008; Wynn and Mostaghimi, 2006a,b). Streambank erosion, a natural process (Florsheim et al., 2008) can be intensified by various anthropogenic activities (Goodwin et al., 1997; Trimble, 1997; Belsky et al., 1999).

Excess sediment loads can lead to significant impairment of natural river channels (Simon et al., 2000; Fox and Wilson, 2010). Recent restoration efforts have focused on bank stabilization to mitigate such detrimental effects (Bernhardt et al., 2005; Palmer et al., 2005).

Vegetation may be one of the most effective measures in streambank stabilization (Thorne, 1982; Simon and Darby, 1999). The above ground biomass intercepts the precipitation and protects the soil from detachment on impact (Osborn, 1954), adds to the roughness and resistance against flow, and alters the velocity profile and shear stress patterns (Curran and Hession, 2013). Loss of soil due to splash and rill erosion has been observed to decrease exponentially with percentage of vegetation cover (Poesen et al., 1994). In channelized flow, above-ground biomass reduces the near-surface velocity and applied shear stress (Millar, 2000). Roots exert significant control on the subsurface moisture condition of the streambanks, create and maintain macropores and determine seasonal variations in pore water pressure and matric suction of soil

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(Pollen-Bankhead and Simon, 2010). Vegetation roots are known to have a wide range of influence on various intrinsic properties of soil such as bulk density (Lipiec, 1990), aggregate stability (Amezketa, 1999), infiltration capacity, and shear strength (Gray and Sotir, 1996).

1.1. Mechanical reinforcement by roots

Traditionally, the focus of utilizing vegetation in hillslope and streambank stabilization has been on bio-mechanical reinforcement of the roots. As roots are strong in tension, roots act similar to steel reinforcement in concrete structures and provide resistance against shear (Waldron, 1977; Wu et al., 1979; Gray and Leiser, 1982; Anderson and Richards, 1987; Simon and Collison, 2002). The bio-mechanical reinforcement provided by the roots was initially modeled as added shear strength in a modified form of the Coulomb equation (Waldron, 1977). It was assumed that all the roots extended vertically and provided resistance against shearing in a horizontal plane. The Coulomb equation was modified to following form:

$$S = c + \Delta S + \sigma_N \tan\phi \tag{1}$$

$$\Delta S = TS\left(\sin\theta + \cos\theta \tan\phi\right)\left(\frac{A_r}{A}\right) \tag{2}$$

where S is the shearing resistance of the soil, c is the cohesion, σ_N is the normal stress applied on shear plane, ϕ is the internal angle of friction, TS is the tensile strength of the roots and A_r/A is the ratio of root area and area of the shear plane. Gray (1974) carried out a sensitivity analysis and demonstrated that the term ($\sin\theta + \cos\theta$ $\tan\phi$) varied from 1.0 to 1.3 for normal angles. Wu et al. (1979) adopted a value of 1.2 to simplify equation (2):

$$\Delta S = 1.2\, TS\left(\frac{A_r}{A}\right) \tag{3}$$

Waldron and Dakessian (1981) suggested this equation overestimated the reinforcement provided by the roots as it assumes that all the roots in a shear plane are mobilized to their maximum strength during shearing. This overestimation was verified by various field and laboratory tests carried out by Pollen et al. (2004). Pollen and Simon (2005) and Pollen (2007) suggested using a fiber bundle model called RipRoot which assumed that roots within the soil mass have different TS. Also, the load was redistributed among the remaining intact roots. This model accounted for progressive failure of roots and was more accurate than the simple perpendicular model suggested by Wu et al. (1979). Studies have incorporated the RipRoot model in bank stabilization models like the Bank Stability and Toe Erosion Model (BSTEM) to investigate the contribution of roots to the factor of safety (Pollen-Bankhead and Simon, 2009; Polvi et al., 2014), but the influence of roots on the erodibility of streambanks is not taken into account at this time.

1.2. Resistance to fluvial erosion by roots

The mass failure of streambanks can be accelerated by fluvial erosion of the bank materials (Carson and Kirkby, 1972; Thorne, 1982). As noted earlier, most research has focused primarily on the role of above-ground biomass in reducing the applied shear stress (Millar, 2000), mechanical reinforcement provided by the roots, and sheet and rill erosion rather than streambank erosion. Quantification of the erosion reduction provided by specifically vegetation roots has proven to be difficult (Pollen-Bankhead and Simon, 2010). Most research on how roots influence fluvial erosion has focused on deriving statistical relationships between the particle detachment rate and specific roots traits.

For example, Gyssels et al. (2005) provided a list of studies which expressed erodibility coefficients or changes in the erodi-

bility coefficient as a function of mean root diameter and/or root length density. However, these studies failed to develop any generic predictive models. Flume experiments have been conducted to quantify the effect of roots on fluvial erosion. Mamo and Bubenzer (2001) reported significant reduction in rill erodibility (k_r) of root-permeated soil and consequent reduction in the soil detachment rate. The critical shear stress required for detachment (τ_c) was reported to be higher for root-permeated soils.

Wynn et al. (2004) compared root densities and distributions in streambanks with herbaceous and woody riparian buffers. Streambanks with primarily herbaceous vegetation were dominated by fine roots (less than 0.5 mm diameter) while woody streambanks had larger roots. Wynn and Mostaghimi (2006a) reported the effects of soil properties, root density, and freeze-thaw cycling on the erodibility of streambanks in Virginia. While soil bulk density was reported to primarily control soil erosion rates, the density of roots also had a significant influence. Similar to Mamo and Bubenzer (2001), increases in the volume of roots with diameters between 2 and 20 mm correlated to detachment rates.

De Baets and Poesen (2010) reported results of flume experiments carried out on 192 bare and 192 root-permeated topsoil samples. The authors measured the absolute sediment detachment rate using an erodibility coefficient (k_c) which is similar to k_r in the Mamo and Bubenzer (2001) study. They developed several regression models which predicted k_c as function of root density, soil bulk density and soil moisture. They performed multiple regression analysis and developed statistical models which predicted relative sediment detachment rate, or the ratio of absolute detachment rate of bare soil and root-permeated soil, as functions of root diameter and root density along with other soil and flow properties. The authors also observed differences in erosion reducing effects for tap versus fibrous root systems. However, model validation contained unexplained variance and called for an improved process-based model.

A similar study carried out by Burylo et al. (2012) focused on roots of two grass species and one tree species. They also used relative sediment detachment rate and investigated a larger set of root traits including root to shoot biomass ratio, root density, root volume, root mean diameter, root length density, root surface area, specific root length, root tissue density, percentage of fine roots and tensile strength (TS). One-way analysis of variance, analysis of covariance, and a principle component analysis identified mean root diameter (direct relationship) and percentage of fine roots with diameters less than 0.5 mm (inverse relationship) to be most influential on the relative sediment detachment rate. Therefore, their study implied that grass species with smaller mean root diameters and a higher percentage of finer roots more resisted erosion.

1.3. Cohesive soil detachment models

Previous studies have called for a more mechanistic and process-based approach to quantify the detachment-reducing effects of roots (De Baets and Poesen., 2010; Burylo et al., 2012). Erodibility equations provide a more process-based approach to estimate soil detachment rates as compared to empirically-based equations or simple adjustment factors for the presence of vegetation. The most frequently used erodibility model is known as the excess shear stress equation (Partheniades, 1965). This model states that the erosion rate (ε_r, cm s^{-1}) is proportional to the difference between the applied shear stress (τ, Pa) and the critical shear stress (τ_c, Pa):

$$\varepsilon_r = k_d(\tau - \tau_c)^a \tag{4}$$

where k_d is the coefficient of erodibility (cm^3 N^{-1} s^{-1}) and a is an exponent usually assumed to be one (Hanson et al., 2002; Khanal et al., 2016a). The τ_c is the minimum stress required to initiate parti-