TEMPORAL AND SPATIAL VARIABILITY IN ROOT-REINFORCEMENT OF STREAMBANKS: ACCOUNTING FOR GEOTECHNICAL PROPERTIES AND MOISTURE.

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Abstract: Riparian vegetation exerts a number of mechanical and hydrologic controls on streambank stability, which affect the delivery of sediment to channels. Estimates of root-reinforcement of soils have commonly been attained using perpendicular root models that simply sum root tensile strengths and consider these as an add-on factor to soil strength. A major limitation of such perpendicular models is that the effect of variations in soil moisture and bank geotechnical properties on root-reinforcement are omitted as root tensile strengths are considered to be independent of soil type and moisture. In reality, during mass failure of a streambank, some roots break, and some roots are pulled out of the soil intact; the relative proportions of roots that break or pull out are determined by soil moisture and shear strength, and root strengths. In this paper an equation to predict the frictional resistance of root-soil bonds was tested against field data collected at Long Creek, MS, under two soil moisture conditions. The root pullout equations were then included in the root-reinforcement model, RipRoot, and bank stability model runs for Goodwin Creek, MS, were carried out in order to examine the effects of spatial and temporal variations in soil shear strength and rooting density, on streambank factor of safety. Model results and collected filed data showed that at low root diameters breaking forces exceeded pullout forces, but at higher root diameters pullout forces exceed breaking forces. The threshold diameter between root pullout and root breaking varied with soil shear strength, with increasing soil shear strength leading to a greater proportion of roots failing by breaking instead of pullout. Root-reinforcement estimates were shown to reflect changes in soil shear-strength, for example, brought about by variations in soil matric suction. Resulting Factor of Safety (F_S) values for the bank during the period modeled ranged from 1.36 to 1.74 with 1000 grass roots/m^2, compared to a range of 0.97 to 1.37 for the non-vegetated bank. Root-reinforcement was shown to increase bank stability under the entire range of soil moisture conditions modeled. However, the magnitude of root reinforcement varied in both space and time as determined by soil geotechnical properties and soil moisture.

INTRODUCTION

Streambank instability poses a number of economic and ecological problems including land loss, and destabilizing of structures (e.g. bridges). The resulting delivery of excessive sediment to channels can cause downstream aggradation and impairment of water quality. Sediment is one of the principal pollutants of surface waters in the United States and recent studies have shown that stream bank materials are a significant if not dominant source (USEPA, 2002). It is therefore important to understand and quantify the controlling processes and the role vegetation can play in stabilizing streambanks and thereby reducing sediment erosion from this source.

Riparian areas are an important component of the overall landscape mosaic, particularly in terms of species diversity (Malanson, 1993). The presence of riparian vegetation on streambanks not only provides ecological benefits, but is also widely believed to increase the stability of stream-banks (Abernethy and Rutherfurd, 1998; Simon and Collison, 2002). As a result of the potential benefits for stability and environmental quality, interest in the use of riparian vegetation in stream restoration and stabilizing schemes has grown in recent years. However, quantification of the interactions between vegetation and bank erosion processes has been unreliable due to limited knowledge regarding the way in which roots affect the geotechnical, hydrological and hydraulic processes within a bank and its adjoining channel. Current stream-restoration designs are, therefore, based on empirical methods and standardized practices (Gregory and Gurnell, 1988; Wynn et al. 2004), as process based models examining vegetation effects are unavailable.

Riparian vegetation exerts a number of controls on bank stability. These controls can be separated into mechanical and hydrologic effects, some beneficial and some negative to bank stability. To quantify vegetation effects, several properties regarding the root network need to be established. Possibly the most challenging aspect of root investigations is the acquisition of data pertaining to root architecture and root-distributions throughout the bank. Despite the difficulties concerned with obtaining root data, a number of papers have attempted to measure and quantify the physical properties of riparian root networks and relate these properties to streambank stability. These include the studies conducted in Mississippi by Simon and Collison (2002), Easson and Yarbrough (2002), in Virginia by Wynn et al. (2004), in California by Simon et al. (in press), in various parts of the USA by Pollen et al. (2004), and in Australia by Abernethy and Rutherfurd (1998; 2000). In addition, the hydrologic effects of riparian vegetation on bank stability have been explored by Simon and Collison (2002), Simon and Pollen (2004) and Pollen (2004).

Quantifying Root-Reinforcement of Soil: It is generally accepted that plant roots provide reinforcement to a soil matrix due to the dramatically different physical properties of roots, and the soil they are embedded in (Greenway, 1987). Soil is strong in compression but weak in tension. Conversely, roots are weak in compression but strong in tension. The presence of roots in the soil thus produces a reinforced matrix in which stress is transferred to the roots during loading of the soil (Thorne, 1990). Estimates of root-reinforcement of soils have commonly been attained using simple perpendicular root models such as those of Waldron (1977) and Wu et al. (1979), which calculate root-reinforcement as an add-on factor to soil strength. The root reinforcement model of Waldron is based on the Coulomb equation in which soil-shearing resistance is calculated from cohesive and frictional forces:

$$S = c + \sigma_N \tan\phi \qquad (1)$$

where S is soil shearing resistance (kPa), σ_N is the normal stress on the shear plane (Pa), ϕ is soil friction angle (degrees), and c is the cohesion (kPa).

Waldron (1977) extended Equation 1 for root-permeated soils, by assuming that all roots extended vertically across a horizontal shearing zone, and that the roots act like laterally loaded piles, so tension is transferred to them as the soil is sheared. The modified Coulomb equation becomes:

$$\mathrm{S} = \mathrm{c} + \Delta\,\mathrm{S} + \sigma_N \tan\phi \qquad (2)$$

where Δ S is increased shear strength due to roots (kPa).

In the Waldron model (1977), the tension developed in the root as the soil is sheared is resolved with a tangential component resisting shear and a normal component increasing the confining pressure on the shear plane. Δ S can be represented by:

$$\Delta S = T_r (\sin\theta + \cos\theta \tan\phi)(A_R/A) \qquad (3)$$

where T_r is average tensile strength of roots per unit area of soil (kPa), A_R/A is the root area ratio (no units), and θ is the angle of shear distortion in the shear zone.

Gray (1974) reported the angle of internal friction of the soil appeared to be affected little by the presence of roots. Sensitivity analyses carried out by Wu et al. (1979) showed that the value of the first bracketed term in (3) is fairly insensitive to normal variations in θ and ϕ (40-90° and 25-40° respectively) with values ranging from 1.0 to 1.3. A value of 1.2 was therefore selected by Wu et al. (1979) to replace the bracketed term and the simplified equation becomes:

$$\Delta S = T_r (A_R/A) \times 1.2 \qquad (4)$$

Thus, according to the simple perpendicular root model of Wu et al. (1979), the magnitude of reinforcement simply depends on the amount and strength of roots present in the soil. However, Pollen et al. (2004) and Pollen and Simon (2005), found that these perpendicular root models tend to overestimate root-reinforcement due to the inherent assumption that the full tensile strength of each root is mobilized during soil shearing, and that the roots all break simultaneously. This overestimation was largely corrected by Pollen and Simon (2005), by constructing a fiber-bundle model (RipRoot) to account for progressive breaking during mass failure.

However, observations of incised streambanks suggest that when a root-reinforced soil shears, two mechanisms of root failure occur: 1) root breaking and 2) root pullout. The anchorage of individual leek roots was studied by Ennos (1990), who developed a function for pullout forces based on the strength of the bonds between the roots and soil:

$$F_P = S * L * 2\pi r \tag{5}$$

where F_P is the pullout force for an individual root (N), S is soil shear strength (kPa), r is the radius of the root (m) and L is the length of the root (m). L can be estimated in the absence of field data using (Waldron and Dakessian, 1981):

$$L = R\, r^g \tag{6}$$

where the constants g and R have ranges: $0.5 < g < 1.0$; $200 < R < 1000$.

For the saturated part of the bank profile the Coulomb equation is used to calculate S (Equation 1). For the unsaturated part of the bank profile the criterion as modified by Fredlund et al. (1978) is used:

$$S = c' + (\sigma - \mu_a) \tan \phi' + (\mu_a - \mu_w) \tan \phi^b \tag{7}$$

where c' is effective cohesion (kPa), σ is normal stress (kPa), μ_a is pore air pressure (kPa), μ_w is pore-water pressure (kPa), $(\mu_a-\mu_w)$ is matric suction, or negative pore-water pressure (kPa), and $\tan \phi^b$ is the rate of increase in shear strength with increasing matric suction.. The quantity $(\mu_a-\mu_w) \tan \phi^b$ represents the additional strength provided by matric suction along the unsaturated part of the failure plane and is reflected in the apparent or total cohesion (c_a) term (although this does not signify that matric suction is a true form of cohesion) (Fredlund and Rahardjo, 1993):

$$c_a = c' + (\mu_a - \mu_w) \tan \phi^b \tag{8}$$

Although root breaking may be independent of soil moisture, root pullout forces are a function of soil shear strength, which is determined by effective cohesion, soil friction angle, and soil matric suction. Thus, the forces required for root-pullout vary spatially with material type, and temporally with variations in soil moisture. The original version of RipRoot (Pollen and Simon, 2005) did not take into account root pullout forces, and as such could not take into account the effect of differing soil types and moistures on estimates of root-reinforcement. This was considered to be a major deficiency of the model and the perpendicular root models that preceded it. In this paper, the forces required to pullout roots were investigated in a field study, and the results tested against Equation 5 (Ennos, 1990). Root pullout forces were then compared to root breaking forces obtained from tensile strength testing, and the RipRoot model was modified to account for both root-failure mechanisms. Results from the newly constructed model are presented to show the variability in root-reinforcement as soil matric suction changed through a wetting and drying cycle following a storm event.

METHODS

Root tensile strengths and root pullout forces were measured using a Root-Puller (based on a design by Abernethy, 1999). The puller is comprised of a metal frame, with a winch attached to a load cell and displacement transducer,and connected to a datalogger. A trench was dug using an excavator, to expose the roots of a stand of mature river birch (*Betula nigra*) trees located on the banks of Long Creek, MS. The Root-Puller was attached to the side of the trench opposite each tree, so that the roots being tested were no longer anchored by the tree. The excavation process may have loosened the bond between the roots and the soil at the trench interface, but any disturbance did not appear to extend more than a few millimeters into the soil, thus limiting the effect on the root-soil friction forces measured. The device was attached to the side of the trench by tying a rope around metal stakes hammered into the ground along the top of the trench. The load cell measured the force required to either pull the root out of the soil, or for it to break. Root-soil friction experiments were carried out at the same site (Long Creek, N. Mississippi), at different times of the year (April and July 2002) to test under varying soil moisture conditions. In each experiment 70 to 80 roots were tested to have sufficient data to distinguish any trends in the data from natural variability.

RESULTS AND DISCUSSION

Hypothetical pullout forces were estimated using Equation 5 and compared to root breaking forces (calculated from tensile strength-diameter relations of the form $y = ax^{-b}$ previously published in Pollen et al., 2004 and Pollen and Simon, 2005). Comparison of the variation in pullout and breaking forces with increasing root diameters (range of root diameters was 0.5 to 8 mm) showed.that smaller diameter roots are more likely to be pulled out of the soil, and larger diameter roots are more likely to break as a soil shears. The threshold between the two failure mechanisms is a function of the shear strength of the soil and thus the strength of frictional bonds between the roots and soil, and the species specific tensile strength curves.

River birch field data: The field data collected from Long Creek, MS were used to examine whether a clear threshold existed between the two root-failure mechanisms (Figure 1). The data show that above a certain root diameter, all of the roots broke. However, below this threshold diameter some of the roots broke and some were pulled out of the soil intact. The breaking of roots below the threshold diameter may have been due to the presence of root branching, causing the friction forces to vary from the idealized situation of straight, un-branched roots as assumed in Equation 5.

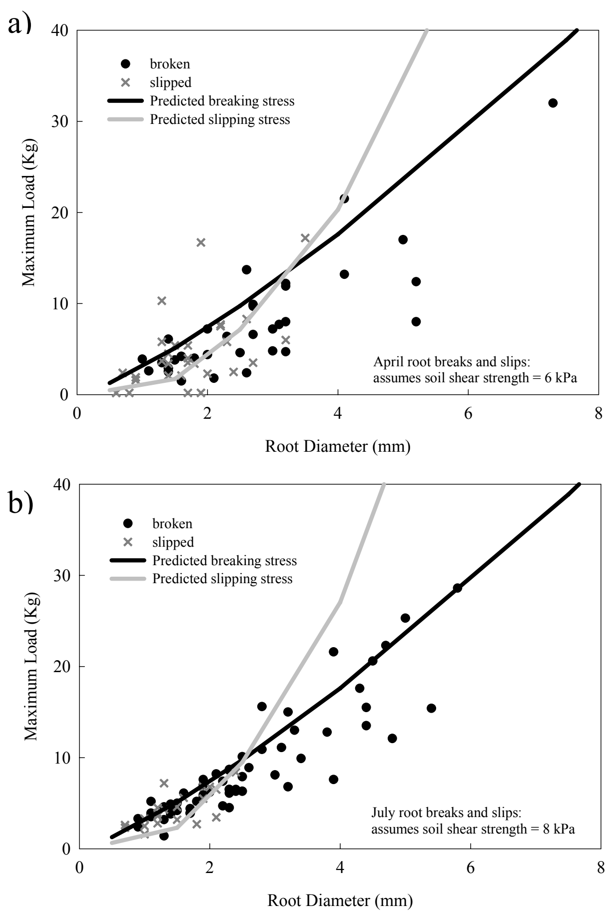

Figure 1 Field data for root breaking and root pullout at the Long Creek site, MS. In a) April and b) July. Also shown are the predicted breaking and pullout forces calculated for the apparent soil cohesion at the site assuming the constants $R = 200$ and $g = 0.7$ (Equation 6).

The root-soil friction tests conducted in April and July 2002, experienced moisture contents of 21.1% and 11.3% respectively. Statistical analysis confirmed that there was not a significant difference between the median root breaking forces for the April and July data (Mann-Whitney Rank Sum Test, $p = 0.220$). This result confirms that the tensile strengths of the roots studied, and therefore their breaking forces, were largely independent of soil moisture. Changes in soil moisture did, however, affect the threshold diameter between root pullout and breaking. Although the mean diameters of roots that pulled out of the soil during the April and July tests were not significantly different (t-test, $p = 0.221$), the range of root diameters that were pulled out of the soil was less in July than in April (range of 1.7 mm and 2.9 mm respectively), and the maximum root diameters that could be pulled out of the soil were different. During the April tests, the threshold value was approximately 3.5 mm whereas in the July tests the threshold value was approximately 2.4 mm. This change in threshold diameter for root pullout suggests that as the soil dries out the frictional bonds between the roots and the soil become stronger, as apparent cohesion of the soil increases with increasing soil matric suction. Root breaking is therefore likely to be the predominant mode of root-failure in dry soils, or those with higher shear strengths, whereas soils that are moist, or have lower shear strength will exhibit greater root-pullout than breaking.

Inclusion of pullout forces in the RipRoot model: Root-pullout forces were included in the progressive breaking algorithm of the RipRoot model using Equations 5 and 6. Root lengths for all species were calculated using values in the suitable range outlined by Waldron and Dakessian (1981) (R = 200 and g = 0.7). Root tensile strength curves used to calculate root breaking forces for each species were obtained from Pollen and Simon (2005). The first set of model runs adding pullout forces, were conducted using a specified number of roots for each species, using varying soil shear-strengths. As soil shear strength increased, the threshold diameter between root pullout and root breaking decreased. Therefore, at higher soil shear strengths, more roots were predicted to break than be pulled out of the soil, and above a certain soil shear strength all roots were predicted to break, similar to the field data collected. Using Figures 2a and 2b it is possible to determine the threshold diameter above which all roots are predicted to break (indicated by a leveling off above a certain soil shear-strength). Thus, the effects of both soil type and soil moisture can now be accounted for in the RipRoot model.

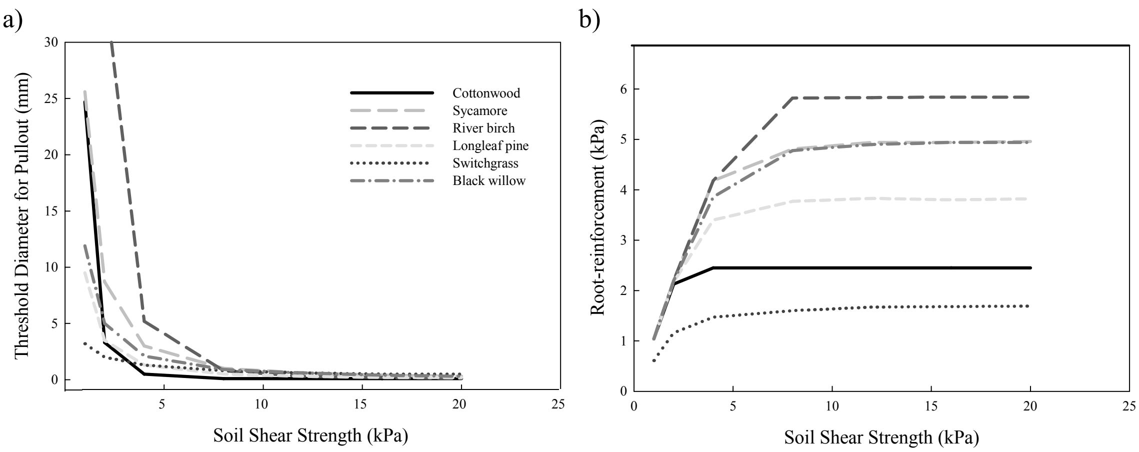

Figure 2 Variations in a) threshold root diameter for pullout with changing soil shear strength and b) root-reinforcement for each riparian species, with changing soil shear strength.

Effect of changing soil matric suction on root-reinforcement values: An additional set of model runs were performed using data from the Goodwin Creek Experimental Bendway (GCEB), to examine temporal variability in root-reinforcement estimates before and after a storm event (December 7th - 23rd 2004). The period of study was chosen because the tensiometer data exhibited a drying curve followed by a large storm event during which the soil matric suction dropped rapidly. To estimate soil shear strength (using Equation 7), the following variables were required: effective soil cohesion, pore-water pressure, σ, ϕ' and ϕ^b. The GCEB was used for these model runs because geotechnical properties were available (c' = 1.4 kPa, ϕ^b = 17 degrees , ϕ' = 28.5 degrees for the upper 1m of the bank profile that contains the root zone, Simon et al., 1999). In addition, detailed matric-suction data were available from nests of tensiometers installed in different vegetative treatments (Simon and Collison, 2002). Normal stress (σ) was calculated for a soil depth of 0.5 m (the assumed center of the root-reinforced zone), using the regression equation established in Simon et al. (1999) that relates soil matric suction to soil unit weight for the upper 1m of the modeled bank.

Mean daily soil shear strength was calculated using the bank-geotechnical properties and mean matric suction value for each day in the top layer of the grass plot, during the period (December 7th to December 23rd, 2004). The values of soil shear strength were used in the RipRoot model to calculate daily root-reinforcement values for root densities of 500 and 1000 roots/m^2. In the case of the upper 1m of the Goodwin Creek bank profile, *c'* was small (1.4 kPa), and values of matric suction recorded by the tensiometers, in combination with soil friction angle produced soil shear-strength values ranging from 7.3 to 10.7 kPa during the period. Soil shear strength was therefore in the range of soil strengths in which most of the roots were predicted to break during soil shearing, with very few roots being pulled out from the soil (Figure 2a and 2b). Variations in this range of soil strengths produced almost indistinguishable (approximately 1-2%) variations in root-reinforcement, ranging from 5.55 to 5.61 kPa (500 root/m^s) and 11.10 to 11.22 kPa (1000 roots/m^2). Slight increases in root-reinforcement were seen with increasing soil matric suction until soil shear strength increased above 10 kPa, at which point root-reinforcement values leveled off because all roots were predicted to break (as seen in Figure 2). Further increases in matric suction above 10 kPa, therefore, had no effect on root-reinforcement.

To test the effect of changing matric suction on a soil with weaker shear strength, RipRoot runs were repeated using mean, daily shear-strength values that were half those calculated for the first set of runs. The results of this second set of runs showed that because soil strength values were in the range where both root breaking and root pullout occurred (Figure 2a and 2b), any variation in matric suction had more of an effect on calculated root-reinforcement values. In this case, changes in matric suction were reflected in root-reinforcement values, with no plateau in root-reinforcement values as soil shear strengths were not great enough to force all roots to break. Root-reinforcement estimates for the lower range of soil shear strengths (3.66 to 5.36 kPa) varied from 9.12 to 11.2 kPa at a root density of 1000 roots/m^2. Therefore, the effect of soil type and moisture on root-reinforcement depends on spatial and temporal variability, and relative contributions of effective and apparent cohesion, matric suction and soil friction angle to soil shear strength.

Effect of dynamic root-reinforcement values on Streambank Factor of Safety (F_S): The streambank stability model of Simon et al. (1999) was run for the grass plot at Goodwin Creek for the period December 7th through December 23rd 2004. Previously published model runs using this bank stability model have included root-reinforcement as a static add-on factor, assuming that all roots broke and that root-reinforcement was independent of soil type and moisture (Simon and Collison, 2002; Pollen et al., 2004). As such, the addition of vegetation to any bank produces F_S for bare and vegetated banks that show sets of parallel lines, with vegetated banks having higher F_S values. Root-reinforcement estimates including root pullout as well as root breaking, result in root-reinforcement forces that vary with soil shear strength. The effect of temporal variability in root-reinforcement values on streambank F_S values is shown in Figure 3. The F_S for vegetated and non-vegetated banks diverges slightly as F_S increases (Figure 3). This trend occurs because root reinforcement is greatest when matric suction and thus F_S are high. Root reinforcement is lowest when bank F_S conditions are critical, although some reinforcement is still provided through soil-root friction forces even when pullout is the dominant root failure mechanism.

F_S values where soil shear strength was high and root-reinforcement thus varied only slightly, showed that F_S for the vegetated and non-vegetated bank diverged slowly as F_S increased. The difference in minimum F_S being 0.35 and the difference in maximum F_S being 0.36 for a density of 1000 roots/m^2 (Figure 3). Figure 3 also shows the F_S runs repeated with root reinforcement estimates for the soil of lower shear strength. In this second set of model runs, at minimum F_S the difference in F_S between the bare bank and the bank with 1000 roots/m^2 was 0.31, but at maximum F_S, the difference was 0.36. At lower soil shear strengths the range of root reinforcement values was thus reflected in a wider range of F_S values. Results of model runs show that for a specified rooting density, the range of root-reinforcement values is dependent on soil shear strengths and how they affect the predominance of species specific root pullout and root breaking mechanisms. Figure 3 shows that the variations in model runs for soil of lower and higher shear strengths were greatest at lower F_S values. This suggests that the inclusion of pullout forces is particularly important when bank stability conditions are critical.

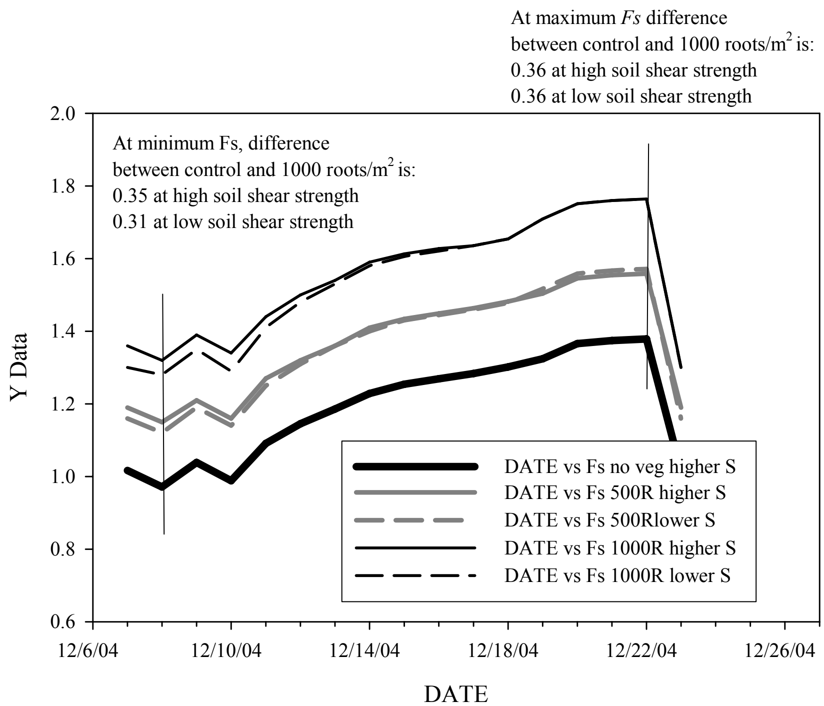

Figure 3 Factor of safety values for the grass plot at Goodwin Creek, MS during December 2004, with no roots, 500 roots per m^2 and 1000 roots per m^2 at high soil shear strengths (7.3 to 10.7 kPa) and lower soil shear strengths (3.66 to 5.36 kPa).

CONCLUSIONS

Field tests confirmed the presence of a threshold root-diameter, above which all roots broke under applied stress, and below which, both root breaking and pullout occurred. The threshold diameter between root-failure mechanisms is determined by the shear strength of the soil. Model results have thus shown that the effect of soil type and moisture on root-reinforcement is dependent on spatial and temporal variability in several factors including soil matric suction and geotechnical properties.

When soil shear strengths were calculated for Goodwin Creek, root reinforcement values during December 2004 ranged from 5.55 to 5.61 kPa (500 grass roots/m^2) and 11.10 to 11.22 kPa (1000 grass roots/m^2). The root-reinforcement values varied very little throughout the period of time modeled because root-breaking was predominant at that range of soil shear strengths; changes in matric suction therefore had little or no effect on root-reinforcement estimates. When soil shear-strength was halved, root-reinforcement estimates decreased correspondingly, but the range of values was greater as both root pullout and root breaking occurred in this range of soil shear strengths. Any changes in soil matric suction therefore affected the proportion of roots that would break or pullout of the soil, thereby causing larger variations in root-reinforcement estimates.

Quantification of spatial and temporal variability in root-reinforcement can now be taken into account in RipRoot by changing input variables such as root density, species assemblage, and soil shear strength. In the first version of RipRoot the roots and soil were considered separately as root breaking was assumed to be independent of soil properties. The addition of root pullout forces in the new version allows for interaction between the root-soil matrix, thereby improving the representation of the processes occurring during mass-failure of a streambank. Future work will use field data to validate the level of improvement made by using varying root-reinforcement estimates instead of static add-on values. More accurate estimates of root-reinforcement of streambanks will ultimately aid in future studies of bank stability, and may help explain and quantify rates of channel widening, and lateral migration of channels with riparian corridors of various species compositions.

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