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Unconfined Compressive Strength of Some Streambank Soils with Herbaceous Roots

Donald Kleinfelder, Sherman Swanson,* Gary Norris, and Warren Clary

ABSTRACT

Streambank stability requires that bank strength exceed destabilizing forces, including compressive forces from sources such as trampling and foot traffic. This study was conducted to determine the unconfined compressive strength associated with herbaceously rooted streambanks, and whether greater compressive strength is developed from greater root-length density (length of roots per volume of sample) or specific plant communities. The unconfined compressive strength, root-length density, plant community, and engineering soil characteristics were measured on 122 samples from six meadow stream reaches. Sample compressive strength emulated an elastic condition in highly rooted samples, and developed negligible compressive strength in samples containing very small amounts of roots. Additionally, compressive strength was found to increase nonlinearly with increases in very fine root-length density (herbaceous roots <0.5 mm in diam.), and reached an apparent asymptote at 50 kPa. The greatest compressive strength was derived from samples dominated by Nebraska sedge (*Carex nebrascensis* Dewey). Correlations between unconfined compressive strength and engineering soil properties were mostly insignificant, primarily because samples were derived from unconsolidated alluvium. Stream morphology parameters showed little correlation to compressive strength, root-length density, or other independent variables, suggesting other unmeasured factors may have an equal or greater influence on stream morphology. Herbaceous roots appear to supply most of the compressive strength and soil stability found in meadow streambanks, especially those dominated by Nebraska sedge.

THE CAVING AND EROSION of meadow streambanks is of principal concern to managers of riparian areas. The loss of these steep and often overhanging banks can lead to altered stream morphology, confinement of flood flows and downcutting, loss of fish habitat, and possible loss of adjacent meadows (Behnke and Raleigh, 1978). Streambanks are maintained through a balance of forces and influences. Destabilizing influences include external disturbances, such as grazing and trampling, as well as natural erosive forces such as storm flow and freeze–thaw events. These forces tend to accelerate soil particle detachment and bank collapse (Henderson, 1986). Of particular concern to this study are soil and vegetation factors that might affect the impact of cattle trampling. Such trampling leads to vertical deformation (compression) of the relatively unconfined surface soils and the shearing of overhanging streambanks.

Stabilizing factors include the cohesive, frictional, and interlocking properties of the soil (Wray, 1986), the amount and type of streambank vegetation, and, at least within smaller stream systems, the additional stabilizing properties provided by streambank root systems (Thorne and Tovey, 1981). Of all these factors, the soil stability provided by roots is perhaps the least understood (Waldron and Dakessian, 1982).

The influence of herbaceous roots on the morphology of small stream channels has been qualitatively noted for some time. Zimmerman et al. (1967) suggested herbaceous roots increased streambank cohesiveness and strength, which reduced the width to depth ratio of a stream in meadow reaches (2.0) from that observed in forest reaches (6.1). Richards (1977) suggested that considerable undercutting is possible in streambanks because bank collapse is prevented or delayed by root mats.

Further understanding of the influence of roots on soil and slope stability has come about as a result of field and laboratory direct-shear tests on root-reinforced soil (Endo and Tsuruta, 1969; Waldron and Dakessian, 1982) and direct-shear tests using different types of fibers to reinforce soil (Gray and Ohashi, 1983; Shewbridge and Sitar, 1989). This last study found a nonlinear relationship between reinforcement fiber concentration and sample shear strength.

The majority of these studies dealt with soil failure under direct shear (i.e., horizontal shearing of the sample). However, streambank failure due to cattle trampling involves loading on the horizontal plane. Such loading would produce shear in an inclined (diagonal) or vertical plane (Wray, 1986). Because near-surface alluvial soils develop little confining pressure (i.e., resistance to horizontal expansion during compression due to the weight of overlying material) (Wray, 1986), the shearing of streambanks is probably best simulated through unconfined compression tests. Assuming this hypothesis, a portable unconfined compression device was used to test the compressive strength of streambank samples. This test involves the compression of soil samples without the benefit of lateral confinement. Compressive strength refers to a sample's resistance to compression with increasing strain, measured as proving ring resistance divided by the changing cross-sectional area.

The objectives of this study were to: (i) quantitatively evaluate the effect of herbaceous roots on the ability of alluvial soils to resist unconfined compression; (ii) compare root-length density, compressive strength, and plant community type with soil plasticity, bulk density, and percentage of fines (silt and clay) to assess the influence of inherent soil properties on compressive strength; and (iii) compare bank overhang, bank angle, and height of sample above bankfull level with the above variables to assess their impact on streambank morphology.

MATERIALS AND METHODS

Six streams were investigated within or near the Toiyabe National Forest. These include Birch, Barley, Kingston,

D. Kleinfelder, 848 Kern St., Chico, CA 95928; S. Swanson, Dep. of Range, Wildlife, and Forestry, and G. Norris, Dep. of Civil Engineering, Univ. of Nevada, Reno, NV 89512; W. Clary, Riparian-Stream Ecosystems, U.S. Forest Service Intermountain Station, 316 Myrtle St., Boise, ID 83702. Received 6 Dec. 1991.
*Corresponding author.

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Abbreviations: ASTM, American Society of Testing Materials; USCS, Unified Soil Classification System; VFR, very fine root-length density; PC, plant community.

and Marysville Creeks, located in central Nevada, and Dog Valley and Slinkard Creeks, located in eastern California. All samples were collected in riparian meadows 1500 m above sea level (msl). Sample sites were located along continuous stream reaches and were selected for their similar channel morphology, nongravelly streambanks, and lack of woody roots. Near Birch and Dog Creeks, soils are Cumulic Haplaquolls; near Marysville Creek, it is a Typic Haplaquoll; near Kingston and Slinkard Creeks, they are Cumulic Hapludolls; and near Barley Creek, it is a Fluventic Hapludoll. All are in the fine-loamy, mixed, frigid family except for the soil near Barley Creek, which is coarse, and near Marysville Creek, which is skeletal (below the sampled depth) (Soil Conservation Service, 1975).

A total of 122 samples were collected (approximately 20 per stream). Samples were collected from approximately four equidistant points along concave banks. Distances between samples depended on meander length and curvature. Each sample was located within 0.5 m of the edge of the streams, and generally within 0.25 m of the stream edge unless prohibited by tension cracks in the banks or severe undercutting. The following data were recorded for each sample: (i) plant community type as defined by a list of major plant species found within 0.5 m of the sample location; (ii) adjacent streambank angle and bank overhang, measured with a clinometer and meter stick (Platts et al., 1987); (iii) height of the sample above the estimated bankfull level (after Dunne and Leopold, 1978); (iv) unconfined compressive strength of the top 80 mm of soil as measured on extracted soil cores in the field with an unconfined compression device (Soiltest U-120, Chicago, IL); (v) rhizome, fine, and very-fine root-length density, defined as the length of woody rhizomes and their attached fine roots, fine roots (>0.5-mm in diam.), and very-fine roots (<0.5 mm in diam.), respectively, as measured within the volume of each sample; (vi) soil bulk density; and (vii) soil texture, per the ASTM USCS (Wray, 1986). The USCS classification system was used because it more appropriately relates to unconfined compressive test results. Classification under the USCS method required the assessment of the soil plasticity (index) and percentage of fine and coarse material. Because USCS soil texture was relatively consistent within each stream, only one-half of the sample sites were sampled for these parameters.

To measure compressive strength in the most heavily rooted portion of the soil profile (i.e., the top 100 mm) (Manning et al., 1989), the 2:1 sample height-to-diameter ratio (normally required to overcome boundary influences created by friction between the end plates and the samples [Wray, 1986]) was reduced to approximately 1:1. This reduction in sample proportion provided more uniform sample deformation and, hence, better stress–strain definition. End-plate boundary influences were minimized by using near-frictionless end plates similar to those described by Bishop and Green (1965). These end plates consisted of thin latex sheets sliced in a crossing pattern, lubricated with petroleum jelly, and placed on the clear plastic end plates. Because very little friction develops between soil samples and end plates, the soil sample, when vertically loaded, deforms uniformly as a bulging vertical cylinder on its enlarged end plates (Bishop and Green, 1965).

The unconfined compressive strength of soil samples was measured from rooted samples extracted with a 63.5-mm (2.5-inch) diam. soil corer (Art's Manufacturing, Idaho Falls, ID). The inside sleeves of the soil corer were split longitudinally for extraction of unit volume samples with minimal disturbance. Samples were removed and trimmed to an approximate height of 80 mm (the top 10 mm of soil was removed to provide a flat surface for testing). Samples were then placed between the near-frictionless end plates and compressed to ≈50% of their original height. During compression, both vertical compression (deformation) and proving-ring resistance were recorded. Because moisture differences between samples will affect unconfined test results, we attempted to equilibrate water potential by ponding water over the sample sites 24 h before sampling and continually for several hours just before sampling.

Following shearing, soil from each sheared sample was removed from its respective root system with a hydropneumatic illutriation system (Gillison's, Benzonia, MI). As the fine-grained soil was carried away by the water, the roots were collected on a 0.5-mm-mesh screen. Once separated from the soil, the roots were sorted and grouped into three categories: (i) very-fine roots (<0.5 mm in diam.), (ii) fine roots (>0.5 mm in diam.), and (iii) rhizomes and their attached fine roots. The fine roots and rhizomes were separated by hand and the length measured to the nearest millimeter. A Comair root scanner (Commonwealth Aircraft Corp., Melbourne, Australia), was used to estimate very-fine root length via a line intercept system, after Newman (1966). The lengths of all three root categories were then divided by the precompressed sample volume to arrive at the estimated root-length densities.

To assess the influence of inherent soil characteristics on measured compressive strength, three basic soil parameters were measured: soil bulk density, soil plasticity, and percentage of fines (<0.075 mm) within the sample. All three soil parameters were measured from a replicate sample obtained from soil located within 0.2 m of the sheared samples. Replicate samples were used because the soil of the sheared samples was necessarily lost during the root washing process. Prior to performing the soil tests, all roots were removed by hand, hand dried with paper towels so as to leave the roots with their internal water intact, and weighed. The remaining soil was then oven dried at approximately 105 °C.

Soil plasticity (index), defined as the soil's liquid limit minus the soil's plastic limit, was obtained following ASTM standards for oven-dried soils (Wray, 1986). The USCS uses the liquid limit and plasticity index to classify soil and to assess its various properties, including soil strength resulting from the cohesive properties of clays and overburden pressures (Sowers, 1965).

Following assessment of soil plasticity, the soil was washed through a no. 200 sieve (0.075-mm openings) to estimate the percentage of fines (silt and clay) (Wray, 1986). This measurement was used in conjunction with soil plasticity and percentage of gravel retained by a no. 4 sieve (4.75-mm openings) to classify the soil texture according to ASTM standards.

Samples were grouped into different plant communities to further assess potential causes of variation in sample compressive strength. Classification was accomplished using the Cornell ecology program Two-Way Indicator Species Analysis (TWINSPAN) (Hill, 1979). The classification technique of TWINSPAN divides the entire sample group using all plant species identified within 0.5 m of each soil sample. The plants associated with each soil sample are referred to as plots. Classifications are determined at several levels using reciprocal averaging (Hill, 1979; Gauch and Whittaker, 1981). This method identifies species that are not necessarily dominant but have high indicator value (those species with high fidelity and constance). These indicator species are then used to successively divide the plots into smaller and smaller clusters, which become less dissimilar with each division. The level of dissimilarity at each division is described by eigenvalues. A division separating two clusters with a high level of dissimilarity will have a relatively high eigenvalue. The first three divisions developed in this study produced relatively high eigenvalues, and were used to define the plots into four distinct clusters, or plant communities.

Following clustering, the entire data set was analyzed using the computer program Statistix II (NH Analytical Software, Roseville, MN). Analyses were divided into two data sets: one containing all samples (122 samples), and one containing only those samples evaluated for USCS soil characteristics (57 samples). Analysis included simple correlations among all variables, one-way analysis of variance (ANOVA) for very-fine root-length density and compressive strength among plant communities (122 samples, $P < 0.01$), and among USCS soil textures (57 samples, $P < 0.01$), and all possible subset regressions for stream morphology characteristics using both data sets.

RESULTS AND DISCUSSION

Results of the study were first analyzed for the entire data set using simple correlations. The most notable finding is that an increase in sample root-length density corresponds to an increase in compressive strength (i.e., the ability of a sample to resist compression under pressure). Increases in the root-length density of very-fine roots (VFR) show moderate correlation ($r = 0.65$, $n = 117$) with an increase in compressive strength at a sample deformation of 40% (Fig. 1). This relationship is further demonstrated (Fig. 2) by the stress–strain relationships of the means of three groups of samples: those with a VFR <0.1 mm/mm^3, those with a VFR >0.1 mm/mm^3 and <1.0 mm/mm^3, and those with a VFR >1.0 mm/mm^3.

Samples with <0.1 mm/mm^3 of very-fine roots (Fig. 2) develop a stress–strain curve similar to that of unrooted, noncohesive soil (Wroth, 1965). That is, initial resistance to compressive stress is developed primarily from friction among the soil particles. Without significant confinement, this initial resistance is soon overcome. Once friction is overcome, the soil maintains a relatively constant resistance to strain (Wroth, 1965). The maximum amount of compressive stress withstood by the sample is then referred to as the unconfined compressive strength of the sample.

The shear strength (as in a direct shear test) may be thought of as one-half the unconfined compressive strength, assuming the shear strength is developed on a 45° inclined plane.

Samples with a moderate amount of very-fine herbaceous roots (VFR > 0.1 mm/mm^3), however, showed an ability to withstand increasing stress with increased strain without failure (Fig. 2). Highly rooted samples (VFR > 1 mm/mm^3) provided more compressive strength at 40% deformation than moderately rooted samples. Interestingly, the rooted samples appeared to behave in an elastic manner; that is, their resistance to strain continuously increased throughout the deformation process (Wroth, 1965). This behavior is similar to that observed when noncohesive soil is placed within an elastic sheath that initially exerts no confining pressure. Once the deformation process begins, confining pressures increase proportionally with deformation due to the stretch of the elastic membrane. The resulting graph of stress vs. strain would be a straight line similar to Fig. 2c.

Although correlations between compressive strength and other variables appeared consistent at different levels of deformation (e.g., Fig. 2), nearly all were highest at 40% deformation. Consequently, the remainder of the study focused primarily on the compressive strength observed at 40% deformation.

Of the three classes of roots measured, compressive strength correlates most with VFR ($r = 0.65$), less with woody rhizomes and their attached fine roots ($r = 0.55$), and least with fine root-length density ($r = 0.42$). However, because the root-length density of very-fine roots is several orders of magnitude greater than the root-length densities attributed to rhizomes or fine roots, the correlation of compressive strength with fine roots and rhizomes may simply reflect the influence of VFR. This is also suggested by the fact that total root-length density (i.e., all three root classes combined) correlates only slightly better to compressive strength than VFR ($r = 0.651$ and 0.649, respectively). Therefore, except where noted, the primary focus of root relations will be with VFR.

Although VFR appears to impact soil compressive strength, the relationship is nonlinear (Fig. 1). The

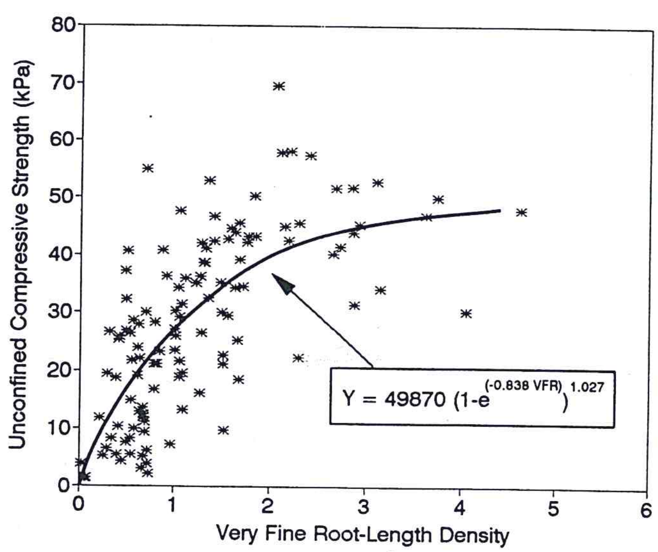

Fig. 1. Scatter plot of very-fine root-length density (VFR) vs. unconfined compressive strength at 40% deformation.

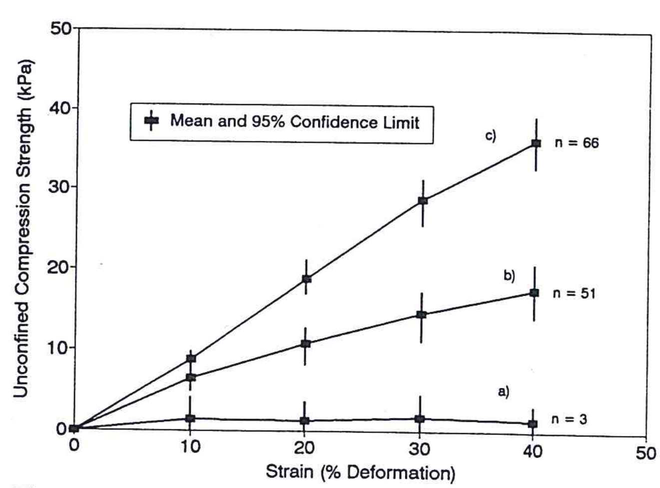

Fig. 2. Stress–strain curves developed from mean values of samples containing (a) very-fine root-length density (VFR) <0.1 mm mm^{-3}, (b) VFR >0.1 mm mm^{-3} but <1.0 mm mm^{-3}, and (c) VFR >1.0 mm mm^{-3}.

Table 1. Plant communities and eigenvalues as determined by TWINSPAN. Dominant species are listed in their order of abundance.

Plant community	Indicator species	Dominant species	Stream
1	*Aster occidentalis* (Nutt.) T. & G. *Deschampsia cespitosa* (L.) Beauv. *Achillea millefolium* L. *Potentilla anserina* L.	*Juncus balticus* Willd. *A. occidentalis* *D. cespitosa*	Birch Creek
2	*Carex nebrascensis* Dewey	*C. nebrascensis* *Poa pratensis* L. *J. balticus*	Dog Valley & Slinkard Creeks
3	*Aster* spp. *Calamagrostis* spp. *J. ensifolius* (Wikstr.) *Stellaria longipes* (Goldie) *A. millefolium*	*Calamagrostis* spp. *Poa pratensis*	Marysville & one-half of Kingston Creek
4	*Poa pratensis* *Carex* spp.	*Poa pratensis*	One-half of Kingston Creek & Barley Creek

increase in mean compressive strength with increasing VFR diminishes with higher values of VFR, and may even decrease slightly with very large values of VFR. The resulting nonlinear relationship suggests that a substantial increase in compressive strength might be obtained from only a moderate amount of root growth, as suggested by Waldron (1977) and Shewbridge and Sitar (1989). In Fig. 1, the samples with the highest compressive strength contained approximately 2 mm/mm^3. Additionally, an apparent asymptote occurs at approximately 50 kPa (Fig. 1). The asymptote was determined using the Chapman–Richards equation (Aguirre-Bravo and Smith, 1986):

$$Y = \theta_1\,[1 - e^{(-\theta_2 V)}]^K$$

where:

Y is the predicted value of compressive strength at 40% sample deformation;

θ_1 is the maximum value for compressive strength at 40% sample deformation (asymptote);

V is the observed value of VFR;

θ_2 is the growth (increase) rate; and

K is an exponent of nonlinearity.

The parameters θ_1, θ_2, and K were estimated using a derivative-free nonlinear regression statistical procedure (Dixon, 1983). An iterative process was used that developed new values for these parameters until the estimates of the values minimized the residual sum of squares of the predicted value (Y) (Aguirre-Bravo and Smith, 1986). This method developed the following values for the parameters:

θ_1 = 49 870
θ_2 = 0.838
K = 1.027
estimated R^2 = 0.51.

Once these parameters were determined, they were substituted back into the Chapman–Richards equation to construct the curve shown in Fig. 1.

Compared with the stress created by moving cattle, estimated to be between 274 and 411 kPa (2.3–4.2 kg/cm^2) (Abdel-Magid et al., 1987), the increased soil compressive strength developed by herbaceous roots appears to be insufficient when that unit of soil is unconfined. However, from this study it is uncertain whether this holds true in streambanks, where a column of soil may be influenced by adjacent soil and a lateral network of unsevered roots.

To assess the influence of different plant (root) systems on soil strength, four plant communities were compared (designated PC1 through PC4). These communities (Table 1) were determined by the first three cut levels of TWINSPAN (eigenvalues between 0.46 and 0.56). The very-fine root-length density and compressive strength at 40% deformation of the four plant communities were compared using one-way analysis of variance (Fig. 3 and 4, respectively). These figures indicate that samples from PC2 (primarily Nebraska sedge) contained significantly larger VFR and greater strength than samples from other communities ($P < 0.01$ and $n = 122$ for both variables). Conversely, PC4 was observed to contain the lowest VFR and strength at 40% deformation, although it was not sig-

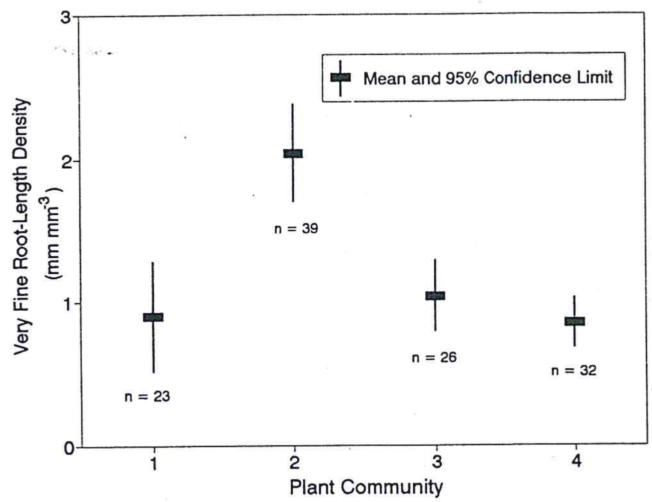

Fig. 3. Very-fine root-length density by plant community. Plant communities are described in Table 1.

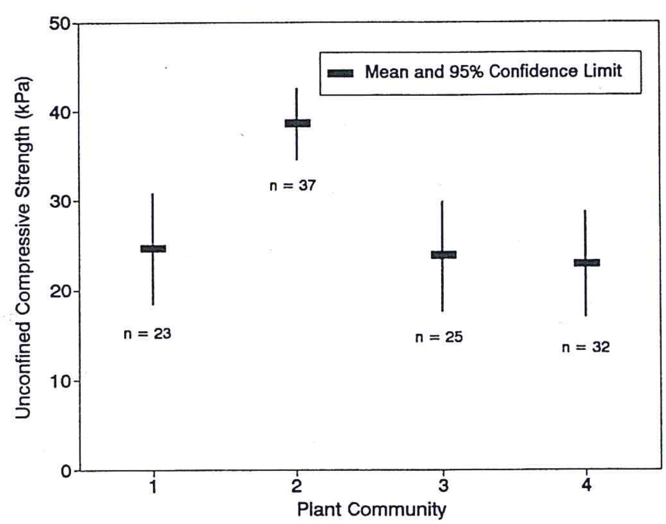

Fig. 4. Unconfined compressive strength at 40% deformation by plant communities. Plant communities are described in Table 1.

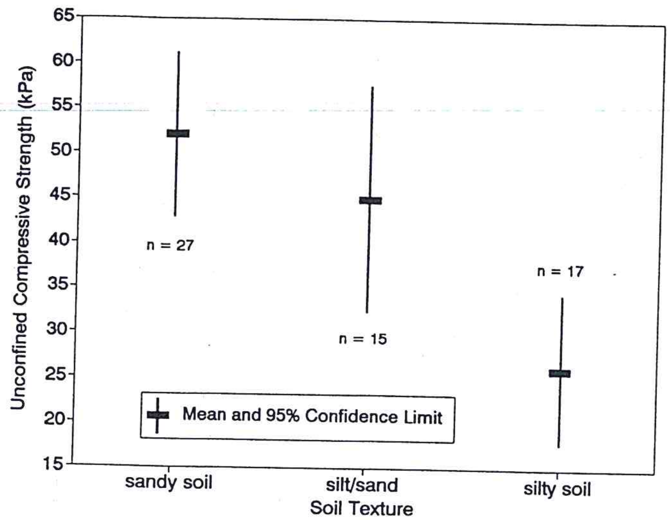

Fig. 5. Unconfined compressive strength at 40% deformation by soil texture.

Table 2. Chi square test for heterogenity or independence between soil textures and plant communities (PC).

Soil texture	χ^2 PC1	PC2	PC3	PC4	n
Sandy soil					
Observed	7	13	3	3	
Expected	5.02	7.75	6.84	6.39	26
Cell χ^2	0.78	3.55	2.16	1.80	
Silt–sand					
Observed	1	2	7	5	
Expected	2.89	4.47	3.95	3.68	15
Cell χ^2	1.24	1.37	2.36	0.47	
Silty soil					
Observed	3	2	5	6	
Expected	3.09	4.77	4.21	3.93	16
Cell χ^2	0.00	1.61	0.15	1.09	
n	11	17	15	14	57

nificantly different from PC1 and PC3 in either VFR or strength.

Correlations of bulk density, plasticity, and percentage of fines to soil compressive strength were relatively low in the 57 samples measured for soil characteristics. Bulk density showed a maximum correlation to soil strength at 10% deformation (r = 0.31); percentage of fines and plasticity both showed a maximum correlation at 40% deformation (r = −0.39 and −0.36, respectively).

Using plasticity and percentage of fines, three basic soil textures were identified under the ASTM classification scheme. These classes included silty soil, containing >60% low-plastic fines (primarily silt); silt–sand, containing between 40 and 60% low-plastic fines; and sandy soil, containing <40% low-plastic fines. Two samples fell outside of these classifications and were not used in this analysis.

Following classification and grouping of soils, soil strength was compared within and among the soil textures (Fig. 5). Soil strength was found to be greatest with sandy soils, and decreased with increasing silt content. Although it is possible that the cohesiveness of the silty soil provided less strength than the internal friction of the sandy soil (Johnson and DeGraff, 1988), the relatively high overall strength suggests it is more likely that the difference reflects differential root-length density. Specifically, the apparent strength attributed to sandy soil may actually reflect the presence of a particular plant community (Nebraska sedge) which, in this study, is characterized by stronger or more abundant roots and a preference for sandy soils. A comparison of plant communities to soil textures using the χ^2 test (Table 2) indicates significant heterogeneity among soils, with a predominance of sandy soil in PC2 producing the largest heterogeneity (overall χ^2 = 16.57, P = 0.01, 6 df).

The conclusion that arises from this is that PC2 develops the most VFR, the greatest compressive strength, and is found primarily in sandy soils. Conversely, PC3 and PC4 contain substantially less VFR, have lower overall strength, and are less abundant in sandy soil. From this it appears that the strength developed by sandy soil is probably a reflection of the influence of roots developed by PC2.

Percentage of fines was the best correlated independent variable for both bank angle and bank overhang (r = 0.44 and 0.39, respectively). Otherwise, correlations of stream geomorphology to soil or root characteristics were insignificant. Interestingly, neither bank angle nor bank overhang showed a correlation >0.12 with soil strength. This result suggests that other unobserved factors, such as stream flow rate, channel pattern, grazing management practices, bank height, or elevated water tables due to seeps or springs, may significantly influence bank overhang and bank angle. This is further substantiated by the fact that the highest of all possible subset regressions that could be developed from the data set showed an adjusted R^2 of only 0.39 for bank angle and 0.36 for bank overhang.

CONCLUSIONS

Several conclusions were developed during this study. First, the resistance of the soil to shearing increases with increased strain (deformation), thus emulating an elastic reinforcement condition of the roots. Second, the relationship between root-length density and compressive strength of noncohesive soils samples is nonlinear, with substantial increases in strength occurring from moderately dense root systems (approximately 2 mm/mm^3). Increased root-length density increases strength by progressively smaller amounts, with an asymptotic limit developing at approximately 50 kPa. Third, root systems of different plant species or communities provide varying amounts of compressive strength. The greatest sample strength was developed in a community dominated by Nebraska sedge. Finally, the independent variables measured in this study showed little correlation to stream morphology.

These conclusions indicate that herbaceous roots play an important role in providing strength to the noncohesive soils found in meadow streambanks. Although the increase does not appear to be large enough for a sample core by itself to withstand the forces exerted by moving cattle, it does provide streambanks with a significant resistance to shearing throughout the deformation process. Whether this apparently elastic re-

lationship is due to abundant root hairs providing a cohesiveness among soil particles (Ennos, 1989), a characteristic of mycorrhizal interaction between the roots and the soil particles, the tensile strength of the roots themselves, or some combination of these or other potential mechanisms is uncertain. Regardless, it is likely that this characteristic plays a crucial role in the development of new streambanks, as well as in the stability of mature streambanks.

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