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Soil Binding Capacity of Different Forage Grasses in Terms of Root Reinforcement Ability toward Soil Slope Stabilization

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ABSTRACT

The use of vegetation in restoring the stability of slopes becomes highly demanded especially to solve the soil of erosion, shallow slope failure in both natural and man-made slopes. Planting or preserving vegetation in areas vulnerable to erosion is therefore considered to be a very effective soil erosion control measure. The above-ground biomass can temporally disappear in semi-arid environments, roots may still be present underground and play an important role in protecting the topsoil from being eroded. The load required to remove the root system of each grass vertically from the soil was used as a measure of soil binding capacity. We have observed maximum and minimum uprooting force for TSH (179.75 kg) and *Chrysopogon fulvus* (85.33kg), respectively. We found highest "soil binding strength index" for *Heteropogon contortus* (5.32) and lowest in *Cenchrus ciliaris* (3.44). The grass, which is having maximum value of Cr will have maximum soil binding capacity. The additional shear strength imposed by the grass roots was observed maximum for H. contortus (365.0 kPa) and minimum was observed for C. ciliaris (139.3 kPa). Root systems lead to an increase in soil strength through an increase in cohesion brought about by their binding action in the fiber/soil composite. From this study, it has proven that grasses are effective for erosion control, providing a complete ground cover and grass roots have a mechanical effect in increasing soil strength. The calculated cohesion values are used to rank species according to their potential to reinforce the soil.

1. Introduction

Soil erosion is a serious problem in semi-arid region, where dry bare soils are very vulnerable to erosion during intensive rainstorms. This results in large on-site soil losses and off-site consequences such as sediment deposition in river channels or reservoirs and flooding (Poesen and Hooke 1997). The use of vegetation in restoring the stability of slopes becomes highly demanded especially to solve the soil of erosion, shallow slope failure in both natural and man-made slopes (Petrone & Preti 2010). It has since long been recognized that slopes under vegetation are much more resistant to soil erosion processes compared to bare soils and improve slope stability. Planting or preserving vegetation in areas vulnerable to erosion is therefore considered to be a very effective soil erosion control measure (de Baets *et al.* 2008). The above-ground biomass can temporally disappear in semi-arid environments; roots may still be present underground and play an important role in protecting the topsoil from being eroded. 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 (Schiechtl 1980; Coppin and Richards 1990; Schmidt *et al.* 2001; Roering *et al.* 2003).

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Roots are equal in importance to leaves as the life support system for plants and thus for all life in terrestrial ecosystems (Arora 1991). The recognition of different types of roots is important because these can have different functions. Roots affect properties of the soil, such as infiltration rate, aggregate stability, moisture content, shear strength and organic matter content, all of which control soil erosion rates to various degrees (Gyssels *et al.* 2005). 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). Reubens *et al*. (2009) points out that most studies on roots-reinforced soils deal with nutrient and organic matter input into the soil and only considers small diameter roots in the upper soil layers. However, in recent years the interest in understanding of the role of vegetation on stability of slopes are increased and the number of studies on this issue is increasing (Bischetti *et al.* 2009).

2. Materials and Methods

The experiment was carried out during 2017-2018 at the research farm of ICAR-Indian Grassland and Fodder Research Institute (IGFRI), Jhansi. The geographical location of the area is 25.43º N, 78.58º E and has an average elevation of 284 metre. The average annual rainfall of Jhansi is 800 mm. Representative two root samples were collected from field *i.e. Cenchrus ciliaris, Dicanthium annulatum, Heteropogon contortus, TSH, Panicum maximum* and *Crysopogon fulvus.*

Measurement of soil binding capacity

In this study, soil binding capacity of experimental forage grasses is estimated using two methods as presented below:

- Large pullout test (Hathway 1962; Mickovski *et al.* 2007; Devekota *et al.* 2009)
- Test for measuring soil reinforcement (Wu *et al.* 1979; De Beets *et al.*2008)

Large pullout test

To obtain an estimation of soil binding capacity, the maximum load reached when the grasses were pulled vertically from the ground was measured. Grasses were pulled from the ground using a rope and tackle (chain pulley) supported by a tripod, as show in Figure 1. A portable hanging dynamometer, capable of measuring load of up to 200 kg with accuracy of ±500 g, was linked between the binding rope and the chain pulley placed on a tripod. The cotton rope (1.5 cm diameter) padded with soft tissue in order not to destroy the grass material was then tied around the tusks of grass. The other end of the rope was connected to the lower hook of the dynamometer for accurate measurement of uprooting force. The force was applied manually with a constant rate and the reading continuously increases. At a particular moment, majority of the roots breaks and the grass with roots comes out of the soil mass. The experimental grasses were removed in November 2017 after carrying out a simulated rainfall experiment and moisture in the field was at field capacity level. The test was terminated once the uprooting force dropped sharply and the plant was uprooted. Soil from around the base of the trunk of each grass was then carefully excavated by hand trowel to a distance of 0.3 m from the trunk for separating the remnants of the roots remained in the soil after pulling the grass out of the soil. Then the roots in the uprooted grass and broken roots remained in the soil was collected carefully, and left on a paper mat to air dry for an hour. In addition the following data were also recorded while carrying this experiment:

- The above-ground biomass of each uprooted grass.
- Total weight of grass which includes grass shoot and root weight along with the soil adhered to the uprooted grass.

Soil binding strength index

To enable comparison of soil binding capacity to be made with regard to the morphology of the root systems, a "soil binding strength index" was calculated. This is defined as the load required for removing the root system of a grass divided by the dry roots weight, and thus, avoiding the effect of the size of the root system on soil binding capacity.

Soil Binding Capacity of the Root Systems

Measurement of soil binding capacity of the experimental grasses was carried out by the large pullout test and through measurement of soil reinforcement. The pullout resistance force of an individual grass species can provide better insight to know the role of an individual grass in erosion process. The species with deep rooted with higher lateral spreading have shown greater pull out resistance which are considered to be suitable species to prevent the torrential runoff. The additional shear strength imposed by the grass roots is used to represent soil binding capacity of grasses (de Beats *et al.* 2008). According to the value of additional shear strength imposed by grasses, they can be used for soil and slope stabilization.

Figure l. Large uprooted test

Figure 2. Instrumentation designed for measurement of root tensile strength

Cohesion value of root

Plant roots tend to bind the soil together in a monolithic mass and contribute to the strength by providing an apparent additional cohesion (Abernethy and Rutherford 2001). The model of Wu *et al*. (1979) is used to estimate the increase in soil shear strength due to presence of roots. Their model assumes that roots grow vertically and act as loaded piles, so tension is exerted to them as the soil is sheared. This model was also used by de Baets *et al*. (2008). If the soil is rooted, the increased soil shear strength can be expressed as an additional cohesion. The additional cohesion provided by grass roots is represented as:

$$S_r = S + C_r \qquad \text{... (1)}$$

Where S is soil shear strength (kPa), S_r (kPa) is the shear strength of the soil reinforced by roots and C_r (kPa) is the increase in shear strength due to the presence of roots.

$$C_r = 1.04 \frac{\sum T_i n_i a_i}{A} \qquad \text{... (2)}$$

Where

T_i is root tensile strength (MPa), n_i is the number of roots in a diameter class, i is root diameter class, a_i is the root cross-sectional area (m^2) and A is the reference area of soil occupied by roots (m^2). Measurement of root tensile strength is the most important step to estimate soil reinforcement because its positive effect to prevent erosion (Lateche *et al.* 2014). For each selected grass species about 50 undamaged roots of mixed diameter was collected from the experiment plots using the dry excavation method (Böhm, 1979).

Gripping the ends of a root was done in such a way that the root should not get damaged or weakened, but still able to withstand the load required to break the root without slipping. Clamping is the most critical issue when measuring root tensile strength. It has been observed that roots with diameters less than 0.1 mm face clamping problems. Hence, it is necessary to conceptualised method for measuring tensile strength of small diameter root samples. One end of the root was glued fixed with one end a rough cotton and the other end the cotton is tied with the hook of the spring balance. The other end of the root was clamped using a binder clips. The most often reported and experienced problem with clamping is that the grips damage the root structure, inducing rupture of roots at the position of clamping. During measuring tensile strength, the attempts in which roots broke near or at the position of clamping were not considered. In order to improve the adhesion between the roots and the clamps without damaging the root structure, rubber band and fine sand paper were attached to the around root. Instrumentation (Figure 2) was designed according followed by the instrumentation described by Teerawattanasuk *et al.* (2014). The following formula was then used to calculate T_r (Bischetti *et al.* 2003).

$$\mathrm{Tr} \; \frac{\mathrm{Fmax}}{\pi(\frac{D}{2})^2} \qquad \text{…(3)}$$

Where,

F_{max} is the maximum force (N) needed to break the root and D is mean root diameter (mm) near the point of rupture before stretching. Before testing, root diameter was measured at three points, *i.e.* near to two ends of root and halfway of the root, using a micrometer.

Weights were kept in the hanging basket and the load at which root breaks is measured by the digital spring balance. The spring balance is capable of measuring loads of up to 50 kg with an accuracy of ±10g. The following measurements were noted while carrying out this experiment:

- The load at which root breaks
- Cross section area of root.

Results and Discussion

Measurement of soil binding capacity of the experimental grasses was carried out by the large pullout test and through measurement of soil reinforcement. The pullout resistance force of an individual grass species can provide better insight to know the role of an individual grass in erosion process. The species with deep rooted with higher lateral spreading have shown greater pull out resistance which are considered to be suitable species to prevent the torrential runoff. The additional shear strength imposed by the grass roots is used to represent soil binding capacity of grasses (de Beats *et al.* 2008). According to the value of additional shear strength imposed by grasses, they can be used for soil and slope stabilization.

Soil binding strength determined from large pullout test

The average force observed for uprooting three of the each grasses from the soil at field capacity moisture condition is presented in Table 1. It has been observed that maximum uprooting force was observed for TSH (179.75 kg) followed by *H.contortus* (166.3 kg) *and* minimum was observed for *C. fulvus* (85.33 kg). This method has several disadvantages and can only be regarded as an estimate. The feature most open to criticism is that the load was not distributed evenly over the whole root system in those grasses with a number of large horizontal roots close to the ground surface. These horizontal roots occasionally broke sometime after the maximum load had been reached, and thus all the roots were not contributing in full to the estimate of soil binding capacity (Hathaway 1973).

Highest uprooting force in *H. contortus* and TSH can be attributed to higher anchorage of the roots of these grasses due to their higher spread both laterally and vertically in the soil profile. After getting the uprooting force for each grass, soil binding strength is determined for each experimental grass. Result showed highest "soil binding strength index" for *H. contortus* (5.32), followed by TSH (4.11), *P. Maximum* (4.09), *D. annulatum* (3.20), *C. fulvus* (3.06*) and C. ciliaris* (3.44) in Table 1. Soil binding capacity the results show that there was considerable variation between grass species in soil binding capacity. It is not proposed that this measure is an accurate determination of soil binding capacity, but at least gives some indication of the tenacity with which the roots are attached to the soil.

Soil binding capacity determined from the concept of soil reinforcement

Root cohesion

Here, additional shear strength through cohesion (C_r) provided by the root system of the experimental grass species, has been calculated using Wu's model. It is to be noted that the C_r value computed using the hypothesis of Wu's model is the maximum possible value of C_r (Operstein and Frydman 2000; Pollen and Simon 2005).

The tensile strength of roots for different diameter class was recorded. Measurement of tensile strength of roots for varying diameter class is needed for determining shear strength imposed by roots to soil. Measurement of tensile strength of roots was carried out for 50 root samples each grass. The grass which is having maximum value of C_r will have maximum soil binding capacity. The additional shear strength imposed by the grass roots was observed maximum for *H. contortus* (365.0 kPa) followed by TSH (298.5 kPa) and minimum was observed for *C. ciliaris* (139.3 kPa) Figure 1.

Table 1. Uprooting force and soil binding strength for grasses

Grass name	**Force (kg)**	**Weight of soil**	**Dry wt of root(gm)**	**Soil binding strength**
C.ciliaris	120.00±1.36	5.27±2.35	38.70±13.90	3.44±1.39
D.annulatum	115.67±59.43	6.46±6.28	36.33±19.00	3.20±1.61
H.contortus	166.5±7.41	13.09±4.16	32.25±6.60	5.32±1.02
TSH	179.75±92.49	17.63±9.70	44.50±22.68	4.11±2.23
P.maximum	137.00±69.03	12.48±6.28	34.33±18.10	4.09±2.16
C.fulvus	85.33±43.35	8.83±5.15	28.23±15.28	3.06±1.60

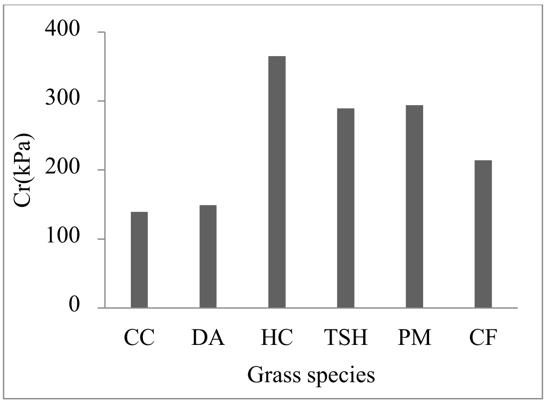


Figure 3. Root cohesionvalue of different grasses

Relationship between tensile strength and root diameter

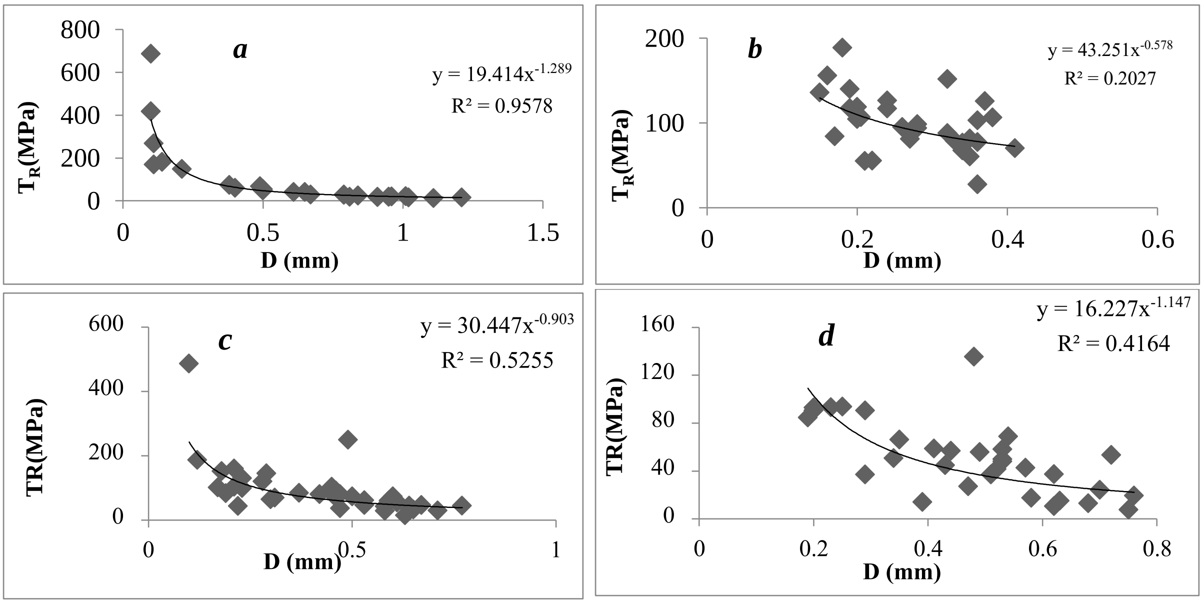
Variation of tensile strength (MPa) with root diameter of grasses is shown in Figure 4(a-f). It shows that the tensile strength of root follows the power law with varying degree of coefficient of determination (R^2). Value of root tensile strength for different root diameter class of six of grass is shown in Table 2. Results for *C. setigerus* are not shown here due to it less number of roots for each diameter class. It was observed that relationship between tensile strength of root (T_R) and root diameter (D) follows power law (Eq. 4) and the same has been reported by many other researchers (Operstein and Frydman 2000; Bischetti *et al.* 2005; Norris 2005; Mattia *et al.* 2005 and Tosi 2007).

$T_R=aD^b$ ...(4)

Where *a* is the scale factor and *b* is the rate of strength decrease (empirical constants which vary between plant species). The values of *a* and *b* are important in making an improved comparison between species. Concerning the behaviour of the different species in terms of root tensile strength, the exponent (b) of the power law equation controls the rate of strength decay with diameter, whereas *a* can be considered as a scale factor (Teerawattanasuk *et al.* 2014). Variation of tensile strength against diameter is described well almost for all grasses (higher R^2 value between the observed and computed tensile strength) except for *D. annulatum* which showed poor fit between observed and estimated tensile strength (Figure. 4). Table 2 shows the details of parameters obtained while correlating observed tensile strength with diameter using power law.

Table 2. Parameters (a and b values) and R^2 values for the power relationships (Eq. 3), expressing the decrease in root tensile strength with increasing root diameter for 6 six species

Grass species name	a	b	Range of tensile strength (MPa)	Range of diameters(mm)	R^2
C. ciliaris	19.34	-1.3	13.02-686.62	0.1-1.5	0.952
D. annulatum	43.25	-0.57	27.45-188.8	0.15-0.41	0.202
H. contortus	30.44	-0.9	14.15-486.87	0.1-0.77	0.525
TSH	16.22	-1.14	7.76-135.46	0.19-0.76	0.416
P. maximum	39.04	-0.79	31.53-324.58	0.09-0.69	0.481
C. fulvus	33.73	-0.9	21.33-195.04	0.16-0.99	0.731



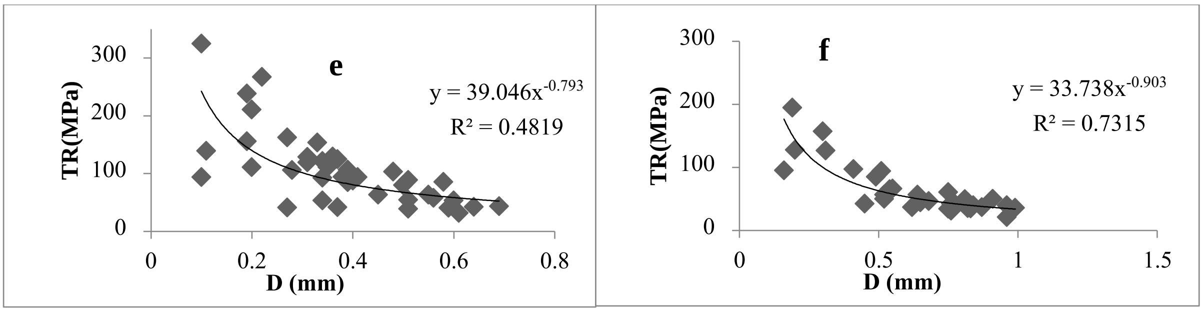


Figure 4. Relationship between root tensile strength and root diameter *a*) *C.ciliaris*, (b) D. annulatum, (c) *H. contortus,* (d) TSH, (e) *P. maximum* (f) *C. fulvus.*

From this experiment, it has been observed that overall maximum tensile strength for different root diameter classes was observed for *D annulatum*, whereas minimum was observed for TSH.

The effect of roots on shear strength of soil erosion

The shear strength of a soil has been recognized as a determinant of its resistance to erosion. From the start of slope stability and soil binding research it was clear that plant roots were vital for soil reinforcement. The shear strength of a soil is a measure of its cohesiveness and resistance to shearing forces exerted by gravity, moving fluids and mechanical loads. Soil is strong in compression, but weak in tension. Grass roots are weak in compression, but strong in tension. When combined, the soil-root matrix produces a type of reinforced earth which is much stronger than the soil or the roots separately (Simon and Collison, 2001) thus, roots reinforce the soil. This conclusion was found independently by different researchers (Gray and Leiser 1982), showing that soil erodibility is inversely proportional to the resistance of the soil to erosion. In this context, the intrinsic properties of the soil such as change in infiltration capacity, physical properties of soil and as a result change in shear strength is the most important determinants. With their traction effect, these roots increase the tensile strength of the upper soil, and protect the soil mass below as well (Bibalani 2006) while the dense lateral roots bind the shallow soil mass to form a membrane with increased tensile strength, the vertical roots anchor the tensile membrane to the deep and more stable soil mass. With the combined effect, the lateral roots are able to stabilize the upper soil against shallow slide and creep.

Highest cohesive value found in *H. Contortus* among all grasses. Root systems lead to an increase in soil strength through an increase in cohesion brought about by their binding action in the fiber/soil composite (Gray and Leiser 1982; Styczen and Morgan 1995; Teerawattanasuk *et al. 2014)* have proven the effectiveness of grass for erosion control, providing a complete ground cover (Brindle, 2003).

Conclusions

Generally, smaller diameter roots had higher tensile strengths, but the decline in root tensile strength with increasing root diameter varied for the 35 tested grass species. Although having many fine roots, not all grass species appeared to have strong roots. Whereas the grasses DA and *P.maximum* had strong roots, TSH had very weak roots. The pullout resistance force of an individual species can provide better insight to know the role of an individual plant in erosion processes. The species with deep rooted with lateral spreading have shown greater pull out resistance and which are considered to be suitable species to prevent natural threat like landslide. Uprooting force of the TSH and *P. maximum* is high and sufficient to withstand the water and sediment loads. Root systems lead to an increase in soil strength through an increase in cohesion brought about by their binding action in the fiber/soil composite, proven the effectiveness of grass for erosion control, providing a complete ground cover.

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