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Experimental Study on Tensile Properties and Reinforcement Ability of Plant Roots

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ABSTRACT

Plant roots have considerable impact on the soil shear resistance. To fully understand the mechanics of how plant roots reinforce soil stability, controlled laboratory test has been conducted on five kinds of pioneer plants that are generally applied to land restoration works. It aims to improve understanding of tensile material behaviour of roots, and proposes a more accurate procedure to calculate the effect of soil reinforcement. We selected five representative species (Alfalfa, *Cynodon dactylon*, Vetiver grass, Ryegrass and *Indigofera amblyantha*) of the ecological restoration projects as the pioneer plants of gentle slope in Mount Cuiping to examine these effects. Results of tensile tests showed that the differences of root tensile strength were significant among five species, and root tensile strength was mainly affected by several factors, such as shape, diameter, moisture and age. Curves of root tensile deformation displayed the whole process root endure under tensile stress. Combined with characters of strength and deformation, an evaluation model of soil reinforcement proposed in this paper was proved to be more rational by contrast test.

INTRODUCTION

Soil erosion is a hazard that influences both natural and cultivated lands significantly and causes considerable soil loss (Cui et al. 2011, Vanwalleghem 2017). Plant root systems may substantially improve the shear strength of soil (Abe & Ziemer 1991, Campbell & Hawkins 2003, De Baets et al. 2008, Ghestem Veylon et al. 2013, Operstein & Frydman 2000, Waldron et al. 1981, Zhang et al. 2010, Zhou et al. 1997) to prevent soil particles from erosion in two types: the hydrological mechanisms of reducing pore water pressure (Abernethy & Rutherfurd 2001, Gyssels et al. 2005) and the mechanisms of soil reinforcement (Abdi et al. 2010, Cheng et al. 2003, Giadrossich et al. 2012, Hejazi et al. 2012, Li et al. 2009, Mickovski et al. 2009, Pollen 2007, Waldron et al. 1981). Comparative studies of these two impacts have manifested that soil reinforcement contributes much more to the soil shear strength increase (Stokes et al. 1996).

Roots increase the soil shear resistance by transforming their tensile strength into shear strength of soil (Docker & Hubble 2008, Genet et al. 2008, Lin et al. 2010, Xiong et al. 2007). Xiong (2007) summarized the former studies on root tensile strength, and confirmed that root tensile strength varies in different species. In aspects of the theoretical research, there are three reviews (Cazzuffi et al. 2014, Gray et al. 1986, Wu 2000, Yang & Wang 1999, Zhang et al. 2010), and they might be adopted to explain the mechanism of how soil reinforcement being generated. Among these reviews, the most preventative one is Friction Reinforcement Principle (Coder 2010, Schwarz et al. 2010, 2011). On the basis of this principle, the first model of soil reinforcement was provided by Waldron (1977) and Wu (1979). Their perpendicular model is derived from the Coulomb equation (Eq. 1), and root growth in the soil leads to shear stress enhancement, as Eq. (2).

$$S=C+\sigma_N \tan\varphi \quad ...(1)$$

$$S=C+\sigma_N \tan\varphi+\Delta S \quad ...(2)$$

Where, S is soil shear strength; C is soil cohesion; σ_N is the stress normal to shear plane; φ is the angle of internal friction and ΔS is the increase in soil shear strength due to the presence of roots.

In this model, the evaluation of ΔS simply depends on root tensile strength (T_R) and on the cross-sectional area of roots in the shear plane (RAR), as shown in Eq. (3), where, K

ranges from 1.0 to 1.3 and is typically approximated as a constant value of 1.2 (Wu et al. 1979).

$$\Delta S = K \cdot T_R \cdot RAR \qquad ...(3)$$

The above model depends on the supposition that all roots are fully mobilized under soil shearing (Wu et al. 1979); all roots break simultaneously (Simon & Langendoen 2010, Waldron 1977). Consequently, the quantitative evaluation of ΔS by this model may overestimate the measured value of soil reinforcement (Thomas & Pollen 2010, Waldron et al. 1981), and hence Eq. (3) should be modified by multiplying with a reduction coefficient K_{red}.

$$\Delta S = K_{red} \cdot K \cdot T_R \cdot RAR \qquad ...(4)$$

A concept of Fiber Bundle Model (FBM) has been studied extensively and been applied to modify this model of soil reinforcement (Comino et al. 2010, Mickovski et al. 2009, Pollen & Simon 2005, Thomas & Pollen 2010), but the specific procedure of getting the exact modification coefficient is quite complicated and still needs to be explored.

Soft roots can usually be treated as a special type of fabric material (Donald et al. 1983, Xia et al. 2011). So it is reliable to measure the root tensile strength by monaxial tension tests. Based on tensile tests, a very useful empirical equation can be applied to estimate the root tensile strength according to their diameters (D), as shown in Eq. (5) (Gray & Sotir 1996), where α and β are empirical values according to the species. Some authors indicated that root tensile strength presents temporal and spatial variations (Abdi et al. 2010).

$$T_R = \alpha \cdot D^{\beta} \qquad ...(5)$$

Therefore, besides the geometry of roots, it is necessary to consider the other factors which may affect root tensile strength, such as root moisture content, age, spatial distribution, etc. Root tensile deformation correlates with soil particles under mechanical erosion. Studies have been carried out to understand the material properties of roots (Li et al. 2009, Zhu et al. 2009, Zhu et al. 2002), but made less quantitative conclusions. Further studies, especially to the tensile constitutive model of roots, should be made.

In this paper, the tensile strength and tensile deformation of root system with five typical pioneer plants were studied, and a feasible method of soil reinforcement for evaluating the existence of roots is established. These conclusions may be meaningful to optimize the traditional calculation model of soil reinforcement by the presence of roots and conduct ecological restoration of degraded lands.

MATERIALS AND METHODS

Test site: The test site is located in Mount Cuiting of China Three Gorges University, Hubei province. Climate of this area is subtropical monsoon, with temperature of autumn higher than spring. The mean annual rainfall of this place is 992.1-1404.1 mm and the mean average temperature is 13.1°C~18°C with 4-5 cold months. The sampling site, with five sampling plots (Fig. 1), is north-east oriented; its altitude is about 100 m.

Studied species: Five species were chosen for the present study among the most dominant in the local vegetation: Alfalfa, *Cynodon dactylon*, Vetiver grass, Ryegrass and *Indigofera amblyantha*. These species represent two vegetation types: herbaceous and shrubby plants. It is worth mentioning that the five species are generally intruded into ecological restoration projects as the pioneer plants because of their rapid growth and hardiness (Chen et al. 2013).

Roots sampling: The sampling time was in June, 2017. The prominent plants in the five sampling sites were Alfalfa, *Cynodon dactylon*, Vetiver grass, Ryegrass and *Indigofera amblyantha* respectively. Soil natural densities corresponding to the aforementioned plants were, 1.39 g/cm^3, 1.37 g/cm^3, 1.55 g/cm^3, 1.36 g/cm^3, 1.52 g/cm^3, and soil moisture contents were 27.8%, 25.4%, 18.8%, 22.9% and 12% respectively.

By means of dig methods from up to down, roots were obtained by separating soil particles carefully. Then a digital caliper with the least precision 0.01 mm was used to measure the diameters of these roots, each measure was repeated five times so as to take an average. Relevant statistical data are listed in Table 1. After this work being finished, intact roots were picked out and put into freshness packets, and then brought to the laboratory and refrigerated at 4°C.

Root moisture content: A dryer was applied to measure the root moisture content of each plant. The measurement process was as follows: cleaned roots in the alcohol with concentration of 15%; then weighed them after the alcohol adhering to roots volatilized; finally, placed these roots into the dryer and roasted them at a temperature of 105°C. Loss contents of root moisture can be calculated as Eq. (6), where, W is the loss content of root moisture, m_0 is the weight before being roasted; m_t is the weight after being roasted for the time.

$$W = \frac{m_0 - m_t}{m_0} \times 100\% \qquad ...(6)$$

Root tensile strength measurement: The tensile strength of the root was measured by uniaxial tensile test. With reference to previous researches about root tensile strength (Tosi 2007), a set of apparatus was selected in the study. It was composed of a HP-500 digital pull tester with maximal range of 50 kg and minimum resolution of 0.01 kg, a support

Fig. 1: Pictures of the five sampling sites with plants.

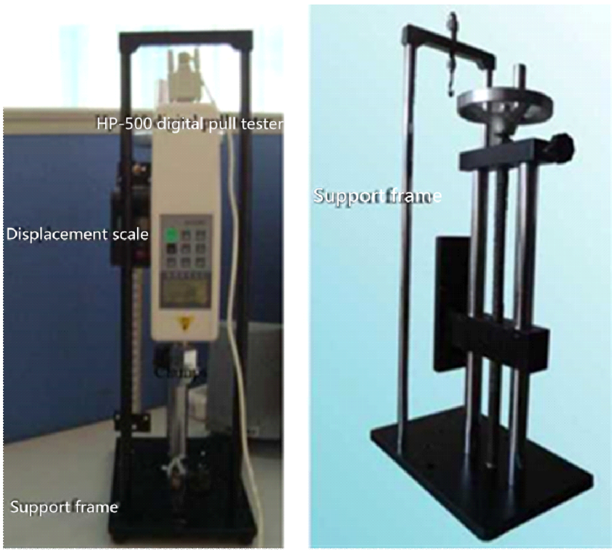

Fig. 2: Pictures of tensile apparatus and its support frame.

frame, a displacement scale with minimum resolution of 0.01 mm, two clamps and a terminal processing computer (Fig. 2).

The damaged roots were removed before the tensile test started. Then the selected roots would be cleaned in alcohol with concentration of 15% (Bischetti et al. 2005), and be fixed between the two clamps axially, at last, axial tensions were applied.

The roots of these five species were soft and their diameters were small. Hence, the roots in this study can definitely be treated as typical flexible fibres without considering their bending rigidity. Root tensile strength maybe calculated as Eq. (7) if the following three conditions are satisfied: (1) the tensile direction is completely axial; (2) the position of tensile failure for each root is distributing within the two clamps; (3) the shape of each root can be considered to be ideal cylinder. In Eq. (7), where, σ_s is the root tensile strength; F is the ultimate tensile force; D is the root diameter.

$$\sigma_s = \frac{4F}{\pi D^2} \quad ...(7)$$

In tension procedures, another two problems need to be paid attention to: (1) several attempts should be carried out to determine adaptive clamping force to anchor the root; (2) pretension should be made properly to render the root in pre-stressed state when the tensile tests begin.

Root tensile deformation measures: The digital scale (in Fig. 2) was used to record root tensile displacements in the measurement process of tensile strength, then root tensile strain can be calculated as Eq. (8), where ε_s is the tensile strain; Δl is root tensile displacement corresponding to an axial load, and presumably L is the axial load.

$$\varepsilon_s = \frac{\Delta l}{L} \quad ...(8)$$

RESULTS

Root Tensile Strength

This part shows the relationship between root tensile strength and root diameter of these five species. Furthermore, Alfalfa being taken an example, the effect of root moisture content on root tensile strength is presented; *Indigofera amblyantha* being the representative plant; it is investigated how root age affects the root tensile strength.

Root tensile strength versus root diameter: The results of the tensile strength tests are shown in Fig. 3. For these four species: Alfalfa, *Cynodon dactylon*, Vetiver grass and *Indigofera amblyantha*, the root tensile strength decreased with increasing root diameter following the power relationship given by Eq. (5). But for Ryegrass, the correction between root tensile strength and root diameter was not significant. Functional relationships between root tensile strength and diameter are listed in Table 2. The analysis of Table 2 showed that the root tensile strength was noteworthy and differed significantly among species. Standard deviation of root tensile strength values was larger for thicker roots (Alfalfa: 52.32; *Indigofera amblyantha*: 36.91; *Cynodon dactylon*: 28.24; Ryegrass: 12.51.). Except Ryegrass, values of the decay coefficient β in the other four fitting relations were nearly -1 (Alfalfa: -0.912; *Cynodon dactylon*: -0.992; Vetiver grass: -0.829; *Indigofera amblyantha*: -0.892).

Table 1: Diameter ranges, max lengths and shapes of roots for the selected five species.

Species	Diameter	Max length	Shape of the roots
Alfalfa	Fiber roots <1 mm, taproot 1~3 mm	15 cm	Approximate cylinder
Cynodon dactylon	<1 mm	12 cm	Approximate cylinder
Vetiver grass	<2 mm	30 cm	Approximate cylinder
Ryegrass	<1 mm	10 cm	Approximate cylinder
Indigofera amblyantha	0.6 ~ 5.8mm with many fiber roots	40 cm	Approximate cylinder

Table 2: Fitting relations between root tensile strength and root diameter.

Species	N	D (mm) mean ± sd	F (N) mean ± sd	σ_s(MPa) mean ± sd	$\sigma_s = \alpha D^{\beta}$	R^2
Alfalfa	21	1.13±0.61	39.20±25.69	56.40±52.32	σ_s =42.168 × $D^{-0.912}$	0.939
Cynodon dactylon	21	0.32±0.17	7.42±3.67	104.72±28.24	σ_s =29.853 × $D^{-0.992}$	0.910
Vetiver grass	60	0.82±0.39	15.80±8.95	34.14±17.10	σ_s = 24.471 × $D^{-0.829}$	0.899
Ryegrass	21	0.35±0.23	11.06±19.78	82.53±12.51	σ_s = 71.249 × $D^{-0.115}$	0.125
Indigofera amblyantha	28	1.04±0.58	33.11±9.37	54.89±36.91	σ_s = 40.996 × $D^{-0.892}$	0.770

Table 3: Tensile tests of Alfalfa roots in different root moisture contents.

T	w (%)	*N*	D (mm) mean ± sd	σ_s(MPa) mean ± sd	$\sigma_s = \alpha D^{P}$	R^2
0	44.30	25	0.98±0.64	67.09±57.45	σ_s = 44.45×$D^{-0.94}$	0.928
10 min	38.33	25	1.02±0.72	67.36±42.33	σ_s = 55.43×$D^{-0.76}$	0.906
20 min	28.28	25	1.26±0.55	67.36±42.33	σ_s = 68.06×$D^{-0.63}$	0.931
40 min	17.09	25	0.91±0.51	59.99±35.95	σ_s = 48.86×$D^{-0.99}$	0.645
100 min	11.68	25	1.12±0.71	51.06±39.15	σ_s = 43.78×$D^{-0.96}$	0.531
480 min	8.19	25	1.18±0.41	25.75±14.57	σ_s = 26.94×$D^{-0.60}$	0.142

Table 4: Basic information about the three different groups of plants.

Group	*N*	Crown diameter (m) mean ± sd	Plant height (m) mean ± sd	Base diameter (mm) mean ± sd
Young	10	0.40 ± 0.05	0.50 ± 0.04	4.53 ± 0.23
Adolescent	10	0.65 ± 0.05	0.80 ± 0.06	6.70 ± 0.45
Mature	10	1.10 ± 0.10	1.50 ± 0.20	11.71 ± 0.53

Root tensile strength versus root moisture content: Taking Alfalfa as an example, measures of root tensile strength in different conditions of root moisture content were carried out. The curve of *w* (root moisture content) versus *T* (roasting time) is shown in Fig. 4. The results indicated the moisture content loss process was composed of two stages: firstly, stage root moisture content changed dramatically with *T*, then changed gradually. There was a distinct turning point (T = 40 min). This point could be considered as the tolerance limit of Alfalfa to moisture variation.

The fitting relations of σ_s(root tensile strength) versus D (root diameter) are listed in Table 3. The analytical results showed that root tensile strength exerted dynamic change with root moisture content. There was a strength increase when T was less than 40 min and the power relationships of σ_s-D given by Eq. (5) were significant. Subsequently, root tensile strength calculated as Eq. (7) was decreasing.

Root tensile strength versus root age: Three groups of *Indigofera amblyantha* were selected (listed in Table 4) by three important indexes (crown diameter, plant height, base diameter), which might be used to distinguish the plants in different growth periods. There are the three growth periods qualitatively (young, adolescent, mature) and also provide estimated ages for each growth period (young: < 6 month; adolescent: 6-12 month; mature: >12 month).

All these plants were sampled in the same plot with identical soil condition and altitude. The fitting relations of σ_s-D in different growth periods are given in Table 5. Results

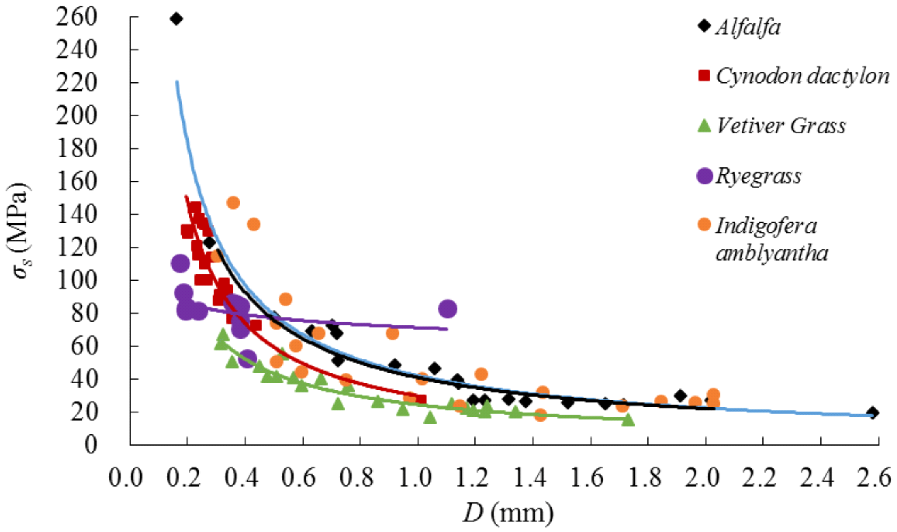

Fig. 3: σ_s-D fitting curves of these five species.

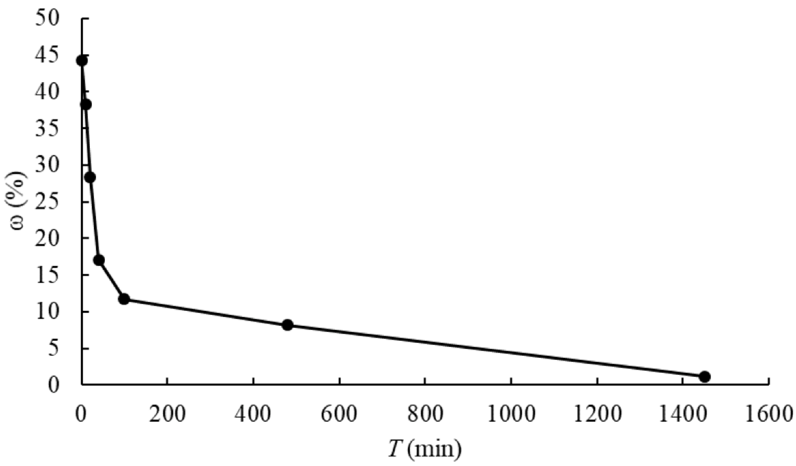

Fig. 4: w-T curve of Alfalfa.

of Table 5 indicated that root tensile strength was varying with growth plant periods. There was a gradual strength increase with the growth (matures) ≥ group (adolescent) ≥ group (young). In addition, fitting relations between σ_s and D were significant as Eq. (5), and the values of the decay coefficient presented an increasing trend [group (young): -0.63; group (adolescent): -0.34; growth (mature): -0.29].

Root Tensile Deformation

In this part, relations between tensile force (F) and tensile displacement (DL) are given. And correlations between tensile modulus of roots and their diameters are displayed for the two species: Alfalfa and *Indigofera amblyantha*.

Tensile process of roots: Results of root tensile deformation about Alfalfa and *Indigofera amblyantha* are presented in Fig. 5. Here the roots being tested were in different diameters. The curves of Fig. 5 indicated that the tensile deformation behaviour of roots were as the same as general fibres in some extent. The whole tensile process of roots might be divided into two phrases. In initial phrase, tensile deformation exerted a drastic increase with tensile force, and then the increasing trend decreased until the tensile failure come out. Besides, the curves between F and Δl differed with root diameter; the roots with lager diameters had steeper curves, which reflected roots with lager diameters had a strong resistance to the tensile force.

Tensile modulus of roots: Tensile modulus is an important index to evaluate the capacity of resisting tensile. Such an index can be computed as Eq. (9), where, E_s is the tensile modulus; σ_s is calculated as Eq. (7); ε_s is calculated as Eq. (8).

Table 5: Tensile tests on roots of different ages.

Groups	N	D (mm)	F(N)	T_s (MPa)	$\sigma_s = \alpha D^{\beta}$	R^2
Young	28	0.88±0.37	32.74±24.64	49.94±8.27	$\sigma_s = 39.81 \times D^{-0.63}$	0.791
Adolescent	28	1.02±0.56	32.49±24.64	53.57±7.18	$\sigma_s = 46.41 \times D^{-0.34}$	0.785
Matures	28	0.81±0.32	32.50±21.66	60.71±10.04	$\sigma_s = 54.25 \times D^{-0.29}$	0.788

$$E_s = \frac{\sigma_s}{\varepsilon_s} \quad ...(9)$$

According to the relations between F and Δl (Fig. 5), the curves of tensile deformation can be simplified as Fig. 6, where the stage of tensile deformation exerting drastic increase can be considered as appropriate linear change. Linear part is the main contribution to resist tensile stress. On a basis of Eq. (7), Eq. (8) and Eq. (9), tensile modulus of linear part can be calculated as Eq. (10), where, $\tan\theta$ is the line slope, shown as in Fig. 6; E_{sL} is the tensile modulus of linear part.

$$E_{sL} = \frac{4L \cdot \tan\theta}{\pi \cdot D^2} \quad ...(10)$$

For Alfalfa and *Indigofera amblyantha*, the relations between E_{sL} and D are given in Fig. 7, respectively. There was a significant power function as the similar type of Eq. (5).

DISCUSSION

Tensile strength tests confirmed that there was a power relationship between root tensile strength and root diameter (Table 2). This well-known relationship (Comino & Marengo 2010, Norris 2005) reveals that thin roots are more resistant to tensile stresses than thick roots, while it was not observed from Ryegrass in this research. The reason is that root architecture contents and their proportions determined root tensile strength essentially.

Roots are composite material. The architecture of perennial roots is formed by four parts: periderm, secondary phloem, microtubule formation layer, secondary xylem and primary xylem; the architecture of herbal roots is composed of three parts: epidermis, cortex and stele (Gibson 1970). Tensile characters of periderm differ greatly with the other compositions (Zhu et al. 2009). To simplify the analysis, the root architecture was divided into two main portions: part I stands for root bark and part II stands for the other compositions except the root bark. Define tensile strength of part I as σ_I; tensile strength of part II as σ; root sectional area as A and sectional area ratio of part I as λ. Based on these assumptions and definitions, root tensile strength can be deduced by Eq. (11), (12) or (13) in different tension broken models. For Eq. (11), tensile failure of part II occurs earlier than part I; for Eq. (12), tensile failure of part I occurs earlier than part II and for Eq. (13), tensile failure of two parts occurs simultaneously.

$$\sigma_s = \sigma_{\mathrm{I}} \quad ...(11)$$

$$\sigma_s = \sigma_{\mathrm{II}} \quad ...(12)$$

$$\sigma_s = \lambda\sigma_{\mathrm{I}} + (1\text{-}\lambda)\ \sigma_{\mathrm{II}} \quad ...(13)$$

Sectional area ratio of part II increases when the root diameter becomes larger (Zhu et al. 2009), hence, root tensile strength might definitely correlate with diameter. In this study, different fitting relations between root tensile strength and diameter were analysed (Table 2). Except Ryegrass, there existed significant function between F (tensile force) and D (root diameter); the phenomenon of the other four kind of roots satisfied the state of Eq. (13). According to the rupture phenomenon tensile tests showed, the tension broken model of Ryegrass roots satisfied the Eq. (12), in this state, the root tensile strength of Ryegrass exerted uncorrelated relation with root diameter.

As for root architecture variability, many other factors can influence root tensile strength excluding soil properties, such as root bark, root age, root structure, etc. (Genet et al. 2007). Besides, root moisture content may definitely affect the flexural rigidity of roots. The test phenomenon of root moisture content measurements indicated that the flexural rigidity of roots increased with the root moisture content decreasing. On account of this phenomenon, it is not correct to consider roots as soft fiber when the roots are in low moisture content, and the effects of flexural cannot be ignored. By this time, the values of root tensile strength calculated as Eq. (7) are irrational. That is why root tensile strength of Ryegrass decreased when the moisture content was less than 28.28% in this study. In order to consider the influence of rigidity, Eq. (14) should be selected instead of Eq. (7).

$$\sigma_s = \frac{4F}{\pi D^2} + \frac{M}{W} \quad ...(14)$$

In Eq. (14), where M is the additional bending moment; W is the cross sectional moment of inertia of roots, and W can be calculated as Eq. (15).

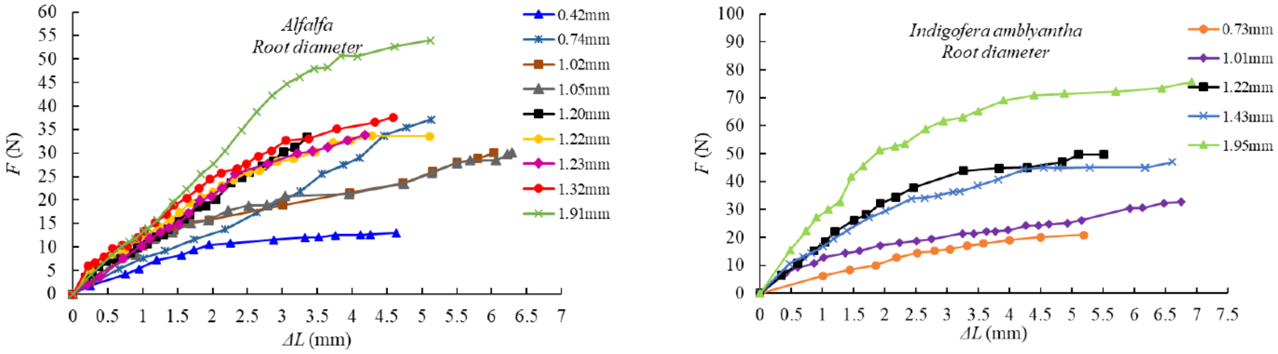

Fig. 5: Tensile deformation curves of roots of Alfalfa and *Indigofera amblyantha*.

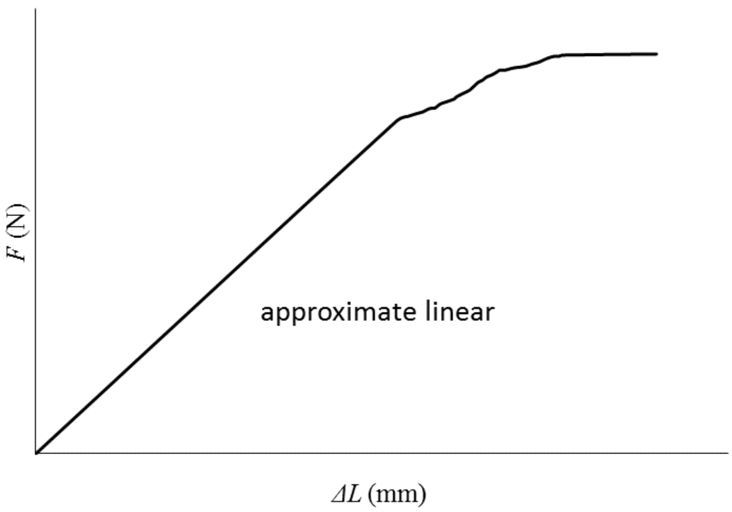

Fig. 6: Simplified schematic diagram of relation between F and ΔL.

$$W = \frac{\pi D^3}{32} \qquad ...(15)$$

Among the factors affecting root tensile strength, root age is another important one. In this study, *Indigofera amblyantha* was taken as a representative plant, and the root tensile strength measurements were carried out. The results showed that there was a gradual tensile strength increase. The tensile strength increase could be seen from the increasing of coefficient α (group I: 39.81; group II: 46.41; group III 54.25), and decreasing of coefficient β (group I: -0.63; group II: -0.34 ; group III: -0.29). Essentially, in different growth periods, root architecture is different and the mechanic characters of root components are also varied. That is why root age can make an influence on root tensile strength. It is believed that the distinction among root components may be diminished with the root age increasing, therefore, the increase of root tensile strength is not limitless. For the mature roots, the format of relation between root tensile strength and root diameter would not be changed any longer.

As for root tensile deformation, the curves (Fig. 5) of Alfalfa and *Indigofera amblyantha* differed significantly among different diameter roots. In addition, according to the shape of curves, tensile deformation process of roots could be divided into two stages: elastic defamation and plastic deformation. It is known to us that elastic deformation can bring elastic resistance, and plastic deformation may lead into non-elastic deformation accumulation. In view of the elastic stage being the main stage in Fig. 5, therefore, an elastic-perfect plastic constitutive model might be adopted to describe the behaviour of tensile process.

Tensile modulus is usually applied to evaluate the capacity of materials resisting tensile deformation. In our study, it could be found that the predominant stage of tensile deformation was approximately nearly linear. Hence, the modulus of this part deserves special attention. Results of

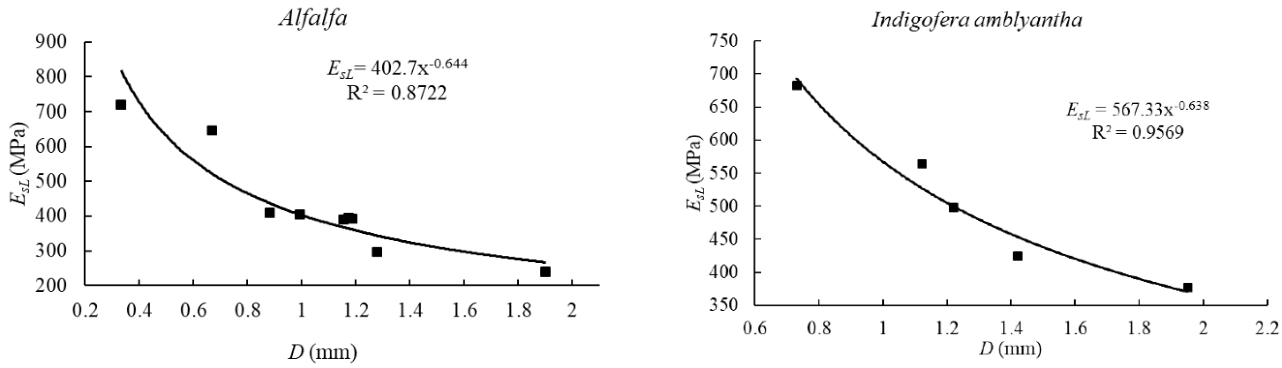

Fig. 7: Relations between E_{sL} and D for Alfalfa and *Indigofera amblyantha*.

tensile deformation in Fig. 6 showed that there was a significant correlation between tensile modulus of linear part and root diameter. Such a correlation relation corresponded to the relation between root tensile strength and root diameter. The study made by Wu (1979), also confirmed these conclusions.

For soil reinforcement, what we exactly concern is the method of quantitative evaluation. The study above, just discussed the tensile behaviour of each single root. These discussions were not enough to describe potentials of the root reinforcement. Previous researches (Pollen 2007, Thomas & Pollen 2010) confirmed that theoretical values calculated as Eq. (2) might overstate the root reinforcement. So asynergistic effect should be understood, and the following problem needs to be solved: How the tensile force distribute among each single root. Pollen (2007) proposed that a Fiber Bundle Model might be used, and a correction factor could be introduced to make a modification as Eq. (3), but it was difficult to get such a factor exactly. Several attempts should be required.

Tensile deformation of roots reflect the change process of root tensile strength to some extent. So, the tensile modulus is an effective index, and the index can be applied to calculate the tensile strength of root systems. Based on these analyses, we designed a verification experiment.

In the verification experiment, a group of Alfalfa roots with diameters 0.79 mm, 0.40 mm, 0.47 mm, 0.77 mm, 0.33 mm, 1.17 mm and 1.34 mm, respectively, were chosen. Following the tensile procedure mentioned earlier, we measured the ultimate tension of this group of Alfalfa roots, which was 125.7 N; tensile strain (Eq. 8) of each single root was 6%~8%. Based on Eq. (16), the ultimate tension of this group of Alfalfa roots was calculated as 176.8 N by accumulating the ultimate tension of each single root, and this result was much larger than 125.7 N. While using Eq. (17), the ultimate tension was just 118.2 N.

$$F = \sum_{i=1}^{7} \frac{\sigma_{si} \cdot \pi D^2}{4} \quad ...(16)$$

$$F = \sum_{i=1}^{7} \frac{E_{SLi} \cdot \varepsilon_i \cdot \pi D^2}{4} \quad ...(17)$$

The calculation value based on elastic deformation nearly equals to the test value, and the error is only 5.9%. This method may be applied to modify the traditional W&W model proposed by Wu (1979), Waldron & Dakessian (1981).

Taking the soil and roots as a whole, roots present three deformation modes: (1) root breaking, (2) root pullout, and (3) root tension (Ennos 1990, Pollen 2007). Based on the process of tensile deformation, it may be available to determine the accurate failure modes of roots, by this way, the calculation value of soil reinforcement will be closer to actual conditions.

CONCLUSIONS

Taking five kinds of plants- Alfalfa, *Cynodon dactylon*, Vetiver grass, Ryegrass and *Indigofera amblyantha* as the study objects, tensile tests were carried out to the roots. Then the relations between root tensile strength and root diameter were analysed. Relevant conclusions are stated as follows. (1) The relations between root tensile strength and root diameter are significant power functions; (2) root tensile strength varies with the change of root moisture content, and if the root moisture is too low, root tensile strength should be calculated by an equation of eccentric tension; (3) root tensile strength presents an increase with the growth of the plants and then may tend to be stable. In order to get the exact root tensile strength, the root structure, root moisture content and root age should be made an overall consideration, including the root space distribution if the root distribution is in a large scale.

The characters of root tensile deformation are as same as general fiber materials, and the deformation process is composed of two parts- elastic deformation and plastic information. In the stage of elastic deformation, the relations between tensile modulus of roots and their diameters are significant power function; in the plastic stage, accumulation deformation lead into the tensile failure of roots.

The method based on tensile deformation was proposed to calculate the tensile resistance of root systems. Results of theoretical calculation and test value showed that the method was effective to be used in evaluating the soil reinforcement well. So, the tensile deformation can help to distinguish the development of tensile strength, and can be applied to modify the traditional calculation models of soil reinforcement.

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