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Mechanisms of root-soil reinforcement in bio-embankments of sloping farmland in the purple hilly area, China

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Abstract: Bio-embankment is an important soil and water conservation measure in the purple hilly area in China, which can effectively improve the ability of cultivated soil layers to resist rainfall erosion and runoff scour. In contrast, the ecological effect of bio-embankment depends on the stability of the earth bank. Taking the natural grass bank as a control (CK), the root distribution, root tensile properties and shear resistance of root-soil composites for 3 typical soil and water conservation bio-embankments, namely, *Morus alba* Linn *(Morus)*, *Zanthoxylum bungeanum* Maxim. *(Zanthoxylum)* and *Medicago sativa (Medicago)* were analysed. The results included the following: (1) The root system of the bio-embankments generally decreased in extent with the soil depth; fine roots in the 0-10 cm depth were most prevalent and significantly higher than those at the other depths, and coarse roots were mainly distributed in the 0-30 cm layer. (2) The stress-strain curves of the roots of each bio-embankment were single-peak curves without clear strain softening phenomena. The smaller the root diameters were, the smoother the stress-strain curves, and the lower the capability of the earth bank to resist collapse. The larger the root diameters were, the lower the tensile strength. The average root tensile force was highest for *Zanthoxylum* (73.91 N), followed by *Medicago* (68.07 N) and *Morus* (61.88 N), and the average root tensile strength showed the same trend, 16.52 MPa for *Zanthoxylum*, 16.08 MPa for *Medicago* and 13.02 MPa for *Morus*. (3) The bio-embankment measures significantly improved the soil shear resistance, especially under vertical loads of 100 kPa and 200 kPa. The soil internal friction angle showed a significant log-positive correlation with root morphological parameters of root length density (RLD), root surface area density (RSAD) and root

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weight density (RWD), while the soil cohesion force showed a positive linear correlation with these parameters. The results provide effective parameters supporting for the design of bio-embankments and promoting the use of soil reinforcement with suitable species selection in protective earth banks for stability in the purple hilly area.

Keywords: Bio-embankments; Root distribution; Tensile properties; Shear strength; Earth bank collapse; Purple hilly area

Introduction

Soil erosion is a serious problem in China, where bare soils are very vulnerable to erosion during intensive rainstorms. Purple soil is the main soil type in southwestern China, accounting for 2.2% of the total soil area of China, and is characterized by a weak corrosion resistance and a large amount of soil erosion by frequent rainstorms in the summer (Tang et al. 2015). For erosion processes such as rill and gully erosion, the presence of roots are as important for the reduction in soil losses as the above-ground vegetation cover (De Baets et al. 2007; Zegeye et al. 2018). Roots reduce soil erosion by binding the soil particles at the ground surface. The larger infiltration capacity and the higher surface roughness caused by roots reduce the volume and velocity of surface runoff. The erosion-reducing potential of plant species was negatively correlated with root diameter and positively correlated with the content of fine roots (Burylo et al. 2012), which are closely combined with soil particles, to resist the external pressure and runoff shearing in the soil (Genet et al. 2005). Fibrous roots (≤1 mm) accumulate organic matter to increase the content of water-stable aggregates in soil, reduce the soil bulk density, and influence the soil saturation and water permeability most significantly (Loades et al. 2010). Fine roots (≤2 mm) directly network throughout soil masses and indirectly improve soil structure, improving the anti-scour ability of soil (Wu et al. 2000). Nevertheless, the influence of coarse roots (>2 mm) should not be neglected, especially for incisive water erosion processes. The potential role of coarse roots is important (Mcivor et al. 2009), and fine roots tend to break during slope failure (Ennos 1990); only the coarse roots penetrate deeply and anchor in firm strata and, as a consequence, are able to fix shallow soil layers to resist runoff erosion (Bischetti et al. 2005). For example, a positive linear relationship between the cross-sectional area of barley roots at the shear plane and subsequent increases in soil shear strength in a silty clay loam soil was observed (Waldron 1977; 1981). In ryegrass, increasing root densities from 0.20 to 1.80 g/cm^3 increased the soil strength from 1 to 5 kPa in a sandy clay loam (Tengbeh 1993). Hence, the presence of roots considerably increases the shear strength, resisting soil erosion.

The sustainable use of plants for soil protection has been widely accepted (Stokes et al. 2014; Li et al. 2016). Soil reinforcement by plants mainly depends on the spatial distribution (Lü et al. 2012) and root reinforcement, tensile mechanical and bio-mechanical characteristics (Capilleri et al. 2016; Cislaghi et al. 2017; De Baets et al. 2008) of the roots. Roots extending perpendicular to the soil surface reinforce the soil by increasing the shear strength of the rooted soil mass on the sheared surface. Roots growing parallel to the soil surface reinforce the soil by increasing the in-plane tensile strength of the rooted soil zone (Reubens et al. 2007). Roots of woody plants are stronger than those of herbaceous species in terms of ultimate tensile resistance (Mao et al. 2012). Such biomechanical property is influenced by many factors such as root diameter (Vergani et al. 2012), specific surface area of roots in the soil (Bischetti et al. 2005), moisture (Yang et al. 2016) and geographical station (Vergani et al. 2012). Roots have a cettain tensile strength, providing up to 100% of the cohesive strength of a root-permeated soil (De Baets et al. 2008; Hales et al. 2009). The additional tensile strength associated with roots is responsible for the transfer of shear stresses via tensile resistance or interface friction within the soil-root matrix (De Baets et al. 2008). There is a linear proportional relationship between the increase of the soil shear strength and root biomass and root tensile strength (Gyssels et al. 2005). Coarse roots mainly serve to support and firm the soil and play a major mechanical role in maintaining slope stability once the bio-embankments collapse, and the anchorage effect of roots strongly depends on their depth and spatial density. Roots do not extend sufficiently deep into the soil to prevent mass wasting processes;

Table 1 Basic situation and soil physical and chemical properties of bio-embankments in study area

Bio-embankments	Plant spacing (m)	Vegetation cover rate (%)	Growing years (Year)	Earthbank Length (m)	Earthbank Slope (°)	Earthbank Height (m)	Length of slope (m)	Slope of field (°)	Width of field (cm)
Morus	0.8	68.8	9	3.1	62.4	1.8	4.8	19.5	4.1
Zanthoxylum	0.8	74.3	9	4	64.3	1.6	5.1	20	5.5
Medicago	0.4	78.8	9	3.5	78.5	0.8	5.4	18.4	4.6
Nature grass	—	82.3	—	1.2	50	1.2	4.3	12	1.8

Bio-embankments	Plant height	Soil water content (%)	Soil organic matter (g/kg)	Soil bulk density (g/cm3)	Total soil porosity (%)	Mechanical composition (%) Sand	Mechanical composition (%) Silt	Mechanical composition (%) Clay
Morus	0.5-1	9.99	4.65	1.58	41.81	44.82	47.19	8.00
Zanthoxylum	0.5-1	12.30	4.74	1.22	53.67	53.01	37.39	9.60
Medicago	0.35-0.5	9.73	4.08	1.69	38.25	47.01	41.59	11.40
Nature grass	0.1-0.2	9.06	3.19	1.48	45.12	41.96	45.50	12.54

furthermore, if the spatial density is not sufficiently high, coarse roots are completely pulled out under stress and cannot contribute to attaining the desired tensile strength and thus have no obvious contribution to slope stability (Mattia et al. 2005). Soil may easily move around roots, in which case there is no strengthening effect. The significance of mechanical slope stabilization by roots primarily depends on the depth of the potential slip surfaces, failure mode and the slope (Nilaweera and Nutalaya 1999). Recently, researchers worldwide have conducted numerous studies on root distribution, single tensile properties, soil reinforcement, soil shear characteristics, slope stability and soil erosion control by different plants (Vandekerckhove et al. 2001; Shi et al. 2017; Boldrin et al. 2018; Zhang et al. 2014; Fu et al. 2016).

Bio-embankment is a type of agroforestry production formed by planting woody or herbaceous plants on an earth bank or terrace (Li et al. 2015) and clearly helps to reduce the velocity of surface runoff and sediment loss, improving the physical and chemical properties of soil (Lü et al. 2012). In this study, we selected a natural grass bank as the control and three typical soil and water conservation bio-embankments of *Morus, Zanthoxylum,* and *Medicago* as research subjects. The goal of this study was to 1) analyse the root distribution of different bio-embankments and 2) quantitatively reveal the effects of root tensile properties and shear resistance characteristics of the root-soil composites of different bio-embankments on slope stability. The results will help to describe the roles of soil reinforcement mechanisms of the plant roots in providing earth bank stability in more detail and deeply analyse the capacity of anti-erosion corrosion of different bio-embankments to provide a theoretical basis for selecting a reasonable bio-embankment design model and protecting the water and soil resources and land productivity of sloping farmland.

1 Materials and Methods

1.1 Study area

The research area, located in the purple hilly area of Southwester University in Chongqing, China, 106°26′E, 30°26′N, is a typical low hilly landform at an altitude of 230 m. This area is characterized by a subtropical monsoon climate, annual average temperature of 18.3 °C and annual rainfall of 1105.4 mm, with rainfall from May to September accounting for 70% of the overall rainfall. The soil type is dominated by neutral purple soil cultivated on the grey-purple to purple sand shale parent material of the Jurassic Shaximiao Formation, whose soil layer is thin and easily disintegrated. The sloping farmland in this area is dominated by natural slopes with little human disturbance. The conventional agricultural model is an interplanting of corn, sweet potato, etc. The basic situation and the physical and chemical properties of the soil in the research area are shown in Table 1.

The three typical plants used in soil and water conservation, *Morus, Zanthoxylum* and *Medicago*, were selected to form a sloping farmland earth bank on the outer side of sloping farmland (Figure 1a). *Morus* and *Zanthoxylum* were planted in two rows, forming woody bio-embankments, and *Medicago* was planted as an herbaceous bio-embankment. The root types of forest and grass include the H-type (most roots extend horizontally and widely), R-type (most main roots grow obliquely, roots have a wide lateral extent), VH-type (plants with a strong tap root, and lateral roots that extend widely and at a low angle with respect to the horizontal plane), V-type (plants with well-developed near-vertical roots, and sparse and narrowly extended lateral roots), M-type (most roots branch and grow in various directions, common in herbaceous), and W-type (lateral roots extend widely, with a shallow taproot). The different types of roots play different roles in maintaining the stability of bio-embankments, and the roots of bio-embankments are mostly horizontal or vertical roots (Li et al. 2016). The roots of *Morus* were VH-type with abundant lateral roots that extended towards the sloping farmland; the diameter of its lateral roots was greater than 10 mm, and it was rich in fine roots (Figure 1b). The roots of *Zanthoxylum* were also of the VH- type, and its lateral root development was similar to that of *Morus* (Figure 1c). As roots increasingly wrapped around the lateral roots, they concentrated in the 0~20 cm soil layer. The root type of *Medicago* was M-type. This root system was undeveloped with fewer lateral roots; its single roots grew downwards, and the maximum depth reached below 1 m of the soil layer, which directly connected the surface soil of the bio-embankments with the parent material of the soil (Figure 1d).

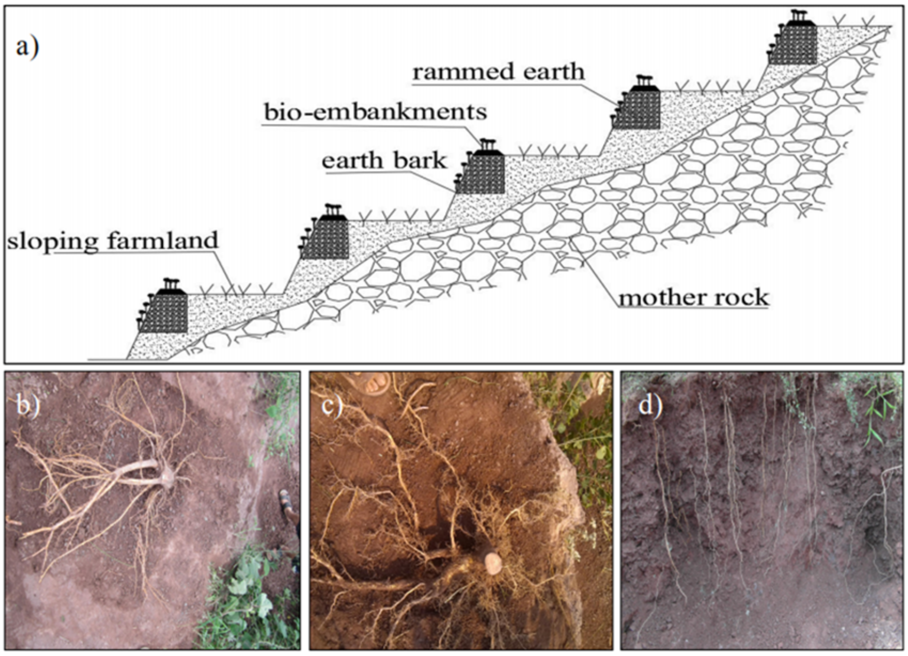

Figure 1 Morphological characteristics of different bio-embankments roots. a) typical profile of bio-embankments on sloping farmland. b) Morus roots of horizontal direction, c) Zanthoxylu roots of horizontal direction, d) Medicago roots of vertical direction.

1.2 Root sample collection

Root and soil samples (10 cm in inner diameter, 10 cm in height) were collected by a root drill. Five standard plants were selected from different bio-embankments in the study area. The root samples were collected at soil depths of 0-10, 10-20, 20-30, and 30-40 cm (to the mother rock) at a distance of 30 cm from the plant, three samples per layer. The root samples were used to measure the vertical distribution characteristics of the roots. The root samples were collected by the root drill and placed into a 0.25 mm diameter soil sieve, rinsed with water and then stored in sample storage bags. WinRHIZO (Pro.2004c) was used to scan the root length, root surface area, average diameter, and root volume. Finally, the roots were placed in an envelope and dried at 105 °C for 72 hours to obtain the root biomass. The root parameters were calculated as follows (Murielle et al. 2014; Fu et al.2016): RLD (cm/cm^3)= root length in the root drill (cm)/ root drill volume (cm^3); RSAD (cm^2/cm^3)= root surface area in the root drill (cm^2) / root drill volume (cm^3); RWD (mg/cm^3) = root biomass in the root drill (mg) / root drill volume (cm^3).

1.3 Root tensile strength test

Five plants with moderate growth were selected at each bio-embankment. The root samples were collected with whole root excavation, avoiding mechanical damage of roots during the excavation. The morphological data of the root system were recorded, and fresh roots with common growth and uniform straight stems were selected and stored in the fridge at 4 °C to keep the roots fresh and reduce test error (Zegeye et al. 2018). The CMT6503 microcomputer-controlled electronic universal ability tester was used to measure the root tensile characteristics of these plants, and the test design mainly referred to the national standard method (GB/T228-2002). Roots with diameters of <1 mm, 1~2 mm, 2~3 mm, 3~4 mm, 4~5 mm, and >5 mm were selected for different bio-embankments (Jiang. 2013). The main function of fine roots (d≤2 mm) is to absorb water and nutrients for plants, while coarse roots (d>2 mm) mainly serve as a framework and support for soil. The root tensile test was conducted at a standard distance of 50 mm and a loading rate of 10 mm/min. The test root section was clamped between the stretching fixtures on a workbench. Turning the hand-wheel to move the clamp up caused the root section between the clamps to be stretched until the root section was broken. Only tests with roots broken within the mid-third of were considered to avoid undesired effects due to concentrated stress near the clamps, and tests were repeated successfully (at least three times) (Ji et al. 2012). The mechanical parameters of the maximum tensile force and tensile strength, of the root segment were calculated by the relevant data obtained in the tests, such as the root diameter and tensile resistance, and the following formulas were used:

$$F = \alpha D^b \tag{1}$$

$$T = \frac{4F}{\pi D^2} \tag{2}$$

where F is the maximum tensile force of the root section, N; D is the diameter of the root section, mm; α is a fitting parameter; T is the tensile strength of the root section, MPa;

1.4 Root-soil composite shear test

Five root-soil composite samples were collected at 30 cm around different bio-embankment plants by anti-shear ring cutter (Φ61.8 mm×20 mm) at soil depths of 0-10, 10-20, 20-30, and 30-40 cm, using the ZJ (three-speed) electric strain control direct shear instrument to measure the shear strength indicators of the root-soil composite samples. The successively applied vertical loads were P_1= 100 kPa, P_2=200 kPa, P_3=300 kP, and P_4=400 kPa. The coefficient of the force ring rate was 1.623 kPa/0.01 mm. The shear rate was 1.2 r/min. Taking the shear stress as Y axis and the shear displacement as X axis, plot the relationship of them under the four vertical loads (P_1, P_2, P_3, P_4), Select the peak point or the stable value on the curve as the shear strength S, or choose the shear stress corresponding to the shear displacement of 4 mm as the shear strength (S), while with no obvious peak point on the curve. Draw the relationship between the shear strength and the vertical load (P_1, P_2, P_3, P_4), with the shear strength as Y axis and the vertical load (P_1, P_2, P_3, P_4) as X axis, the inclination of the straight line is the soil internal friction angle, and the intercept of the straight line on the ordinate axis is the soil cohesion. The test method mainly references the standard method (SL/237-1999). The indicators reflecting soil shear strength were calculated by the Coulomb formula as follows:

$$\tau_f = CR / A_0 * 10 \tag{3}$$

$$\tau = \sigma \tan \varphi + c \tag{4}$$

where τ_f is the soil shear strength of the fth sample, C is the dynamometer rate coefficient, n/0.01; 10 is the unit conversion factor; R is the ring micrometer force reading, 0.01 mm; and A_o is the transverse cross-sectional area of the sample, cm². τ is the soil shear strength, kPa; φ is the soil internal friction angle (°); and c is the soil cohesion, kPa.

2 Results

2.1 Root distribution characteristics of the bio-embankments

2.1.1 Root distribution with depth

The root distribution of the three bio-embankments generally decreased with increasing soil depth (Figure 2). The average total RWD was highest for *Morus* (1.42 g/cm³), followed by *Zanthoxylum* (0.85 g/cm³) and *Medicago* (0.18 g/cm³) at the 0~40 cm soil layer, and the average

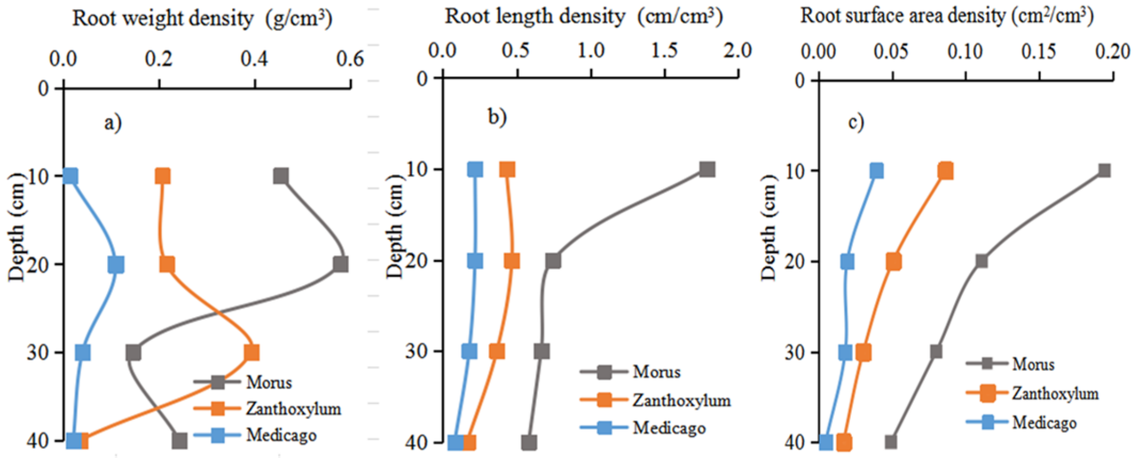

Figure 2 Roots vertical distribution characteristics of different bio-embankments. a) Root weight density, b) Root length density, c) Root surface area density.

Table 2 Root distribution characteristics and variance analysis of different diameters

Bio-embankments	Soil depth (cm)	Root length density (cm/cm³)			Root surface area density (cm²/cm³)		
		<1 mm	1-2 mm	2-5 mm	<1 mm	1-2 mm	2-5 mm
Morus	0~10	1.7630 c	0.0132 c	0.0135 b	0.1353 a	0.0052 c	0.0124 c
	10~20	0.7394 b	0.0067 b	0.0000 a	0.0511 b	0.0025 b	0.0000 a
	20~30	0.6207 b	0.0339 c	0.0127 b	0.0363 b	0.0145 d	0.0136 c
	30~40	0.5738 b	0.0049 b	0.0040 ab	0.0283 b	0.0019 b	0.0048 b
Zanthoxylum	0~10	0.3886 b	0.0421 c	0.0004 a	0.0402 b	0.0158 d	0.0003 a
	10~20	0.4606 b	0.0076 b	0.0000 a	0.0385 b	0.0027 b	0.0000 a
	20~30	0.3454 ab	0.0083 b	0.0128 b	0.0236 b	0.0033 bc	0.0392 c
	30~40	0.1642 a	0.0003 a	0.0000 a	0.0133 b	0.0001 a	0.0000 a
Medicago	0~10	0.2180 ab	0.0002 a	0.0000 a	0.0139 b	0.0001 a	0.0000 a
	10~20	0.2009 ab	0.0127 c	0.0043 ab	0.0165 b	0.0057 c	0.0039 b
	20~30	0.1687 a	0.0095 b	0.0003 a	0.0096 c	0.0041 c	0.0002 a
	30~40	0.0862 a	0.0006 a	0.0000 a	0.0046 c	0.0009 a	0.0000 a

total RWD of *Morus* was 1.67 and 7.89 times higher than that of *Zanthoxylum* and *Medicago*, respectively (Figure 2a). The root length of the bio-embankments showed a significant decrease with soil depth. The average RLD of *Morus* (1.79 cm/cm³) was significantly higher than that of the other two plants at 0-10 cm depth, which were 4.15 and 8.20 times higher than that of *Zanthoxylum* (0.43 cm/cm³) and *Medicago* (0.218 cm/cm³), respectively. In addition, the RLD in the topsoil (0-10 cm) was significantly higher than that of other soil layers; however, the difference between other soil layers was insignificant (Figure 2b). The RLD of *Morus* in the 0-30 cm soil layer accounted for 86.4% of the total RLD, and the RLD of *Zanthoxylum* and *Medicago* accounted for 88.50% and 88.48%, respectively. This result showed that the 0-30 cm soil layer was the main root distribution area. The average total RSAD was highest for *Morus* (0.43 cm²/cm³), followed by *Zanthoxylum* (0.18 cm²/cm³) and *Medicago* (0.09 cm²/cm³) in the 0-40 cm soil layer (Figure 2c). Based on the analysis described above, the root parameters (RWD, RLD and RSAD) of the woody bio-embankments (*Morus* and *Zanthoxylum*) were significantly higher than those of the herbaceous bio-embankment (*Medicago*).

2.1.2 Root distribution with diameter

The distribution of roots with different diameter grades varied significantly with increasing soil depth (Table 2). Fine roots were the most prevalent. The fine root RLD of the three bio-embankment plants accounted for 99.07%~99.34% of the total root RLD, for which *Medicago* had the highest values (99.34%), followed by *Morus*

(99.20%), and *Zanthoxylum* (99.07%). The coarse root RSAD of *Morus* was 10.07% of the total RSAD, and *Zanthoxylum* accounted for 22.27%, while *Medicago* accounted for only 6.88%.

The fine roots of *Morus* had the maximum RLD and RSAD values of the three bio-embankments in the 0-10 cm depth, 1.776 cm/cm^3 and 0.141 cm^2/cm^3, respectively, which were significantly higher than the RLD and RSAD values observed in other layers. Coarse roots were concentrated in the 0-30 cm depth, and the coarse root RLD (0.0135 cm/cm^3) was the greatest in the 0-10 cm layer, while the RSAD of the coarse roots was the greatest in the 20-30 cm depth (0.0136 cm^2/cm^3). The fine root RLD of *Zanthoxylum* was the greatest in the 10-20 cm layer, while the RLD of the coarse roots was the greatest in the 20-30 cm depth (0.0128 cm/cm^3). The RSAD of the coarse roots was the greatest in the 20-30 cm soil layer (0.0392 cm^2/cm^3), which was significantly higher than that of other layers. The fine root RLD of *Medicago* was maximal in the 0-20 cm layer (0.4318 cm/cm^3), but the RLD and RSAD of the coarse roots were low (0.0043 cm/cm^3 and 0.0039cm^2/cm^3, respectively).

2.2 Root tensile properties

2.2.1 Stress-strain relationship of roots

The root diameters with the highest content of fine a nd coarse roots among the three bio-embankments were 2 mm and 4 mm, respectively, which could reflect the basic characteristics of fine and coarse roots. The initial stage of root pulling was the linear elastic stage, in which the stress-strain curve increased linearly. When the stress reached the maximum tensile strength of 40%~60%, the strain increased faster than the stress, reflecting the plastic stage in the tensile process, in which the slope of the tensile stress-strain curve gradually decreased. When the stress reached the maximum tensile strength of 80%~90%, the strain continued to increase, and the stress tended to be gentle until the root broke, which reached the elastic and plastic deformation stages (Figure 3).

The bio-embankment roots with diameters of 2 mm showed good linear elasticity when subjected to external forces. Although the stress-strain curves were similar, they were not identical, indicating that the root characteristics were not identical among the different bio-embankment plants and that their mechanical properties were also different (Figure 3a). The root stress increased as the strain increased, and the root stress of *Medicago* and *Zanthoxylum* increased more than that of *Morus*. The maximum value of the root stress of *Medicago* reached 13.82 MPa, and that of *Zanthoxylum* and *Morus* were 13.01 MPa and 11.63 MPa, respectively. The maximum root stress in the 4 mm diameter roots was highest in *Zanthoxylum* (14.50 MPa), followed by *Morus* (12.42 MPa) and *Medicago* (9.13 MPa). The root stress-strain curve of the bio-embankment plants all had single-peak curves without strain softening, in which the stress-strain curve of 2 mm diameter roots was smoother (Figure 3b).

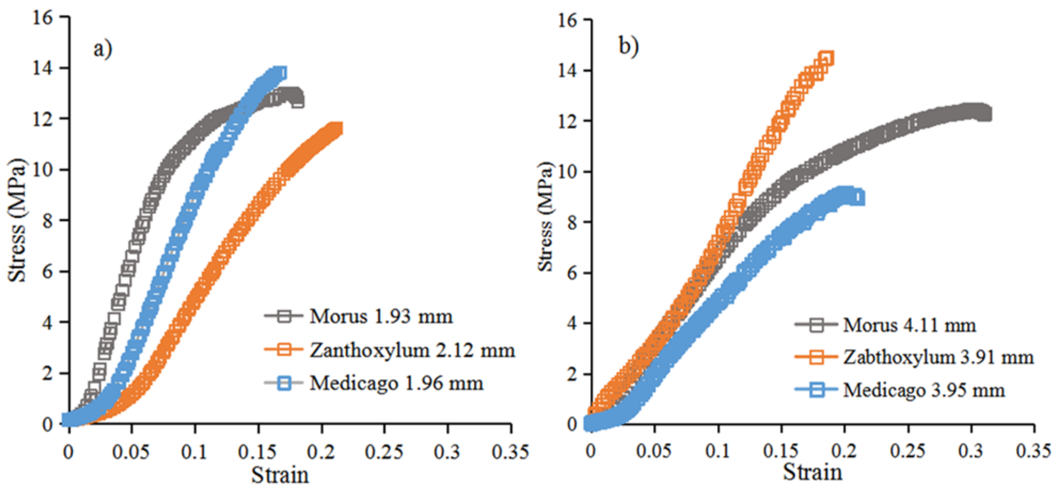

Figure 3 Stress-strain curve of roots for different bio-embankments . a) 2 mm diameter root system, b) 4 mm diameter root system.

2.2.2 Maximum root tensile force and tensile strength

The *Morus, Zanthoxylum* and *Medicago* root diameters ranged from 0.61 to 8.27 mm, and tensile strength tests were carried out on the roots of the three bio-embankments plants to analyse the relationship between the maximum tensile force and root diameters (Figure 4a). The root tensile force of three bio-embankment plants decreased as the root diameter increased. There was a clear power function relationship between them, with a range of R^2 values from 0.9601 to 0.9856, indicating that the roots of the bio-embankment plants had high tensile force, showing clear scaffold and soil fixation effects. At the same diameter of 5 mm, the root tensile force of *Zanthoxylum* was the largest, at approximately 300 N, while the roots of *Morus* and *Medicago* were approximately 200 N. As root diameter increased, the maximum tensile force increased on different scales. The average root tensile force of the bio-embankment plants, which was associated with the main components and physiological characteristics of the different plant roots, was highest in *Zanthoxylum* (73.91 N), followed by *Medicago* (68.07 N), and by Morus with the lowest value (61.88 N).

The average root tensile strength decreased as the root diameter increased (Figure 4b). There was a clear power function relationship between them, with a range of R^2 values of 0.956-0.986. The highest average root tensile strength was observed for *Zanthoxylum* (16.52 MPa), followed by *Medicago* (16.08 MPa) and *Morus* (13.02 MPa). The root diameter of the herbaceous was mainly concentrated at ≤ 2 mm and dominated by fine roots that fully contacted the soil to promote the increasing tensile strength of the root-soil composite. The fine root tensile strength of *Medicago* was the greater than those of *Morus* and *Zanthoxylum*. When the root diameter was smaller than 1 mm, the maximal root tensile strength of *Medicago* reached 56.37 MPa, while those of *Zanthoxylum* and *Morus* were lower, 37.96 MPa and 33.05 MPa, respectively.

2.3 Soil shear resistance properties of the root-soil composite

2.3.1 Soil resistance strength

Compared with natural grass-covered earth banks, the entanglement and extrusion of plant roots in the bio-earth bank increased the soil internal friction angle and cohesion force and then improved the soil shear strength (Table 3). The average soil internal friction angle of the 0~40 cm soil layer for the three bio-embankments was highest for *Morus* (24.29°), followed by *Zanthoxylum* (21.68°) and *Medicago* (20.53°), which were all higher than that of natural grass (17.06°), with increases of 142%, 127% and 120% compared with the natural grass, respectively. The average soil cohesive force of *Morus* was 29.05 kPa, that of *Zanthoxylum* was 21.99 kPa, and that of *Medicago* was 19.3 kPa, which was greater than that of natural grass (11.94 kPa), showing increases of 243%, 184% and 162% compared with the natural grass, respectively. Simultaneously, the soil internal friction angle and cohesive force of each bio-embankment decreased with soil depth.

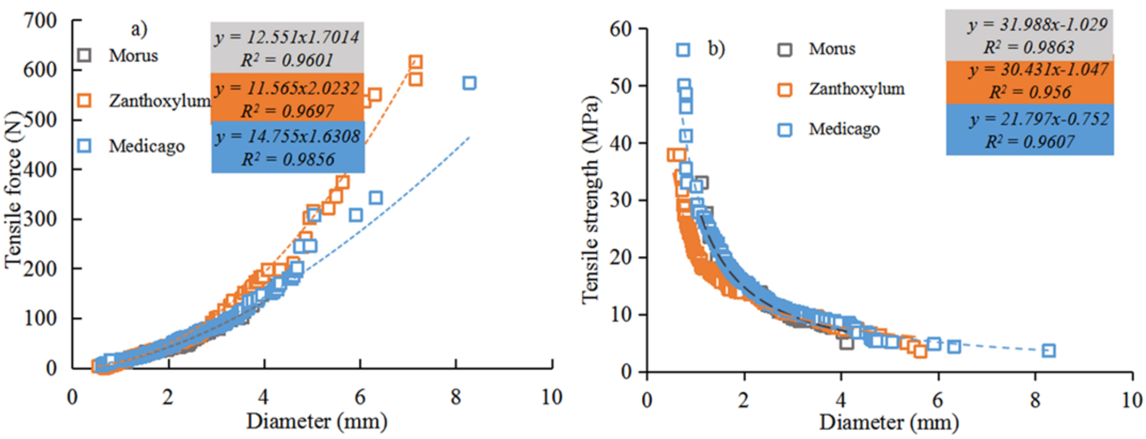

Figure 4 Relation between tensile strength and root diameter of different bio-embankments.

Table 3 Soil shear performance of different bio-embankments

Depth (cm)	Bio-embankments	Internal friction angle (°)	Cohesion Force (kPa)	Soil shear strength under different vertical loads (kPa)			
				100	200	300	400
0-10	Morus	29.97	38.27	95.94	153.6	211.27	268.93
	Zanthoxylum	25.08	26.49	73.29	120.09	166.89	213.69
	Medicago	22.1	19.68	60.29	100.89	141.5	182.1
	Nature grass	19.38	6.82	42	77.17	112.35	147.53
10-20	Morus	23.56	38.9	82.51	126.11	169.72	213.32
	Zanthoxylum	24.47	25.92	71.43	116.94	162.45	207.96
	Medicago	23.85	19.85	64.06	108.27	152.48	196.69
	Nature grass	18.94	15.65	49.97	84.28	118.6	152.91
20-30	Morus	23.56	38.9	82.51	126.11	169.72	213.32
	Zanthoxylum	20.81	18.79	56.8	94.8	132.81	170.82
	Medicago	20.3	20.97	57.96	94.95	131.94	168.93
	Nature grass	15.92	14.1	42.62	71.15	99.67	128.19
30-40	Morus	18.41	22.7	55.98	89.27	122.55	155.84
	Zanthoxylum	16.34	16.74	46.06	75.38	104.69	134.01
	Medicago	15.87	16.7	45.13	73.56	101.99	130.42
	Nature grass	13.99	11.17	36.08	61	85.91	110.83

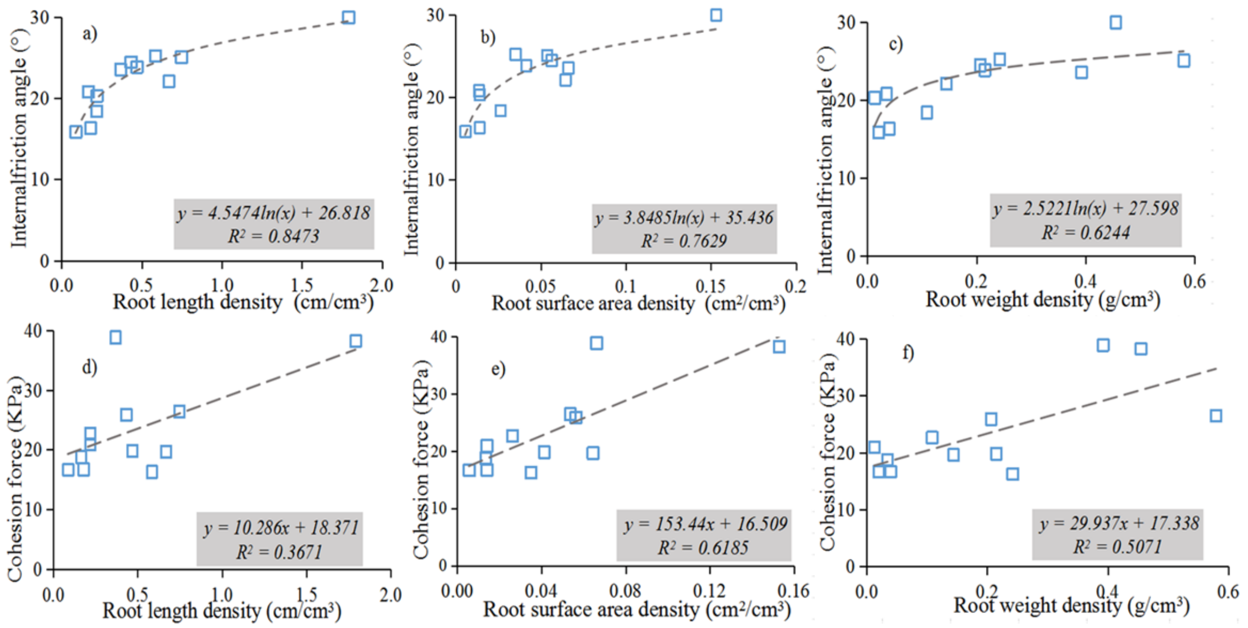

Figure 5 Regression analysis of soil shear strength index and root parameters. a) Root length density with internal friction angle, b) Root surface area density with internal friction angle, c) Root weight density with internal friction angle, d) Root length density with cohesion force, e) Root surface area density with cohesion force, f) Root weight density with cohesion force.

The average soil shear strengths exhibited the following order: *Morus*> *Zanthoxylum* > *Medicago* > natural grass. The soil shear strength of the three bio-embankments was significantly higher than that of the natural grass under loads of 100 and 200 kPa, and the enhancement effects of *Morus* (175 and 163%), *Zanthoxylum* (145 and 139%) and *Medicago* (133 and 129%) increased significantly compared with the natural grass earth bank. The soil shear strengths of the woody bio-embankments were higher than that of the herbaceous bio-embankment.

2.3.2 Effects of root morphology parameters on soil shear strength

The root morphology parameters reflect the distribution characteristics of plant roots in soil. Regression analysis was carried out between the RLD, RSAD and RWD with soil internal friction angle and cohesion force, separately (Figure 5). The soil internal friction angle showed a significant logarithmic relationship with RLD, RSAD and

RWD, and R^2 was 0.8473, 0.7629 and 0.6244 (Figure 5a, 5b, 5c). The RLD, RSAD and RWD of bio-embankments were mainly concentrated in the range of ≤ 1 cm/cm³, ≤0.08 cm²/cm³ and≤ 0.3 g/cm³; in these ranges, the soil internal friction angle increased faster. However, when RLD > 1 cm/cm³, RSAD> 0.08 cm²/cm³, and RWD> 0.3 g/cm³, the rate of increase in the soil internal friction angle gradually slowed. The soil cohesion force had a significant linear relationship with RSAD and RWD, with R^2 values of 0.6244 and 0.5071 (Figure 5e, 5f). The linear relationship with RLD was not as obvious (R^2=0.3499) as the other relationships (Figure 5d).

3 Discussion

3.1 Soil-fixing mechanism of roots

Soil erosion is one of the most serious environmental problems of sloping farmland (Feng et al. 2018) and negatively affects agricultural production and sustainability (Nyssen et al. 2015). Due to abundant summer rainstorms, erosive topographic conditions and tremendous soil loss occur during summer rainstorms. The soil erosion chain of sloping farmland was formed under the interaction of erosion forces dominated by slope runoff and the erosion resistance of the underlying surface (Figure 6) (Zhang et al. 2014). The soil particles of sloping farmland are carried below the slope with splashing rainfall. A seepage layer is formed after water infiltration, which glides between the soil and parent material and infiltrates the soil, and then soil erosion occurs and affects soil stability (Cammeraat et al. 2002). The earth bank was approximately 10-15 cm higher than the surface of the sloping farmland, which had an interception effect on the runoff accumulating on the slope and potentially stemmed erosion-induced crop productivity losses (Nyssen et al.2015; Wei et al.2018). Plant root systems have the potential to reduce runoff and soil loss, especially in steeply sloped areas (Capilleri et al.2016; Donjadee and Tingsanchali, 2013; Chen et al. 2013). The roots force their way through the soil, allowing runoff to seep into the soil along the contact area between the roots and their surrounding soil. The root system can bond the individual soil particles together and promote the formation of fine aggregate structures and porosity (Ward. 1990).

Plant roots can provide slopes with "hydrological-mechanical reinforcement" effects due to the combination of the mechanical effects of plant root anchoring and the hydrological effects of plant water absorption (Boldrin et al. 2018; Stokes et al. 2014); furthermore, in deeper layers, the effects of increasing soil shear strength and reducing pore pressure (mechanical-hydrological effect) provide this reinforcement. The friction and cohesion could increase between soil particles and the root system based on the reinforcement and anchorage of plant roots and then improve the soil shear strength, soil fixation, erosion resistance and maintenance of soil structure stability. Roots with different diameters have different soil-fixing effects. The coarse roots (d>2 mm), which function to support plant stability, were mainly distributed in the surface soil layer (0~30 cm) (Mcivor et al.

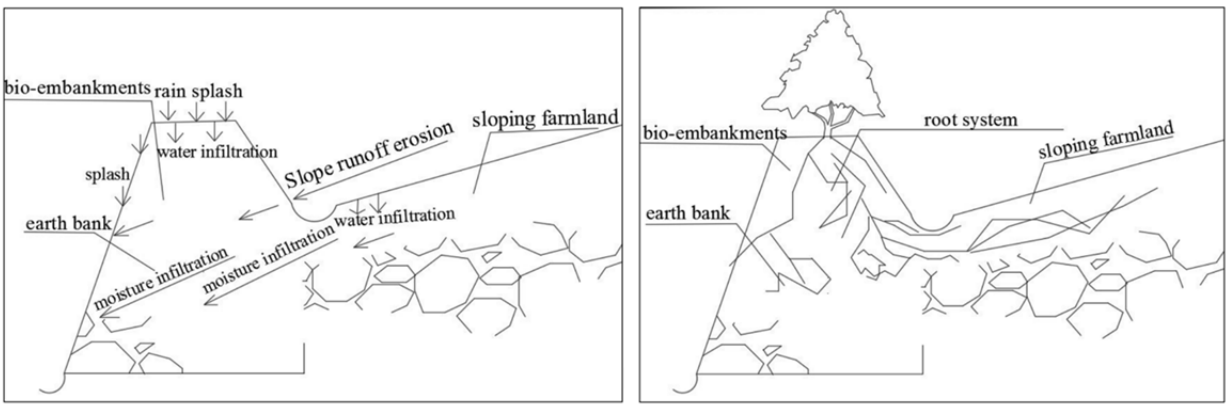

Figure 6 Analysis of the action mechanism by bio-embankments roots. **Note:** 1) the skeletal roots of >10mm support and maintain plants stability which above ground; 2) the coarse roots of 2-10mm anchoring interspersing and enhancing soil stability; 3) the fine roots of 1-2mm improving soil shear strength; 4) the fibrous roots of <1mm increasing soil impact resistance.

2009). In particular, the skeletal roots (d>10 mm) acted as the main supporting force to maintain the stability of the above-ground plants. When the bio-embankments collapsed, coarse roots exerted their tensile strength and functioned as reinforced concrete, firmly binding soil and plants to maintain the stability of the bio-embankments (Philips et al. 2013). Fine roots with diameters of 1~2 mm were the most prevalent roots distributed in the 0-40 cm soil layer of the bio-embankments. The interpenetration effect of these roots in the soil increased the contact area between the roots and soil particles and increased the frictional force formed at the contact surface of the roots and soil, improving the shear strength of the bio-embankments (Genet et al. 2005; De Baets et al. 2007). The entanglement and network consolidation of fibrous roots (d<1 mm) prevented soil particles from dispersing and improved the soil anti-erodibility (Ennos 1990). Roots have different diameters and thus different maximum tensile forces, and a single 50 mm root is equivalent to 500N and 1 mm fine roots in terms of the maximum tensile force (Vergani et al. 2017). These results demonstrate the importance of the role of root diameter (coarse versus fine roots) and root distribution on root reinforcement at the standard scale (Vergani et al. 2017). As the spacing between the root system increases, the effect of vegetation on the slope stability decreases (Fan and Lai.2014). maintaining a high level surface coverage and biodiversity, to improve the excellent availability of soil nutrients, and constant action to guard against surface soil erosion and the instability of shallower soil layers (Cislaghi et al. 2019). The comprehensive effects of roots with different diameters could significantly improve the erosion resistance of the bio-embankments.

3.2. Effects of root morphology parameters

The morphology of plant root systems strongly influences the resistance to rainfall-driven erosion (Danjon et al. 2008). Root morphology parameters are probably more important than root mechanical traits with regard to the additional cohesion conferred on soil by the roots (Murielle et al. 2014; Docker et al. 2008). The root morphology parameters reflect the distribution characteristics of plant roots in soil, and the root morphology parameters of RLD, RSAD and RWD were closely related to the soil shear strength (Maetei. 2004; Fattet et al.2011). Soil loss exponentially declines with increasing root morphology parameters (De Baets et al. 2010). Because most roots were concentrated in the topsoil (0-30 cm) of the plants (De Baets et al. 2007; Zhong et al. 2016), the values of the root morphology parameters generally decreased with soil depth (Figure 2) (Zhong et al. 2016). The RLD reflects the extent of extension, interspersion and interweaving of the root system in the soils. The entanglement and extrusion of plant roots increases the internal friction angle and cohesion of soil and improves the soil shear strength (Helsen et al. 2016). The RSAD reflected the tightness of the roots and soil, and soil cohesion was observed to be the sum of the shearing force and the anchoring force of the roots. These two forces increased with the increase of RSAD (Li et al. 2013), which was mainly attributed to the dependence of soil cohesion on cementing material among the soil particles. RWD directly reflects the ability of roots to absorb nutrients and water, which clearly affects soil porosity and increases the resistance to erosion (Wu et al. 2001).

Root exudates could act as cement and enhance the binding strength of the soil particles (Wu et al. 2001). Below-ground root systems reduce soil erosion by concentrated flow (Cammeraat et al. 2002). Root-permeated soils are generally more capable of withstanding soil erosion than plain soils mainly because of physical overlapping (RLD, RSAD, RWD, etc.) (Vannoppen et al. 2015; Li et al. 2017). The results indicated that when RLD, RSAD and RWD increased to a certain extent, their effects on the rate of increase in the observed soil parameters decreased (Figure 5a, 5b, 5c). The roots and soil particles were arranged into a certain soil structure, causing interpenetration and entanglement of the roots. The increment of the increase in the root morphological parameters per unit volume promoted the increase in the biting force between the root and soil particles and further promoted the increase in the soil internal friction angle. However, when the soil morphological parameters of RLD, RSAD and RWD increased to a certain range, per unit volume, the biting force between the soil particles and roots decreased, and the soil internal friction angle stopped increasing (Kok and McCOOL.1990; Chen et al.2012; Fu et al.2016), such as the increase of RLD of Alnus incana roots does not necessarily correspond to an increase in permeability, and set the RLD of 0.1 cm/cm^3 as a suitable threshold, and a decrease in soil permeability whereas after this threshold was observed (Vergani et al.2015). Soil cohesion increased with RSAD and RWD (Figure 5e, 5f). Soil cohesion mainly depends on the cementation of soil particles, and root exudates can increase the binding strength of soil particles. Therefore, the greater the root morphological parameters are, the more cement the root system secretes, and the greater the soil cohesive (Czarnes 2000). The correlation of RLD and soil cohesion is relatively poor (Figure 5d), and its formation requires further study. These results indicate that there is an optimal root content with which to maximize the shear strength indexes of the rooted soil. With suitable values of 1 cm/cm^3, 0.08 cm^2/cm^3, and 0.3 g/cm^3 for RLD, RSAD and RWD, respectively, the soil internal friction angle and cohesion force of the bio-embankment were approximately 25° and 30 kPa.

4 Conclusions

The root systems of bio-embankments generally decrease in extent with the soil depth; the number of fine roots in the 0-10 cm depth was significantly higher than that of other soil layers, and the coarse roots were mainly distributed in the 0-30 cm soil layer. The root morphological parameters of the bio-embankments of woody plants were significantly higher than those of herbaceous plants. The tensile strength increased as the root diameter increased, indicating that coarse roots had a clear effect on the support and retention of slope stability, and the likelihood of earth bank collapsing was lower. The soil retention capacity of woody bio-embankments was significantly higher than that of herbaceous bio-embankments. The combination of the anchoring effect of coarse roots and the fixing effect of fine roots increased the soil shear strength and the stability of the bio-embankment. The soil internal friction angle showed a significant log-positive correlation with the studied root morphological parameters, while soil cohesion showed a clearly linear positive correlation with these parameters.

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