

Effects of root architecture characteristics on soil reinforcement in undisturbed soil

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The effects of plant roots on the increase in soil shear strength involve a complex interaction of mechanical and hydrological processes operating over a scale of very diverse root architecture. Understanding the effects of mechanical mechanisms on soil shear strength is challenged by this inherent complexity. A high level of inaccuracy in field measurements of soil reinforcement makes field measurements much more challenging than that of indoor observations. This paper presents a simple experimental study where the shear strength of undisturbed soil is measured at different soil depths and at different distances from the main stems of 7 tree species, a bamboo, a herbaceous perennial, perennial grass and a fern by measuring their root area ratio, diameter class, and tensile strength. The result confirms that root distribution varies widely within root diameter classes and root area ratio between species and soil layers. Root architecture characteristics were the dominant factors influencing shear strength in the 0.2–0.4 m soil layer. In the process of vegetation restoration, *O. compositus* and *H. fulva* were used as colonizing vegetation. Later, *S. lucida* and *L. kwangtungensis* were recommended to stabilize the shallow soil in the Three Gorges reservoir region.

Keywords: Direct shear test, plant roots, soil shear strength, theory model.

THE field of soil bio-engineering has provided technologies to use plants to protect slopes from shallow landslides and these technologies have been extensively used worldwide. The mechanism of these technologies mainly relies on the ability of roots to reinforce the stability of slopes¹. Plant roots substantially improve soil shear strength through both hydrological and mechanical mechanisms^{2–6}. The hydrological mechanisms of plant roots mainly refer to the ability of roots to lower pore water pressure in soil while increasing the strength of chemical interactions between the roots and soil and the activity of organisms and communities^{7,8}. These factors change the organic matter content in soil and affect soil physical and chemical properties^{9,10}. However, previous analyses of these effects were mostly qualitative discussions. Further research is needed to better characterize the hydrological

mechanisms of plant roots. Reubens *et al.*¹¹ summarized the effect of mechanical mechanisms of plant roots on the shear strength of soil, including properties of the roots (root tensile strength, density, diameter class, length density, root area ratio (RAR) and maximum root depth), properties of soil–root interface, characteristics of the configuration of the root system in the soil, etc. These characteristics have been studied both analytically^{2,12–14} and experimentally^{2,15–18}. Wu *et al.*¹² proposed one of the most common root reinforcement models. This model was applied to both vertical^{2,12} and inclined roots¹⁹. However, many experiments indicate that different reinforcement effects exist for different regions with different species^{16–18}.

Yen²⁰ proposed a classification system for root system architecture and structure using five branching patterns as defined in Table 1: the H-, R-, VH-, V- and M-types. Kutschera *et al.*^{21,22} also classified plant root system architecture into five branching patterns: tuft root, taproot, heart-shaped root, and plate-shaped root systems as well as root system with a large taproot and large lateral roots from which vertical sinkers emerge. Burylo *et al.*²³ classified root structures into only three branching patterns: tap-like root systems with either: (i) a vigorous central vertical root and few fine laterals, or (ii) an identifiable larger central root and many thinner laterals, and (iii) heart root system with many fibrous roots. Yen's classification is typically used for young trees and the other classification systems are typically used for big trees⁴. Based on Yen's classification, Fan and Chen²⁴ discussed the relationship between configuration characteristics of root systems and soil shear strength, for all types of root architecture. R-type root architecture was reported to be the most effective root system against shear failure in the soil, followed by the VH- and H-types. The optimal orientation of a single reinforcement to obtain the maximum increase in shear resistance was approximately 60° with respect to the opposite of shear direction in soil. However, their studies are not concerned about other relationships, e.g. soil–root interface properties and rhizopores created by dead roots in the soil.

This paper aims at investigating the reinforcement of root architecture characteristics and soil–root interface properties on soil shear strength in undisturbed soil

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Table 1. Classification of root architecture for the plants used in this study

Species	Description of root architecture description	Modified classification based on Yen
<i>Neolitsea aurata</i> <i>Cinnamomum bodinieri</i>	Most of the roots extend horizontally and widely	H-type
<i>Symplocos lucida</i> <i>Lindera kwangtungensis</i>	Most of the main roots grow obliquely. Lateral roots are observed in some of the samples. Roots have a wide lateral extent	R-type
<i>Pinus massoniana</i> <i>Gordonia acuminata</i>	Plants with a strong tap root. Lateral roots extend widely and in a low orientation with respect to the horizontal plane	VH-type
<i>Woodwardia japonica</i>	Plants with well-grown near-vertical roots. Lateral roots sparse and extend narrowly	V-type
<i>Oplismenus compositus</i> <i>Hemerocallis fulva</i>	Most of the roots branch and grow in various directions, common in herbs	M-type
<i>Cunninghamia lanceolata</i> <i>Phyllostachys heterocycla</i>	Lateral roots extend widely and plants with a shallow taproot. Roots having root–root interactions.	W-type

through a simple field study by measuring shear strength of undisturbed soil at different soil depths and different distances from the stem of 11 plant species. Root area ratio, root diameter and root tensile strength were measured and discussed in this paper. The modified Wu's model²⁵ was used to compare differences between actually measured values and estimated values, while investigating the factors related to shear strength reinforcement provided by plant roots in undisturbed soil. This study will help reveal the mechanism involved in root reinforcement on slope stability and provide a theoretical basis for preventing the occurrence of geological disasters such as shallow landslides and slope instability.

Materials and methods

Study site

The test site, located on Jinyun mountain in Chongqing Beibei (29°45'N, 106°22'E), has a typical subtropical monsoon climate, with an annual average temperature of 13.6°C, annual average rainfall of 1783.8 mm, and an elevation of 951 m. The test samples were taken on the south-facing slopes of Jinyun mountain with an average slope of 5°. A large area of evergreen broad-leaved forest in the study area is dominated by *Pinus massoniana* and *Cinnamomum camphora* trees with associated herbs and shrubs. The study area is located in the Three Gorges reservoir region and has climatic and geological conditions similar to other parts of this region.

Soil and plant properties

The soils in the Jinyun mountain area are derived from sandstone and shale of the Triassic Xujiache formation. The Orthic Acrisols soils also have a small amount of

Aric Anthrosols²⁶. The 0.6 m and 0.8 m thick soil typically has about 50 mm of litter attached to the top soil. Soil moisture varies vertically; however soil moisture in the upper 0–0.4 m of soil remains around 27% with little variation. A small number of macropores penetrate the soil and are caused by plant and animal activities.

Eleven common plant species within the study area were analysed, including six tall evergreen trees (*P. massoniana* Lamb., *Cinnamomum bodinieri* Levl., *Lindera kwangtungensis* (H.Liu) C. K. Allen, *Cunninghamia lanceolata* (Lamb.) Hook., *Gordonia acuminata* Chang, *Neolitsea aurata* (Hay.) Koidz) and an evergreen tree (*Symplocos lucida* (Thunb.) Siebold et Zucc.), a bamboo (*Phyllostachys heterocycla* (Carr.) Mitford cv. *pubescens*), a herbaceous perennial (*Hemerocallis fulva* (L.) L.), perennial grass (*Oplismenus compositus* (L.) Beauv.) and a fern (*Woodwardia japonica* (L.f.) Sm). Plants were 4–5 year-old, 2–3 m high, with a crown less than 2 m, and diameter at breast height (DBH) of 0.1–0.15 m. Roots of young trees were easy to collect and observe. Most roots were distributed in a 0.5 m radius^{27–29}, and most major vertical roots penetrated the soil to 0.4 m or less. The morphological growth forms of root systems were varied by system type and species, but were all similar in depth. *P. heterocycla* (Poaceae) generated large amounts of adventitious roots; therefore, root distribution was not and cannot be easily measured without excessive labour³⁰; *H. fulva* is a perennial grass while *O. compositus* is a cluster grass and both show a graminoid shape (many fibrous roots develop from the plant base), with the distribution of all roots within a radius of 0.3 m. *W. japonica*, a pteridophyte, is commonly found under all forest stands. The growth pattern and root distribution for this species are the same as other herbs. The plant species selected in this study are all grown on sides of mountain roads or steep slopes. Road construction personnel planted them on the slopes because they are widely

distributed with a strong ability to grow and survive. Figure 1 shows the typology of roots of all 11 plant species listed above.

Soil shear strength measurements

To measure the shear strength of undisturbed soil, direct shear tests were performed with a 14.05 vane shear tester (three vanes: 16 × 32, 20 × 40, and 25.4 × 50.8 mm; Eijkkamp Agrisearch Equipment, The Netherlands). During the experiment, the existence of soil macropores could lead to incorrect measurements of shear strength; correct measurement requires re-measurement using the same radius and soil depth if macropores are present. Figure 2 shows the experiment process where shear

strength was measured at different soil depths (0–0.2 m and 0.2–0.4 m) and different distances from the main stem of 11 plant species (0–0.1, 0.1–0.2, 0.2–0.3, 0.3–0.4, and 0.4–0.5 m). Because herbal root growth extended into a small range, roots of herbs were only measured using a distance to the stem of 0–0.1, 0.1–0.2, 0.2–0.3 m. During the experiment, isolated young trees with no neighbours within a 1.5 m radius were selected to limit plant–plant interactions which can dramatically affect root system development thus making sampling easier. The litter layer on the surface of soil was removed by hand in each sample area. Soil was measured to a depth of 0 to 0.4 m. Soil augers were not used to remove the upper soil of measuring points, but a vane shear tester was pressed directly into soil and rotated clockwise at a speed of 6 s/turn by hand until the shear strength value decreased for the first time. Each plant was measured 30 times (herbs and ferns were measured 18 times) and three individuals of each plant were sampled. Additionally, shear tests on root-free soils were also performed in the field and 1125 tests were performed in field. Each plant was excavated carefully by hand to keep the root architecture intact to a depth of 0.6 m. Field tests lasted for about 3 weeks from 2 to 25 July, 2016. Photos of root architecture were taken, and the roots were then placed in plastic bags and brought to the laboratory for further measurements for one week from 25 to 31 July 2016.

Root architecture classification

Root architecture was classified based on photos captured in the field; Yen's classification method²⁰ was referenced and complemented. Although Yen's system provided a simple classification for root architecture, it guaranteed a good basis for identifying different plant species in terms of soil fixation^{11,31}. In this paper, a potential type was added to Yen's system. This type had a shallow tap root but widely extended lateral roots. This type of root architecture was almost a bunch type. We tentatively named this the W-type, a type that was distributed everywhere in the Three Gorges reservoir region. Thus, a new potential type, W-type, was added in Yen's system to provide a full scale of root type classification for research related to root reinforcement in the study area. Table 1 shows the root architecture descriptions of 11 plant species.

Root area ratio measurements

For each plant, RAR was estimated and then referenced to the method described by Mattia *et al.*³². The diameter of all roots was measured at two soil depths (0–0.2 m and 0.2–0.4 m). For each soil depth, roots were measured in different positions: at the upper end (0–20 mm or 200–220 mm, depending on the sample source), in the middle (90–110 mm or 290–310 mm) and at the bottom



Figure 1. Typology of roots of 11 common plant species analysed in this study.

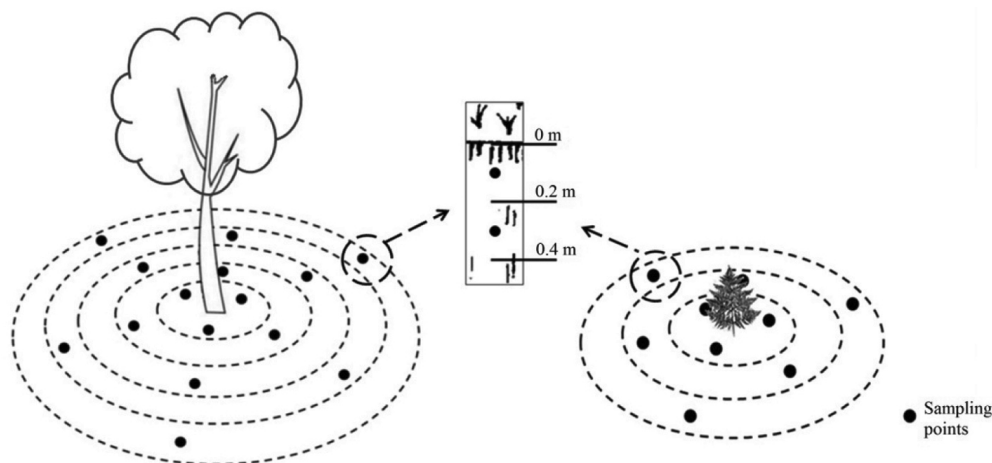


Figure 2. Schematic drawings of *in situ* direct shear test.

(180–200 mm or 380–400 mm). The diameter of each root was then calculated as the average of these three values. If roots did not reach a depth of 0.2 m or 0.4 m, diameter was calculated by the average of top and middle of root measurements. Roots were divided into six diameter classes: < 2, 2–4, 4–6, 6–8, 8–10 and > 10 mm. Finally, for each plant species, the average root number of each different diameter class was counted and RAR was calculated using eq. (1)

$$RAR = \frac{\sum_{i=1}^N \frac{\pi n_i d_i^2}{4}}{A} (N = 6), \tag{1}$$

where n_i is the number of roots in each diameter class; d_i mean diameter of each level (mm); A the area of the shear test, 1963.50 mm² for trees, 706.86 mm² for others and N is the number of the diameter classes (the six diameter class listed above) used in this study.

Root tensile strength measurements

Root tensile strength (T_R) tests were performed with a S9M universal mechanical testing machine (Shanghai, China). Roots were inspected and the damaged roots were removed from the study. Root samples 0–8 mm wide were selected for testing. Before the test, root ends were tied with tape to increase friction and then moved at a constant speed of 0.02 m/min to apply a tensile force to the root. When the root ruptured, a caliper was used to measure the diameter at the breaking point. The success rate of the test result was 40% to 50% because of the presence of root bark. For each plant, the number of successful trials must be more than 40. According to many studies^{33,34}, eq. (2) was used to calculate a and b values

$$T_R = a \cdot D^{-b}, \tag{2}$$

where T_R represents root tensile strength (MPa), D represents root diameter (mm), and a and b are constants.

Data analysis and statistics

To evaluate the potential effects of roots on soil shear strength, two methods (ΔS_w and ΔS_s) were used; ΔS_w was calculated by modified Wu's model²⁵ eq. (4)

$$\Delta S_w = 0.63 \cdot t_R, \tag{3}$$

where t_R represents tensile strength in roots per unit area of soil (kPa) when failure occurs; it is assumed that all roots were cracked in soil; taking into account T_R and RAR for different diameter classes, eq. (4) was written as

$$t_R = \frac{\sum_{i=1}^N T_{Ri} \cdot A_i}{A} (N = 6). \tag{4}$$

To calculate the influence of different root architecture characteristics and soil–root interface properties on shear strength in undisturbed soil, the shear strength changes among different points within the same soil depth was assumed to be linear. Thus, the equation was built between the average shear strength and different distances from the main stem in the same soil depth of different positions. The closed curve formed was then rotated by the coordinate and the equation, finally, the solid of rotation, was regarded as ‘the space reinforcement body’ of root on shear strength for a soil depth. Figure 3 shows the calculation used to determine ΔS_s , where x represents the average shear strength at different locations within the same soil depth, $f(x)$ represents the relationship of x and the distance to the main stem. In addition, V_S was the volume

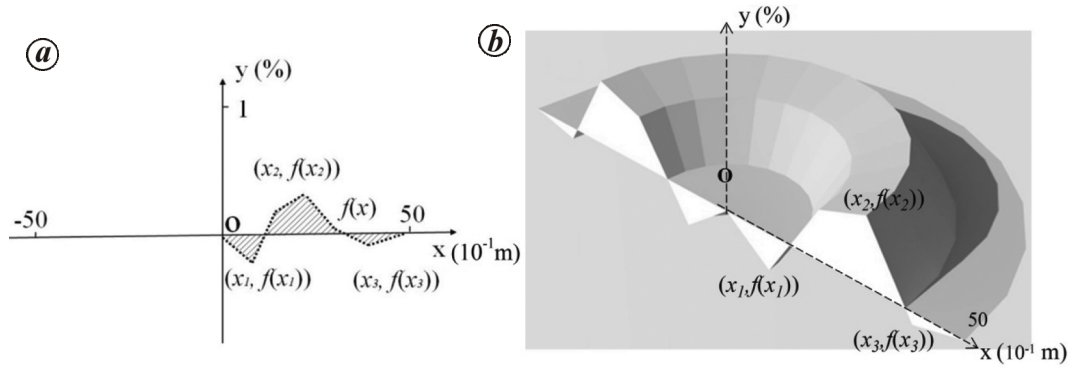


Figure 3. Calculation principle of ΔS_i ; *a*, variation in shear strength with distance from the main stem; *b*, schematic of a revolved body.

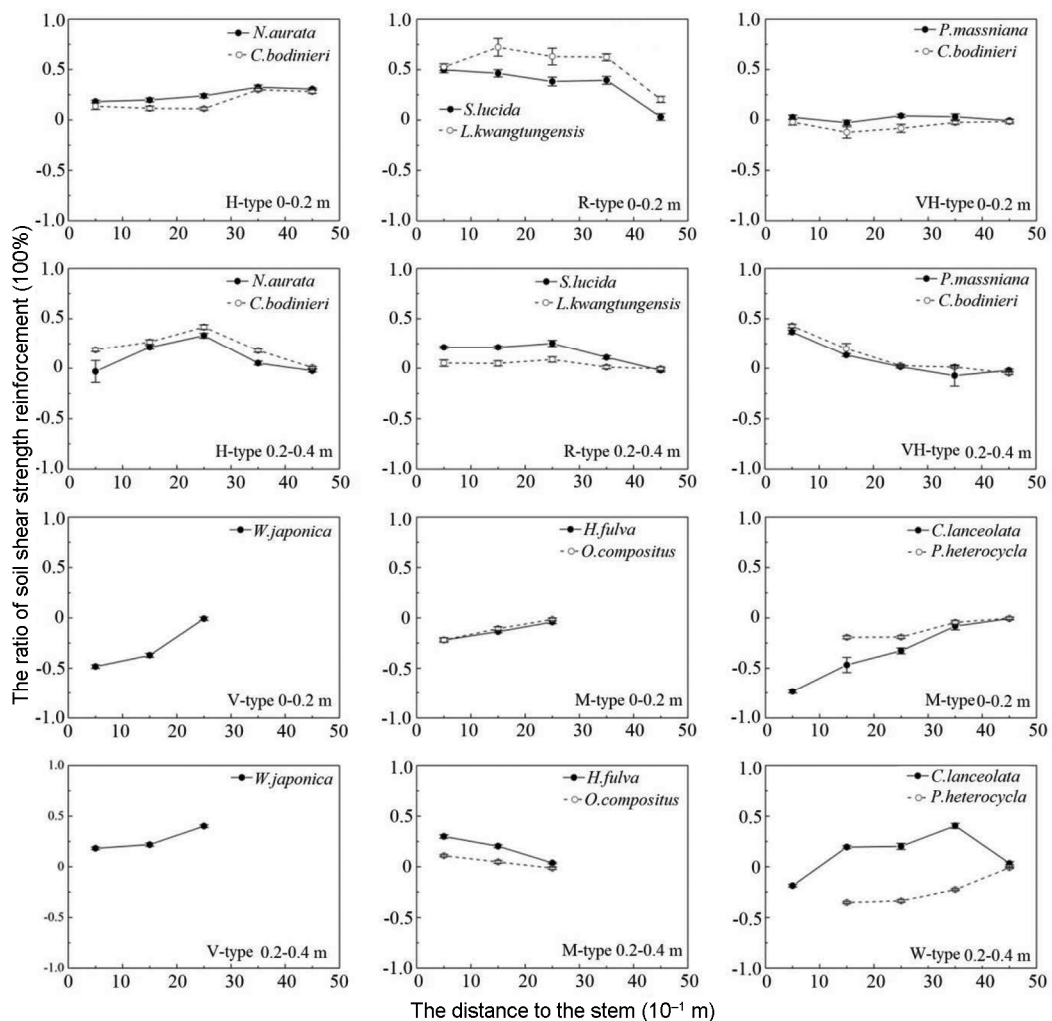


Figure 4. Change rates of shear strength reinforcement for different types of root architecture at different distances from the main stem. Genus names are abbreviated in the figure for these species.

rotated by $f(x)$ along the y axis, and ΔS_i was the integral of the difference between the measured shear strength and the root-free soil shear strength value. However, in the actual calculation process, ΔS_i was calculated by the rate of the integral (eq. (5)). Hence, the solid of rotation

obtained by computing needed to be multiplied by the root-free soil shear strength S_s (eq. (6))

$$\Delta S_i = \int \pi x^2 df(x) \cdot S_s / A, \quad (5)$$

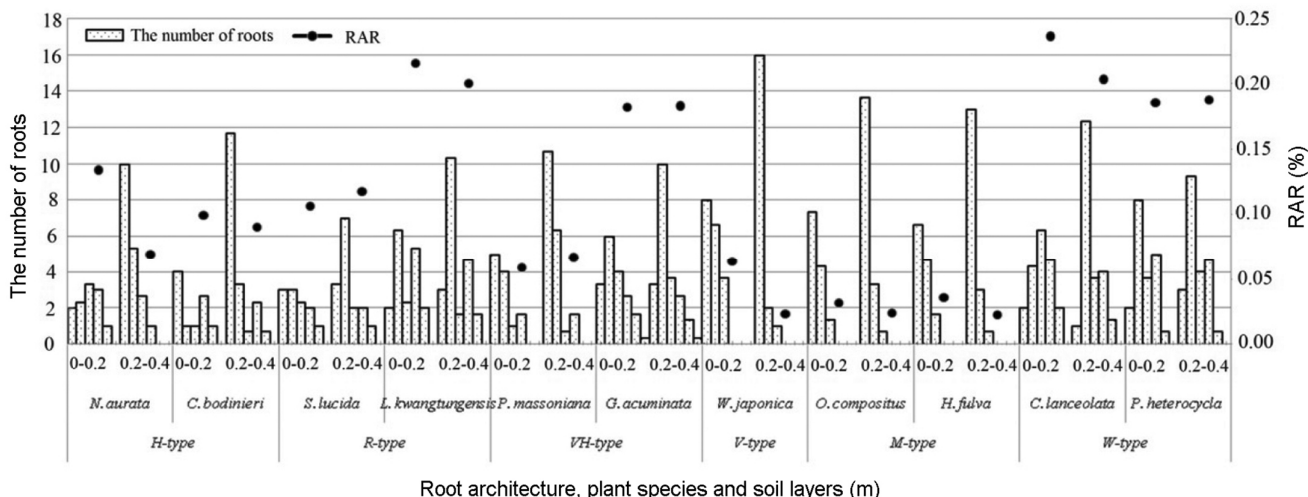


Figure 5. Related parameters of eleven kinds of plant root characteristics. The bars in one chart represent the diameter class of <2, 2–4, 4–6, 6–8, 8–10 and >10 mm.

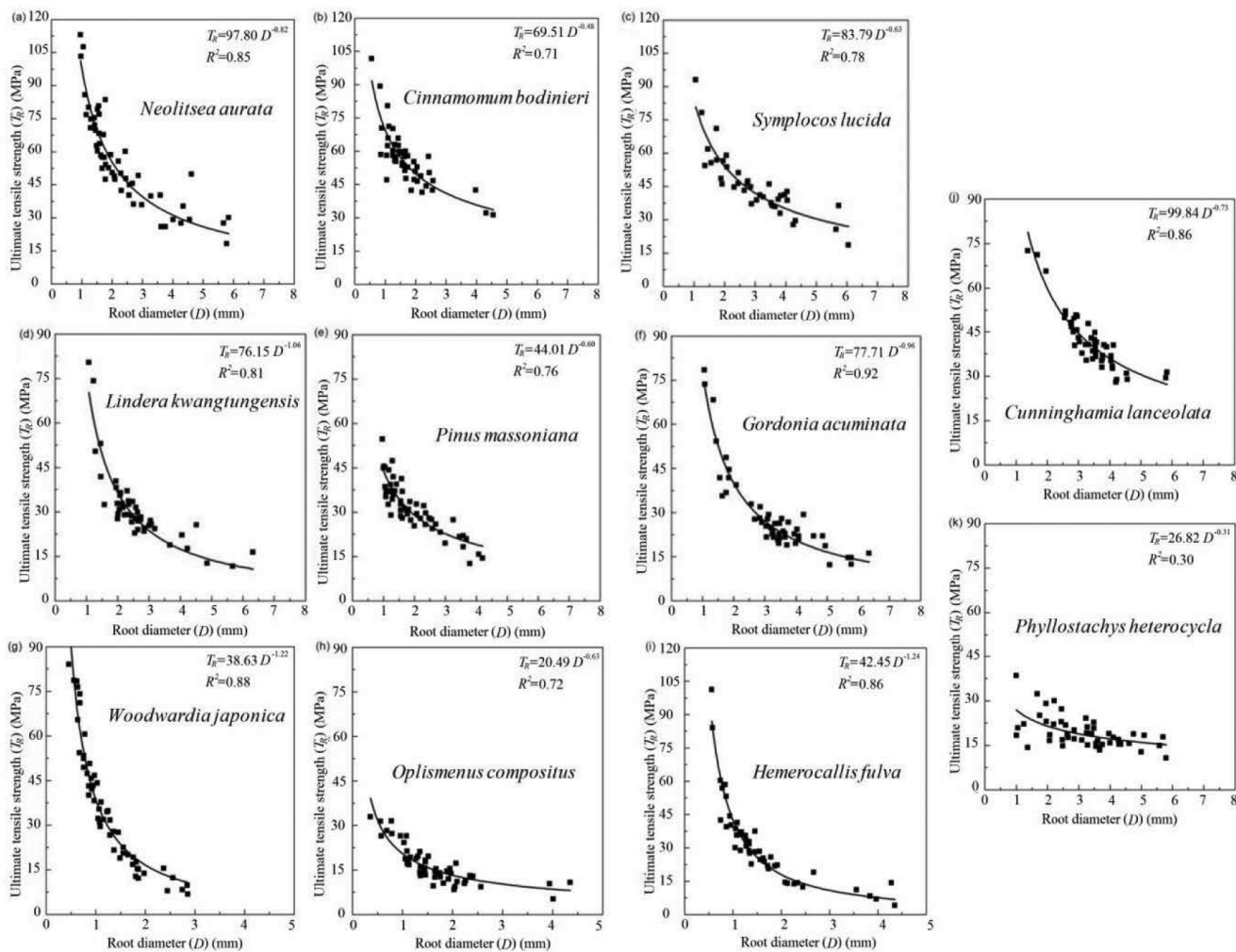


Figure 6. Relationship between root tensile strength (T_R , MPa) and root diameter (D , mm) for the eleven plant species studied here. Note: species are listed based on their root architecture.

Table 2. The value of ΔS_w and ΔS_t in different soil layers; Table 1 provides definitions of root architecture types

Root architecture	Species	Soil shear strength reinforcement					
		ΔS_w (kPa)		ΔS_t (kPa)		Efficiency (%)	
		0–0.2 m	0.2–0.4 m	0–0.2 m	0.2–0.4 m	0–0.2 m	0.2–0.4 m
H-type	<i>Neolitsea aurata</i>	18.72	14.11	9.11	10.31	11.03	9.95
	<i>Cinnamomum bodinieri</i>	17.35	17.40	1.93	16.71	3.19	17.55
R-type	<i>Symplocos lucida</i>	6.49	7.97	12.90	24.20	27.07	24.97
	<i>Lindera kwangtungensis</i>	16.33	17.79	15.08	21.43	46.16	19.79
VH-type	<i>Pinus massoniana</i>	18.31	21.55	0.79	0.87	1.39	0.86
	<i>Gordonia acuminata</i>	15.23	15.70	-7.69	4.55	-17.56	3.78
V-type	<i>Woodwardia japonica</i>	3.65	2.42	-57.56	21.71	-	24.92
M-type	<i>Oplismenus compositus</i>	2.01	1.80	-42.1	18.89	-46.66	11.56
	<i>Hemerocallis fulva</i>	2.47	2.37	-30.14	5.59	-31.98	4.15
W-type	<i>Cunninghamia lanceolata</i>	39.30	37.28	-58.30	18.20	-96.64	17.82
	<i>Phyllostachys heterocycla</i>	18.28	18.65	-355.42	-289.48	-	-

$$f(x) = \begin{cases} f_1(x) & 0 < x \leq x_1 \\ f_2(x) & x_1 < x \leq x_2 \\ f_3(x) & x_2 < x \leq x_3 \\ f_4(x) & x_3 < x < 50 \end{cases} \quad (-1 < f(x) < 1). \quad (6)$$

By comparing ΔS_w and ΔS_t of different soil depths and using an analysis of covariance (ANCOVA) we could investigate the influence of roots on soil shear strength reinforcement.

Results

Root–soil shear strength

Figure 4 shows the rate of change in shear strength for different soil depths and different distances from the main stem. In the 0–0.2 m soil layer, only R-type (*L. kwangtungensis* and *S. lanrina*) plants had a positive effect on the rate of soil shear strength reinforcement while the types H (*N. aurata*), VH (*P. massoniana* and *G. acuminata*), and M (*O. compositus* and *H. fulva*) exhibited no change. Types W (*C. lanceolata* and *P. heterocycla*) and V (*W. japonica*) decreased soil shear strength. For the same types of root architecture, the change trend of soil shear strength reinforcement was the same (except M-type). The biggest average change rate of shear strength reinforcement was type R (44.80%), followed by type H (9.70%), type VH (-2.00%), type M (-12.30%), type W (-22.80%) and type V (-28.80%). In the 0.2–0.4 m soil layer, all types of plant roots had positive effects on soil shear strength reinforcement except for M-type. The plant roots performed as: type V (26.80%), followed by type R (21.75%), type H (16.00%), type M (11.40%), type VH (10.50%) and W (-3.10%). In each soil layer, linear relationships were found in types W (0–0.2 m soil layer), M (0–0.2 m soil layer and 0.2–0.4 m soil layer), VH (0.2–

0.4 m soil layer), and V (0–0.2 m and 0.2–0.4 m soil layer); in all soil layers, H- and R-types always resulted in increased soil shear strength.

Root area ratio

Figure 5 shows the root characteristics of eleven plant species. In 0–0.2 m soil layer, most of roots were smaller than 2 mm in diameter and no roots larger than 6 mm were observed in herbs and ferns. For tree species, roots were concentrated in the 2–8 mm diameter class (only *G. acuminata* had above 10 mm diameter). In the 0.2–0.4 m soil layer, herbs and ferns still had some roots in the 0–2 mm diameter class. For other species, the number of roots that ranged from 0 to 4 mm in diameter increased with soil depth. RAR distributions were different between species and soil depth, and ranged from 0.0227% (*H. fulva* 0.2–0.4 m) to 0.2360% (*C. lanceolata* 0–0.2 m). RAR decreased with soil depth in all species (except VH-type). Overall, the root distribution in diameter classes and RAR was highly variable between species and soil layers.

Root tensile strength

Root tensile strength–root diameter relationships depended on plant species and root architectures (Figure 6) with all species having a good relationship with the inverse function. *G. acuminata* had the most significant correlation. The correlations of trees were greater than herbs and ferns and the value of a ranged from 20.49 to 99.84. There was no significant regularity in the value of b .

Root reinforcement

Table 2 showed shear strength reinforcement with different measurement methods in different soil layers. ΔS_w was

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Table 3. Root tensile strength and root diameter differences between species and types of root architecture (ANCOVA, Tukey HSD test, $\alpha = 0.05$); Table 1 provides definitions of root architecture types

Species	Significant differences				Root architecture	Significant differences			
	T_R		D			T_R		D	
<i>N. aurata</i>	a		a	b	H-type	a		a	
<i>C. bodinieri</i>	a			b	c	d			
<i>S. lucida</i>	b			b	d				
<i>L. kwangtungensis</i>	b				e				
<i>P. massoniana</i>	c				e	f			
<i>G. acuminata</i>	b		a						
<i>W. japonica</i>	b	d		a	c				
<i>O. compositus</i>			e		c	d			
<i>H. fulva</i>	b				c	d			
<i>C. lanceolata</i>		c	d				e		
<i>P. heterocycla</i>			e			e	f		d

calculated by modified Wu's model. ΔS_t was calculated by the volume of the rotating body. Percentage values in Table 2 represent the effective rate of root-soil shear strength by comparing with root-free soil shear strength S_s in different soil depths. Values of ΔS_w indicated soil shear strength in all soil layers were reinforced. ΔS_w of types H, R, and VH increased with soil depth while herbs and ferns exhibited a reverse pattern, decreasing with depth. However, except for *G. acuminata*, values of ΔS_t in the root architectures of other species in different soil layers were obviously different. ΔS_t of types H, R and VH increased with soil depth. Herbs and ferns decreased in the 0–0.2 m soil layer but increased in 0.2–0.4 m soil layer. Because of the special distribution of W-type in soil, there was no obvious rule in soil shear strength reinforcement.

The results of the ANCOVA showed that root tensile strength T_R and root diameter D differed significantly between species (T_R : $F = 43.34$, $P < 0.0001$; D : $F = 29.04$, $P < 0.0001$) and between types of root architecture (T_R : $F = 52.56$, $P < 0.0001$; D : $F = 41.65$, $P < 0.0001$, Table 3).

Table 3 shows that root tensile strength T_R and root diameter D exhibited large differences, which meant there was no obvious regularity. In different types of root architecture, root tensile strength of H-type had a significant difference with others, while there was no obvious significant difference between root diameter D in those types in addition to herbs (M-type) and ferns (V-type).

Discussion

Effect of branching characteristics and root spatial distributions on soil shear strength reinforcement

The experimental results showed that different root architectures had different effects on the shear strength in undisturbed soil (Figure 4). The branching characteristics

and spatial distribution of a root system in soil caused changes to soil shear strength³⁵. They affected soil shear strength by changing the distribution of stress in a soil medium³⁶. In the horizontal direction, the number of roots with different root architectures was almost perfectly consistent, resulting in the same types of effects on soil shear strength (e.g. soil shear strength increased significantly for root types H and VH in 0–0.2 m soil layer with the same value in same soil depth). Inclined roots greatly enhanced soil shear strength (e.g. R-type had a large number of inclined roots, and showed a stronger soil shear capacity. V-type roots had a shallow root system but much stronger soil shear capacity because of the existence of large numbers of inclined roots). Jewell and Wroth³⁷ conducted laboratory direct shear tests on reinforced sand to investigate the effects of reinforcement orientation on shear strength reinforcement of soil. Their results showed that the optimal orientation of a single reinforcement to obtain the maximum increase in shear resistance to soil is approximately 60° with respect to the opposite direction of shear. Other scholars came to the same conclusion^{19,24}. Similarly, taproots positively affect soil shear strength reinforcement, especially for those with branches near the taproot (e.g. taproots were present in the VH-type in the 0.2–0.4 m soil layer, so soil shear strength near the taproot was much stronger than at any other position on the horizontal direction). For herbs, the existence of a large number of adventitious roots in the shallow soil layer did not increase the soil shear strength. Loose soil caused by root growth^{38,39} weakened soil shear strength. However, with an increase in soil depth and a decrease in the number of roots, soil shear strength in 0.2–0.4 m soil layer was higher than that in 0–0.2 m soil layer. Burylo *et al.*⁴⁰ reported that herb roots had the most efficient action related to soil reinforcement in shallow soil layer. Effects of W-type roots on soil strength had no obvious regularity because of their complex physiological growth and interaction with soil.

Effects of root properties and root architecture on soil shear strength reinforcement

Tobin *et al.*⁴¹ introduced a commonly employed classification of root diameters to distinguish roots as so called fine ($D \leq 2$ mm) and coarse ($D > 2$ mm) roots. Tall trees produce many fine roots and these roots provide more than 90% of water and nutrient uptake of a root system^{42,43}. Therefore, the shear strength of the soil–root contact surface is not only contributed by friction, but also affected by a ‘cementing force’ that resulted from the exchange and interaction of gas and materials between root and soil particles. Coarse roots make up 15–25% of total tree biomass of small trees⁴³. Roots consist of three classes: taproots, lateral roots and adventitious roots. In the study area, a majority of root diameters are below 10 mm, if soil conditions are suitable (medium soil temperature, high soil moisture content and good soil permeability). In addition, strong branching capabilities also led to an increase of root numbers but decrease of root diameters. The total number of herb roots was more than that of other species, especially for fine roots. Large numbers of fine roots caused complex topological characteristics and root branching forms^{44,45}; therefore, the influence of root numbers and root diameters on soil shear strength cannot be satisfactorily explained.

RAR was highly variable among different species with most of the variability caused by environmental heterogeneity. Environmental factors affecting RAR include soil bulk density⁴⁶, soil moisture⁴⁷ and natural obstacles⁴⁸. Meanwhile, results of the tensile strength tests in the present study showed a slight difference with the results of other research studies^{49–51}. The value of b was lower than -1 . Further, many earlier studies have provided similar results^{16,52} (-0.52 to -1.75).

Different plant roots with different root architecture, might have different effects on soil shear strength. For a given plant species, root architecture was regarded as a constant factor in a specific environment. In undisturbed soil, the effects of root architecture were sorted by type as R (18.40 kPa), followed by H (9.51 kPa) and VH (-0.37 kPa) with no obvious difference between types V , M and W . R -type had the greatest soil shear strength reinforcement, which was contributed by its branching characteristics. Lateral roots strengthened the ability of soil shear failure resistance and abundant branching points also increased the friction between roots and soil⁴³. Although no tap roots existed in R -type root systems, multiple branch events caused root numbers to increase with soil depth and roots of this type performed better than other root architectures. The W -type decreased soil shear strength and their roots formed a network structure as if a skeleton of roots existed in the soil⁵³. They improved soil shear strength theoretically but such an increase in strength failed to be observed because of the lack of single point measurement.

Variation of root architecture reinforcement in plant species

Table 2 shows the shear strength reinforcement (ΔS_w) provided by roots per unit area of the soil. ΔS_w was calculated by root tensile strength and RAR directly²⁵, which was mainly reflected as mechanical mechanisms (root architecture characteristics). However, ΔS_t was measured in undisturbed soil and was reflected as the combination of hydrological and mechanical mechanisms (root architecture characteristics and soil–root interface properties). Exploring the relationship between ΔS_w and ΔS_t could reflect the effect of them on changes in shear strength in undisturbed soil. In 0–0.2 m soil layer, ΔS_w was much larger than ΔS_t . Negative values even appeared in herbs and ferns (*W. japonica*: -57.56 kPa, *O. compositus*: -42.10 kPa, *H. fulva*: -30.04 kPa). The litter in the upper layer caused high levels of biological and microbiological activity, causing passages to appear coupled with root respiration⁷. Soil conditions that were favourable to plant growth resulted in weaker soil shear strength and hence the influence of hydrological mechanisms was negative in this layer. In the 0.2–0.4 m soil layer, the level of shear strength reinforcement of some plants (*S. lucida*) exceeded the threshold that the root system could provide. For this soil depth, the effects of litter in the upper layers were minimal. Root architecture characteristics were the dominant factors influencing shear strength. For instance, the contact surface of roots and soil is surrounded by a thick layer of wall called the rhizosphere^{8,10}. Many chemical and biological activities (such as root respiration and nutrient uptake) occurred in rhizosphere. The rhizosphere provided a certain level of shear failure resistance. Hence, how to distinguish the effects of rhizosphere and root–soil interface frictions should be given more consideration for future research.

Observed the changes in soil shear strength, ΔS_t , were significantly different with variations in root architecture. Differences in species with the same root architecture was 0.29 to 2.4 kPa. However, differences ranged from 2.19 to 30.34 kPa between different root architectures. Root architectures had a larger effect on the shear strength of undisturbed soil. Combined with the knowledge on vegetation dynamics and ecological site properties, as a contributing role and as a component of the forest plant community, young trees played an important role in slope stability. Previous studies demonstrate that after environmental disturbance, herbaceous species initially recolonize the substrate⁵⁴. Then, vegetation cover evolves and the proportions of shrub to tree species slowly increases. In particular, in the Three Gorges reservoir region, *O. compositus* and *H. fulva* represented an important part of the colonizing vegetation. Later, *S. lucida* and *L. kwangtungensis* grew and stabilized the shallow soil layers. Furthermore, study paper used single point measurements. The plant species were all young

trees, thus, additional macro process such as the interactions of plant roots and bedrock could not be observed well. Hence besides hydrological mechanisms, large scale actions of roots or root clusters should be discussed in future research.

Conclusion

This paper presents a simple experimental study that measures shear strength of undisturbed soil at different soil depths and different distances from the stem of 11 plant species by combining RAR, root diameter class and root tensile strength into the discussion. Modified Wu's model was applied to compare the difference between measured and estimated values. Results confirmed that root distribution within diameter classes and RAR are highly variable between species and soil layers; root tensile strengths measured here are similar to those of previous studies. The values of b generally fall in the range of -0.5 to -1.5 and are close to those of previous studies. In addition, root architectures have a larger effect on the shear strength of undisturbed soil. R-type had the biggest shear strength of 18.40 kPa, followed by H-type (9.51 kPa) and VH-type (-0.37 kPa); no other root architectures had obvious differences. Except for the effects of mechanical mechanisms at different soil depths, hydrological mechanisms play a significant role in soil reinforcement. This work suggests that future studies should focus not only on root architecture and branching characteristics, but should also quantify the effects of hydrological mechanisms on soil shear strength. The present findings can be used as guidance to enhance the effectiveness of how roots perform in ecological engineering projects and to provide a theoretical basis for preventing the occurrence of geological disasters related to shallow landslides and slope instability.

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