

Mechanical properties of root-soil composite in tree-covered landslide area based on field prototype test

LIN Yun-zhao^{1,2}, JIAN Wen-bin^{1,2}, LAI Zeng-rong^{1,2}, ZHONG Xin^{1,2}, ZHANG Jun-yi^{1,2}, XIA Chang³

1. Institute of Geotechnical and Geological Engineering, Fuzhou University, Fuzhou, Fujian 350108, China

2. Geological Engineering Research Center of Fujian University, Fuzhou University, Fuzhou, Fujian 350108, China

3. Fuzhou Planning Design and Research Institute, Fuzhou, Fujian 350108, China

Abstract: In order to understand the mechanical characteristics of tree roots and their mechanical effects on slopes, the landslide in Wuping high vegetation coverage area of Fujian province was selected as the research site, and the root tensile mechanical properties of typical tree roots in the study area were tested after classification by diameter class. Furthermore, in-situ direct shear tests of root-soil composites under different root cross-sectional area ratios (RAR) and moisture content were conducted at the landslide site, and investigations were made into the distribution characteristics of roots in the profile to explore the mechanical effects of roots on shallow landslides. The results showed as follows: (1) The tensile force of *Pinus massoniana* and *Cunninghamia lanceolata* ranged from 12.45–673.09 N in 1–7 diameter class, and the tensile force was positively correlated with the root diameter by power function; The tensile strength ranges from 7.16 MPa to 60.95 MPa, and the tensile strength is negatively correlated with the root diameter as a power function. The average tensile force and tensile strength of *Cunninghamia lanceolata* root were higher than those of *Pinus massoniana*. (2) Tree roots significantly improved the shear strength of soil, and the additional cohesion provided by roots to soil was significantly positively correlated with the shear plane RAR. The root structure of *Cunninghamia lanceolata* is closer to R type, and that of *Pinus massoniana* is VH type. Under similar RAR, *Cunninghamia lanceolata* roots has a better reinforcing effect on the soil than *Pinus massoniana*. (3) With the increase in moisture content, the shear strength of the root-soil composites of *Pinus massoniana* and *Cunninghamia lanceolata* significantly decreases, as water infiltration diminishes the additional cohesion provided by the root systems to the soil. (4) Based on the Wu model, considering the influence of moisture content on soil cohesion and additional root cohesion, an estimation model for the shear strength value of root-soil composites considering moisture content was established. Upon verification, the accuracy of this model proved to be higher than that of the Wu model, and the results were reasonable. (5) Although the root system has a reinforcement effect on shallow landslides, its contribution to the stability of shallow landslides under heavy rainfall is limited due to the influence of root distribution depth, density and water infiltration.

Keywords: tree root; tensile strength; in situ shear tests; root-soil composite; shallow landslide

1 Introduction

Landslides occur frequently in the vegetation-covered areas along the southeastern coast due to the impact of typhoons and heavy rainfall. With the continuous advancement of soil and water conservation concepts, the critical role of plant root systems in slope stabilization and erosion control has been widely acknowledged^[1–3]. Plant roots can reinforce soil by maintaining or reducing soil moisture content and enhancing soil shear strength^[4–6]. Based on the mechanical scale effects of roots, widely accepted theories include the anchoring effect of coarse roots^[7] and the reinforcing effect of fine roots^[8]. During the shearing process, tensile stress can be transferred to the roots due to the frictional and biochemical bonding between soil particles and roots^[8]. Root tensile strength plays a vital role in soil reinforcement and slope stability and is a key indicator of soil consolidation and plant anchorage^[6]. It is influenced

by factors such as root type and diameter.

Research has shown that vegetation can influence slope stability by affecting both the hydrological processes of the soil and its mechanical structure. On vegetated slopes, the combination of high-strength plant roots and low-strength soil forms a root-soil composite, which enhances the soil's shear strength and resistance to deformation through their physical and mechanical interactions^[9–10]. Scholars have conducted laboratory direct shear and triaxial shear tests to investigate the strength characteristics of root-soil composites under varying conditions, including root content, root diameter, root orientation, degree of root decay, soil particle size, and moisture content^[11–15]. Due to the size limitations of laboratory shear apparatus, most existing studies have used remolded root-soil composites. However, the diversity and complexity of root systems mean that laboratory shear tests cannot fully replicate actual field conditions. Consequently, some researchers have explored the mechanical

Received: 30 December 2023

Accepted: 19 February 2024

This work was supported by the National Natural Science Foundation of China (U2005205, 41861134011) and the Natural Science Foundation of Fujian Province (2023J01423).

First author: LIN Yun-zhao, male, born in 1997, PhD candidate, specializing in slope engineering. E-mail: Linyunzhao1997@163.com

Corresponding author: JIAN Wen-bin, male, born in 1963, PhD, Professor, research interests: geotechnical engineering and engineering geology. E-mail: jwb@fzu.edu.cn

properties of root-soil composites through in-situ shear tests^[1, 16–19]. Nevertheless, most in-situ direct shear studies have focused on herbaceous plants, shrubs, or small trees, while in-situ investigations of the shear strength characteristics of root-soil composites formed by large-diameter trees under different moisture conditions remain relatively rare.

Given the widespread occurrence of vegetated landslides and the frequent impact of typhoons and heavy rainfall in the Fujian region, this study focuses on typical arboreal vegetation in Fujian as the research subject. The tensile properties of tree roots are analyzed through single-root tensile tests. In addition, large-scale in-situ shear tests on root-soil composites and field investigations of root systems in typical shallow vegetated landslides are conducted. The study examines the shear strength characteristics of tree root-soil composites under varying root area ratios (RAR) and moisture contents, as well as their influence on landslide stability. By exploring the mechanical effects of roots from the scale of individual roots to root-soil composites and further to root distribution across landslides, the study provides a comprehensive understanding of the role of root systems in shallow landslide mechanics.

2 Study area

Wuping County is located in the southwestern part of Fujian Province, with geographical coordinates ranging from North latitude $24^{\circ} 47'$ to $25^{\circ} 29'$ and East longitude $115^{\circ} 51'$ to $116^{\circ} 23'$. It has a subtropical oceanic monsoon climate, with an average annual rainfall of 1 768.6 mm. The rainy season occurs from March to June, during which the average precipitation reaches 927.51 mm, accounting for 52.44% of the annual total, making it a period prone to geological disasters. The landslide site discussed in this study is located in Shifang Town, Wuping County. The slope has an overall height ranging from 43 to 49 m and an inclination of 35° to 68° . Based on field drilling data, the landslide strata can be divided into three layers: eluvial sandy clay soil, completely weathered granite, and sand-like strongly weathered granite. The surface soil layer is primarily composed of eluvial sandy clay soil. The physical and mechanical properties of the soil are detailed in Table 1^[20]. Vegetation on the slope is well developed, mainly consisting of *Pinus massoniana* and *Cunninghamia lanceolata*, with a small amount of *Phyllostachys edulis*. The vegetation coverage rate is 90%, with an arbor density of approximately 2 500 trees per hectare, an average diameter at breast height (DBH) of 108.36 cm, and an average tree height of 5.6 meters. An overview of the landslide in the study area is shown in Fig. 1.

Table 1 Physical and mechanical properties of slope-eluvial sandy clayey soil

Density /(g · cm ⁻³)	Dry density /(g · cm ⁻³)	Internal friction angle/(°)	Cohesion /kPa	Saturated hydraulic conductivity /(m · s ⁻¹)	Plastic limit /%	Liquid limit /%
1.68	1.35	29.07	19.57	1.75×10^{-6}	17.3	28.3



Fig. 1 Landslide in study area

3 Test on root-soil mechanical properties

3.1 Root sampling

To avoid damage to the root systems during sampling, trees of similar age and growth condition were selected and felled. The roots, along with their original soil, were placed in a refrigerated container for transport to maintain root freshness. Roots were then separated from the soil, categorized by diameter, and stored in plastic bags at 4°C ^[6]. Roots of *Pinus massoniana* and *Cunninghamia lanceolata* with diameters ranging from 0.5 to 7.5 mm were selected, with approximately 200 samples collected for each species. Mechanical property tests of the roots were completed within 7 days after sampling^[20].

3.2 Root tensile test

Before testing, a digital vernier caliper (DL91150, Deli Co., measuring range 0–150 mm, resolution 0.01 mm) was used to measure each root at both ends and the midpoint, with the average value taken as the root diameter. Roots of each tree species were classified into seven diameter classes based on these measurements: class 1 ($0.5 \text{ mm} < D \leq 1.5 \text{ mm}$), class 2 ($1.5 \text{ mm} < D \leq 2.5 \text{ mm}$), class 3 ($2.5 \text{ mm} < D \leq 3.5 \text{ mm}$), class 4 ($3.5 \text{ mm} < D \leq 4.5 \text{ mm}$), class 5 ($4.5 \text{ mm} < D \leq 5.5 \text{ mm}$), class 6 ($5.5 \text{ mm} < D \leq 6.5 \text{ mm}$), and class 7 ($6.5 \text{ mm} < D \leq 7.5 \text{ mm}$), where D represents the average root diameter.

Many researchers conduct tensile tests on plant roots using electronic universal testing machines^[6]. In this study, a Dongri DR-503A microcomputer-controlled electronic universal testing machine (as shown in Fig.2) was used, with a maximum load capacity of 10 kN, a resolution of 0.004%, a strain rate control range of 0.01–500 mm/min, and a displacement measurement resolution of 0.01 mm. Currently, there is no unified standard for the gauge length of root tensile test specimens. This experiment conducted tensile

tests in accordance with the *Metallic materials—tensile testing at ambient temperature* (GB/T 228–2002) [21], setting the gauge length at 100 mm and the loading rate at 10 mm/min [6, 20]. During testing, data were considered invalid if root failure occurred at or near the ends of the clamps [6]. This study deemed data valid only if a single root fractured at or near the middle of the gauge length to ensure that the failure was caused by tensile force rather than damage incurred from other factors during testing. A total of 408 root samples were tested in this study, of which 140 were successful (detailed in reference[20]).

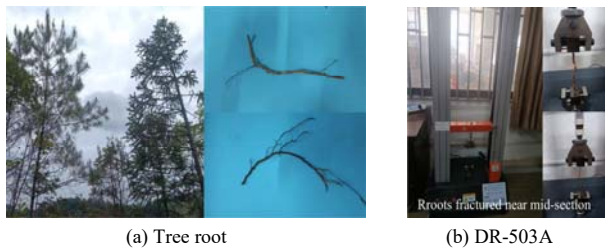


Fig. 2 Roots and test instruments

The universal testing machine can directly output the tensile force and deformation of roots at the moment of fracture. By measuring the root diameter and the gauge length, the tensile strength and ultimate strain of the roots can be calculated [22]:

$$T = \frac{4F}{\pi D^2} \quad (1)$$

$$\varepsilon_{\max} = \frac{\Delta L_{\max}}{L} \quad (2)$$

where T is the tensile strength of the root (MPa); F is the tensile force at failure (N); $\varepsilon_{\max}$ is the ultimate longitudinal strain of the root; $\Delta L_{\max}$ is the deformation at fracture (mm); and L is the original gauge length of the root segment (mm), which is set to 100 mm in this study.

3.3 In-situ shear test of tree root-soil composites

Compared with laboratory direct shear and triaxial tests, in-situ shear testing in the field allows for the determination of the strength of root-soil composites under minimally disturbed conditions, thereby better reflecting actual conditions. The resulting data are of practical significance for evaluating slope stability [23]. To assess the influence of *Pinus massoniana* and *Cunninghamia lanceolata* on the shear resistance of soil at the landslide site, a specialized in-situ shear apparatus suitable for arbor roots was designed and constructed. The apparatus consists of a shear box, dial gauge displacement meters, a jack, and a hydraulic pump (as shown in Fig. 3). The shear box measures 60 cm × 60 cm × 40 cm and is made of 15 mm thick steel. Dial gauges with a precision of 0.01 mm were used to measure shear displacement.

The jack has a load capacity of 0–10 tons and a displacement range of 0–150 mm. Shear force applied to the soil is measured through the hydraulic pump and its attached pressure gauge.

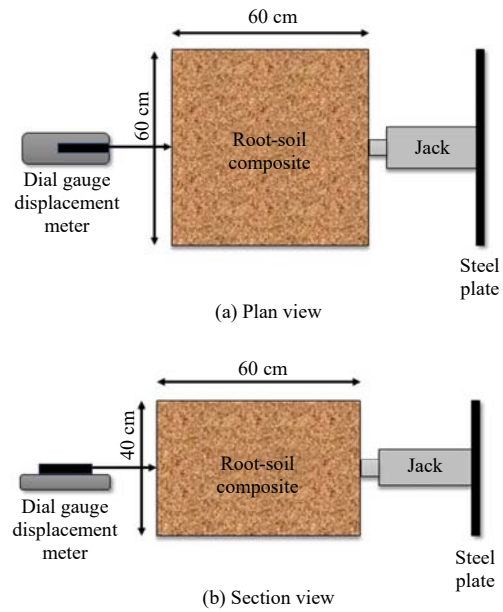


Fig. 3 In-situ shear instrument

In this experiment, *Pinus massoniana* and *Cunninghamia lanceolata*, which are widely distributed at the landslide site, were selected. Since root-soil composite samples are irreversibly damaged after in-situ shear testing, the root cross-sectional area ratio (RAR) cannot be determined prior to testing. Therefore, the following approach was adopted:

(1) Sixteen trees with different diameters at breast height (8 *Cunninghamia lanceolata*, 8 *Pinus massoniana*) were selected. After removing the upper parts of the trees, excavation was carried out according to dimensions of 60 cm × 60 cm × 40 cm. Shear boxes were then installed, leaving a 200 mm space for shear displacement. Instruments such as jacks, pressure pumps, and dial gauge displacement meters were set up, as shown in Fig.4. After the shear tests, the excavation method was used to quantify the RAR across the shear surface in order to investigate the mechanical behavior of arbor root-soil composites under different RAR conditions.

(2) As the Fujian region is frequently affected by typhoons and heavy rainfall, this experiment aimed to investigate the impact of water infiltration on the mechanical properties of root-soil composites. Ten arbor trees with similar diameters at breast height and comparable growth conditions were selected in advance (*Cunninghamia lanceolata*: 95–110 mm; *Pinus massoniana*: 99–115 mm). A portable moisture meter (accuracy: 0.1%) was used to measure the natural moisture content of the soil. Artificial rainfall was then applied to the root-soil composites using multiple

portable electric sprayers (each with a capacity of 20 L), adjusting the volumetric water content of the composites to between 20% and 45%. The shear testing procedure was the same as described in (1). After testing, the RAR across the shear surface was recorded to examine the effects of different moisture levels under rainfall conditions on the shear strength of the root-soil composites.

(3) To better analyze the influence of roots on soil shear strength, in-situ direct shear tests were conducted on soil without root under different moisture contents (ranging from 20% to 45%, corresponding to those used in the root-soil composite tests). Due to the relatively large size of the in-situ shear apparatus, it was not feasible to apply high vertical stress in the field. Therefore, in order to determine the cohesion and internal friction angle of soil without root under varying moisture contents, samples of eluvial sandy clay were collected from the site and brought back to the laboratory. Remolded soil samples with volumetric water contents ranging from 20% to 45%, corresponding to field conditions, were prepared. Fast shear tests were then performed using a strain-controlled direct shear apparatus to measure the cohesion and internal friction angle of the eluvial sandy clay under different moisture conditions. The results were compared with those of the field in-situ direct shear tests on soil without root for validation.



Fig. 4 In-situ shear and moisture content sensor

3.4 Root distribution in tree-covered landslide sites

This study conducted a survey of root distribution characteristics at a vegetated landslide site in the Wuping area. Using the profile method, an excavation was made 50 cm away from a *Cunninghamia lanceolata* tree to a depth of 3 meters. Following excavation, root characteristics were quantified on the exposed root-containing profile using tools such as digital calipers, as illustrated in Fig. 5.

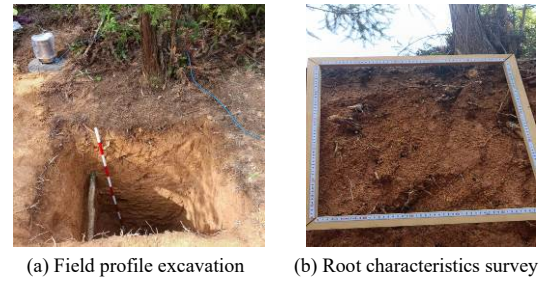


Fig. 5 Field root profile survey

The root characteristics quantified include:

(1) Root number density (RND), defined as the ratio of the number of roots to the cross-sectional area of the soil at different depths^[24]:

$$RND = \frac{n}{A} \quad (3)$$

where n is the number of roots; and A is the cross-sectional area of the soil (cm^2).

(2) Root cross-sectional area ratio (RAR):

$$RAR = \frac{A_s}{A} = \frac{\sum_{i=1}^n \frac{\pi d_i^2}{4}}{A} \quad (4)$$

where A_s is the total root area within a region (cm^2); and d_i is the root diameter (mm).

4 Test results and analysis

4.1 Root diameter and tensile properties

A total of 70 *Pinus massoniana* root samples were successfully tested in tensile experiments. The root diameter ranged from 0.72 to 7.47 mm, with tensile force ranging from 13.63 to 458.52 N and an average tensile force of 173.68 N. The tensile strength ranged from 7.16 to 33.48 MPa, with an average of 15.47 MPa. The ultimate elongation ranged from 11.09% to 15.59%, with an average of 13.64%. For *Cunninghamia lanceolata*, 70 root samples were also successfully tested. The root diameter ranged from 0.51 to 7.49 mm, tensile force from 12.45 to 673.09 N, with an average of 230.60 N. The tensile strength ranged from 7.26 to 60.95 MPa, with an average of 19.72 MPa. The ultimate elongation ranged from 7.91% to 16.69%, with an average of 12.74%^[20]. The relationships between tensile force and diameter, as well as tensile strength and diameter, for both tree species are shown in Figs. 6 and 7 (R^2 represents the coefficient of determination, and P denotes the p -value).

The average diameter, tensile force, and tensile strength of roots from diameter classes 1 to 7 for both *Pinus massoniana* and *Cunninghamia lanceolata* are shown in Table 2^[20]. According to the Kruskal-Wallis test, the differences in tensile force among different diameter classes of *Pinus massoniana* roots were statistically significant ($P < 0.01$), and the differences in tensile strength were also significant ($P < 0.01$).

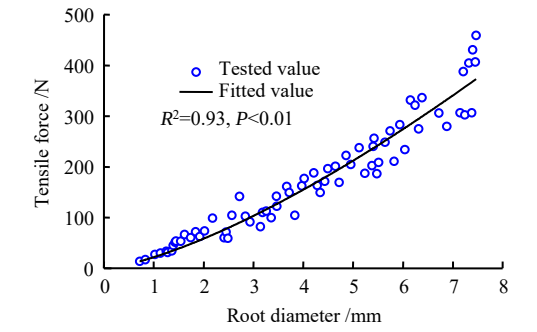
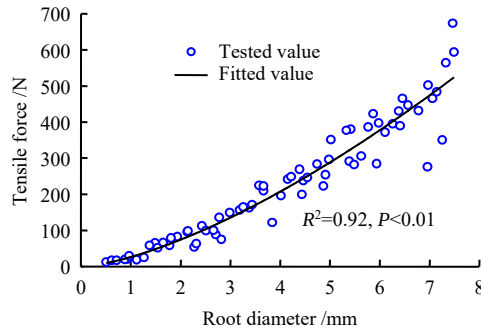
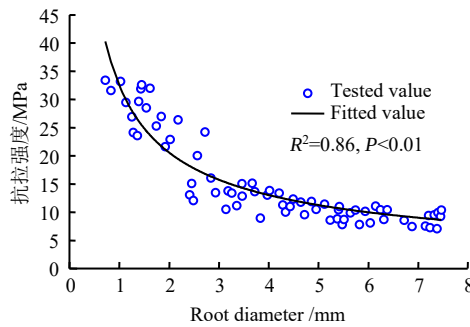
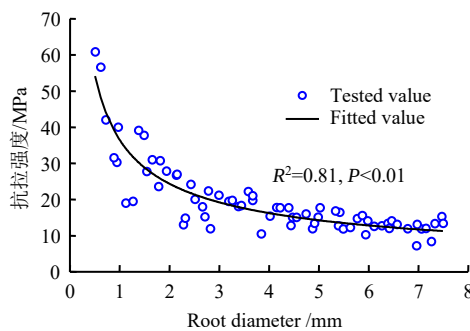

 (a) Tensile force–diameter relationship of *Pinus massoniana* roots

 (b) Tensile force–diameter relationship of *Cunninghamia lanceolata* roots

Fig. 6 Root tensile force–diameter trend diagrams

 (a) Root tensile strength–diameter relationship of *Pinus massoniana*

 (b) Root tensile strength–diameter relationship of *Cunninghamia lanceolata*
Fig. 7 Root tensile strength–diameter trend diagrams

Similarly, for *Cunninghamia lanceolata*, both the tensile force and tensile strength varied significantly across diameter classes ($P<0.01$). As shown in Figs. 6 and 7, the tensile force of both *Pinus massoniana* and *Cunninghamia lanceolata* roots increases with root diameter, exhibiting a positive power-function correlation. The relationship between tensile force and root diameter for *Pinus massoniana* is as follows^[20]:

$$F = 22.08D^{1.41} \quad (5)$$

where F is the root tensile force (N).

The relationship between tensile force and root diameter for *Cunninghamia lanceolata* is given as^[20]

$$F = 26.75D^{1.48} \quad (6)$$

Tensile strength exhibits a decreasing trend with increasing root diameter, showing a negative power-function correlation. The relationship between tensile strength and root diameter for *Pinus massoniana* is given as^[20]

$$T = 32.46D^{-0.66} \quad (7)$$

where T is the root tensile strength (MPa).

The relationship between tensile strength and root diameter for *Cunninghamia lanceolata* is given as^[20]

$$T = 36.55D^{-0.58} \quad (8)$$

Compared with coarse roots, fine roots have lower ultimate tensile force, but exhibit greater strength per unit area. This phenomenon can be attributed to differences in root chemical composition^[6, 20].

Table 2 Average tensile properties of roots of different diameter classes

Class of diameter	<i>Pinus massoniana</i>		<i>Cunninghamia lanceolata</i>	
	Tensile force /N	Tensile strength /MPa	Tensile force /N	Tensile strength /MPa
1	33.67	29.72	28.47	37.73
2	67.74	22.47	72.26	24.74
3	110.70	15.12	130.40	18.51
4	162.22	12.35	217.09	17.06
5	210.62	10.27	298.55	14.76
6	271.91	9.64	384.76	13.23
7	358.89	8.72	478.66	12.01

As shown in the box plots in Fig.8, *Cunninghamia lanceolata* roots exhibit higher average tensile force and tensile strength compared to *Pinus massoniana*. Based on the median lines, the tensile force distribution for both species is closer to a normal distribution, while the tensile strength displays a right-skewed distribution. The median values of tensile force and tensile strength for *Cunninghamia lanceolata* are both higher than those for *Pinus massoniana* (Tensile force: *Cunninghamia lanceolata* 223.02 N > *Pinus massoniana* 162.85 N; Tensile strength: *Cunninghamia lanceolata* 16.28 MPa > *Pinus massoniana* 11.94 MPa). The interquartile ranges indicate that the tensile force of *Cunninghamia lanceolata* roots is more dispersed and variable across different diameter classes, whereas the tensile strength of *Pinus massoniana* roots shows greater dispersion. However, the tensile strength distribution of *Cunninghamia lanceolata* roots contains more outliers.

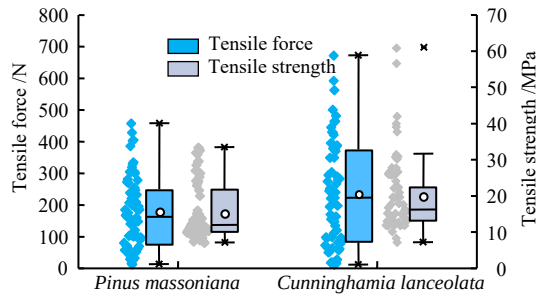


Fig. 8 Box diagram of root tensile force, tensile strength distribution

4.2 Root deformation characteristics under tensile force

Significant differences were observed in the stress–strain curves of roots with different diameters during single-root tensile tests. Four stress–strain curves from different diameter classes of *Pinus massoniana* and *Cunninghamia lanceolata* roots were selected for comparison, as shown in Fig. 9.

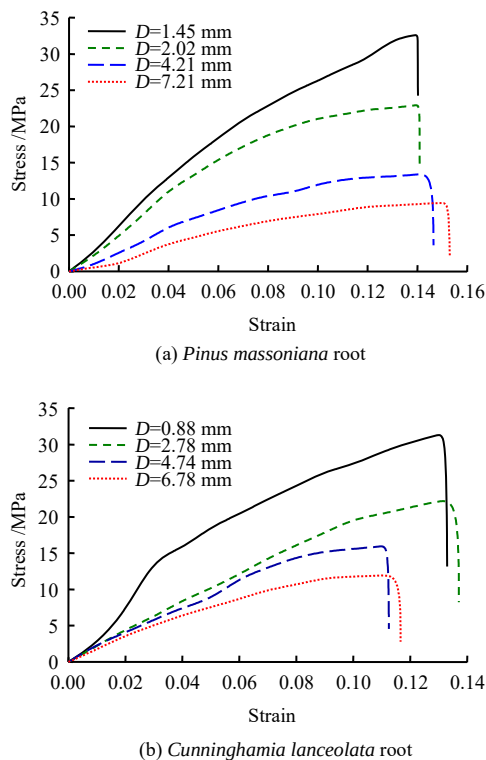


Fig. 9 Stress–strain curves of root tensile process

The stress–strain curves of roots with different diameters exhibit two distinct stages. In the first stage, elastic deformation occurs initially, where the stress–strain relationship is linear and follows Hooke's law. Experimental results show that for both *Pinus massoniana* and *Cunninghamia lanceolata* roots, this stage generally occurs at an initial strain range of 0.00 to 0.02, and for some roots, it ends when the strain exceeds 0.01. The elastic deformation stage is more pronounced in *Cunninghamia lanceolata* roots

compared to *Pinus massoniana*, with a larger average strain at the end of this stage. In the second stage, as stress increases, the roots undergo plastic deformation, displaying elastoplastic characteristics with a nonlinear stress–strain relationship. Following this stage, root failure occurs, and the curve shows a steep decline. Smaller diameter roots exhibit a greater slope (e.g., the 0.88 mm *Cunninghamia lanceolata* root in Fig.9(b) shows a noticeably steeper stress–strain slope than the 6.78 mm root), indicating higher stress required per unit strain. Throughout the deformation process, *Pinus massoniana* roots demonstrate better ductility, with an average ultimate strain of 13.64%, compared to 12.74% for *Cunninghamia lanceolata* (as reported in Section 4.1).

4.3 Shear strength characteristics of root-soil composites under in-situ direct shear testing and their relationship with RAR

In-situ shear tests without vertical surcharge were conducted on root-soil composites of *Pinus massoniana* and *Cunninghamia lanceolata*. According to the *Standard for soil test method* (GB/T 50123–2019) [25], failure in in-situ soil shear tests is considered to occur when shear deformation increases sharply or when the shear displacement reaches one-tenth of the specimen size (60 mm in this study). Taking into account the specific characteristics of the root-soil composites and the displacement range of the jack (0–150 mm), the maximum displacement in this experiment was set at 140 mm. A total of 16 tests were performed on the two tree species within a shear area of 0.36 m², with an average shear depth of 0.4 m. The relationship between RAR and shear strength is shown in Fig.10, while selected shear strength–displacement curves of root-soil composites under different RAR are presented in Fig. 11.

As shown in Fig.11, the shear stress increased rapidly at the beginning of the test. As the test progressed, the rate of increase in shear force slowed down and gradually reached the maximum shear stress of the specimen. After exceeding the peak, the shear stress gradually decreased and then stabilized. During the test, slight sounds of root breakage could be heard when the shear force declined. The stress–strain curves of different root-soil composite samples varied significantly. In some tests, the peak shear strength may not have been reached, and certain root-soil composites exhibited strain hardening, although most showed a decline in strength after reaching the peak [1]. Figures 10 and 11 indicate that a higher RAR requires greater displacement to reach peak shear strength. The presence of roots significantly enhances the shear strength of the soil, and the additional cohesion provided by the roots is positively correlated with the root area intersecting the shear plane.

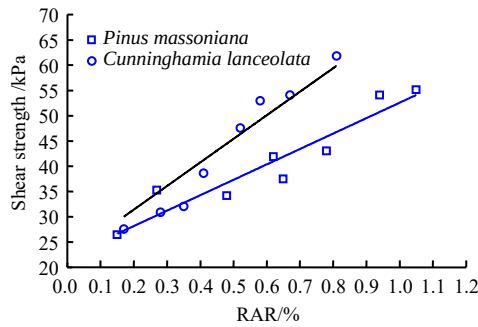
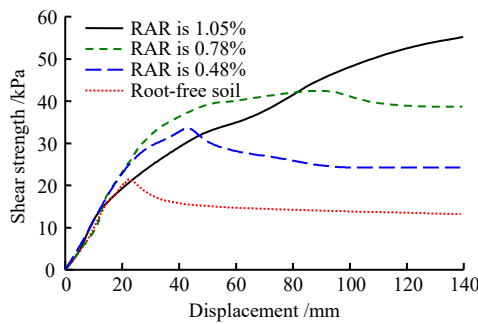
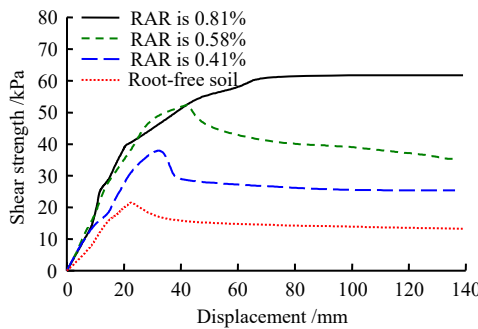


Fig. 10 Relationship between RAR and shear strength of two arbor root-soil complexes



(a) Shear strength–displacement relationship of *Pinus massoniana* root-soil composite



(b) Shear strength–displacement relationship of *Cunninghamia lanceolata* root-soil composite

Fig. 11 Shear strength–displacement curves of two arbor root-soil composites

4.4 Relationship between root tensile strength and shear strength of root-soil composites

When root-soil composites are subjected to shear, the frictional force and biochemical bonding between soil particles and roots convert the shear force into tensile stress within the roots [8]. If the ultimate tensile strength of the roots is lower than the root-soil frictional force, the roots fail by tensile rupture, and the additional cohesion provided depends on the tensile strength of the roots. In this case, the higher the root tensile strength, the greater the shear strength of the root-soil composite [1,19]. This is also why root tensile strength is considered a key parameter in many shear strength prediction models for root-soil composites [1,9]. In the case of arboreal root-soil composites, fine roots tend to fail by rupture during shearing, fully mobilizing their tensile strength, while coarse roots more often fail by pull-out, with their

tensile strength not fully mobilized. A comparison of the shear strength of *Pinus massoniana* and *Cunninghamia lanceolata* root-soil composites reveals that despite the overall RAR of *Cunninghamia lanceolata* being lower, its root-soil composite exhibits slightly higher shear strength. According to tensile test results of single roots, *Cunninghamia lanceolata* roots have a higher average tensile strength (19.72 MPa) than *Pinus massoniana* roots (15.47 MPa), which is one of the contributing factors to this outcome.

Building upon previous studies, Li et al.^[26] proposed a root structure classification system based on branching patterns, dividing plant root systems into six configurations: R-type, V-type, VH-type, M-type, H-type, and W-type. Research has indicated that among these root architectures, the R-type is the most effective in resisting shear failure in soil, followed by the V-type and VH-type [27]. Field excavation of root systems revealed that *Cunninghamia lanceolata* exhibits a root architecture closer to the R-type, while *Pinus massoniana* corresponds to the VH-type. Compared to the VH-type, the R-type root system features a less prominent taproot but a greater number of fine roots, which better facilitates the conversion of root tensile strength into additional cohesion within the root-soil composite. In contrast, *Pinus massoniana* has more coarse roots, and its dominant taproot is less likely to break during shear, making slippage more likely and preventing full mobilization of tensile strength. Tensile tests on individual roots showed that *Cunninghamia lanceolata* roots have higher tensile strength than those of *Pinus massoniana*, which helps explain why *Cunninghamia lanceolata* root-soil composites exhibit slightly greater shear strength under similar RAR conditions. Fig.12 shows the excavated root systems of *Pinus massoniana* (with a DBH of 67.38 mm) and *Cunninghamia lanceolata* (with a DBH of 128.97 mm).



(a) *Pinus massoniana*



(b) *Cunninghamia lanceolata*

Fig. 12 Root configuration of *Pinus massoniana* and *Cunninghamia lanceolata*

4.5 Relationship between shear strength characteristics of root-soil composites and moisture content under in-situ direct shear

The shear strength of 10 trees with a similar DBH under different moisture contents is shown in Fig.13. As the moisture content increases, the shear strength

of the root-soil composites of trees with similar DBH shows a decreasing trend. According to the study by Wu et al. [28] and the results in Section 4.4, the shear strength of root systems increases within a certain range as the RAR increases. As shown in Fig.13, despite differences in RAR among various root-soil composites, a comparison of the shear strength of *Pinus massoniana* root-soil composites at soil moisture contents of 31.1% and 40.1% reveals a significant decline in shear strength. At 40.1% moisture content, the RAR of the root-soil composite is 1.21%, higher than the 0.86% RAR at 31.1% moisture content, yet the shear strength decreases notably (41.93 kPa at 31.1% moisture content versus 34.21 kPa at 40.1%). This reduction is due to soil softening caused by water infiltration during rainfall, which reduces the cohesion of eluvial soil. Plant roots are also affected by moisture; some studies indicate that root tensile strength decreases with increasing moisture content [29], and the interface friction between roots and soil is also reduced as moisture content rises [30]. Consequently, the overall shear strength of the root-soil composite declines significantly with increasing moisture content. For vegetated slopes, although plant roots enhance soil shear strength, during intense rainfall events, water infiltration reduces the additional cohesion provided by roots, and plant roots can promote infiltration. This phenomenon is an important factor contributing to the instability and failure of vegetated landslides under heavy rainfall conditions.

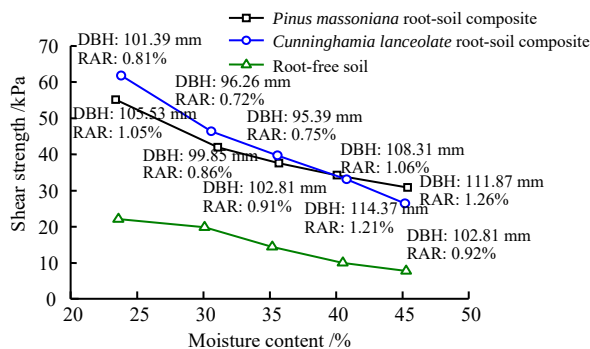


Fig. 13 Water-shear strength curves of root-soil composite

4.6 Mechanical properties of eluvial sandy clay soil on slopes under different moisture contents

To compare with the in-situ tests, eluvial sandy clay soil samples consistent with the root-soil composites were collected from the slope site and reconstituted in the laboratory at volumetric moisture contents of 25%, 30%, 35%, 40%, and 45%. Direct shear tests were conducted on these samples, and the variation of shear strength parameters of the eluvial sandy clay soil under different moisture contents is shown in Fig.14. As the moisture content increases,

the shear strength of the eluvial sandy clay soil decreases. Among the shear strength parameters affected by moisture content, the cohesion of the soil exhibits a significant reduction, while the decrease in the internal friction angle is comparatively limited.

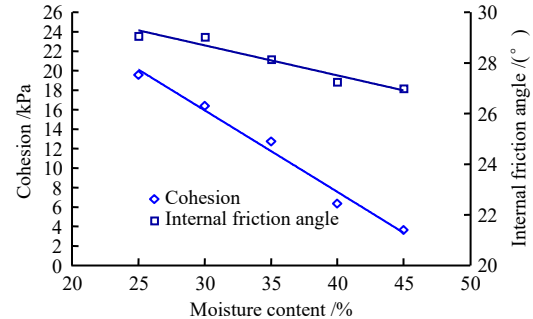


Fig. 14 Relationships between shear strength index and moisture content of eluvial sandy clay soil

4.7 Estimation model for shear strength of root-soil composite considering moisture content

Wu et al. [28], based on theories from soil mechanics and material mechanics, developed a simplified model for estimating the shear strength of root-soil composites. The model assumes that the tensile strength of roots in root-reinforced soils is fully mobilized, and that all roots reach their ultimate tensile strength and rupture simultaneously when the soil fails. Accordingly, the mechanical reinforcement effect of roots on the soil is calculated using their tensile strength. The contribution of roots to the overall soil strength is thus expressed as

$$s_r = \sigma_r \tan \phi' + \tau_r = t_r (\cos \theta \tan \phi' + \sin \theta) \quad (9)$$

where s_r is the additional cohesion provided by the root system; τ_r is the normal stress; t_r represents the average tensile strength generated by roots per unit area of soil (kPa); ϕ' is the effective internal friction angle; and θ is the shear deformation angle (°).

Based on relevant sensitivity analyses, Wu et al. [28] suggested that when the shear deformation angle ranges in the interval of $48^\circ < \theta < 72^\circ$, the value of $(\cos \theta \tan \phi' + \sin \theta)$ approaches 1.2, and thus Eq.(9) can be simplified as

$$s_r = 1.2 T_r (A_s / A) \quad (10)$$

where T_r is the average tensile strength of the root. According to Eq.(10), the increase in shear strength due to root reinforcement in the Wu model depends on both the RAR and T_r . When roots are oriented perpendicular to the shear plane, the shear strength of the root-soil composite can be expressed using the Mohr-Coulomb criterion as follows:

$$s^* = s + s_r = \sigma \tan \phi + c + s_r \quad (11)$$

where s^* is the shear strength of the root-soil composite (kPa); s is the shear strength of the plain soil (kPa); σ the normal stress on the shear plane

(kPa); c is the cohesion of the soil (kPa); and φ is the internal friction angle of the soil ($^\circ$).

Regarding the additional cohesion provided by roots, many researchers have found that the Wu model tends to overestimate its contribution. Consequently, several studies have introduced correction factors into the model to calibrate its predictions [31–32]. Eq. (10) can thus be rewritten as:

$$s_r = k' 1.2 T_r (A_s / A) \quad (12)$$

where k' is a correction factor, defined as the ratio between the measured and modeled values of the additional cohesion provided by the root system. Essentially, k' accounts for the overestimation of root tensile strength in the model due to partial root slippage under natural moisture conditions, where some roots fail to fully mobilize their tensile capacity.

Based on the results of in-situ shear tests (see Fig.10) and Eq.(12), the relationship between RAR and soil shear strength under natural moisture conditions for *Pinus massoniana* is given by ($k'=0.16$, $R^2=0.89$):

$$s^* = s + 0.19 T_r^* \cdot \text{RAR} \quad (13)$$

For *Cunninghamia lanceolata* under natural moisture conditions, the relationship between RAR and soil shear strength is characterized by ($k'=0.20$, $R^2=0.92$):

$$s^* = s + 0.24 T_r^* \cdot \text{RAR} \quad (14)$$

During the rainfall infiltration process, as the soil moisture content increases, both the soil cohesion c and the additional cohesion s_r provided by roots significantly decrease with increasing water content in the root-soil composite.

In the in-situ direct shear test, the normal stress σ on the shear plane of the root-soil composite is given by

$$\sigma = \rho V g / A = (\rho_d + \rho_d w) V g / A = (\rho_d + \rho_d w) h g \quad (15)$$

where ρ is the soil density (g/cm^3); V is the total volume of the soil sample (cm^3); g is the gravitational acceleration; ρ_d is the soil dry density (g/cm^3); w is the gravimetric moisture content (%); and h is the thickness of the overlying soil layer.

Since many soil moisture sensors used in landslide monitoring are based on time domain reflectometry (TDR) technology, the measured moisture content is volumetric moisture content. The conversion relationship between volumetric moisture content and gravimetric moisture content is given by

$$\theta_w = V_w / V = w \rho_d / \rho_w \quad (16)$$

where θ_w is the volumetric water content (%); V_w is the volume of pore water (cm^3); and ρ_w is the density of pore water (g/cm^3). Therefore, Eq.(15) can be expressed as

$$\sigma = (\rho_d + \theta_w \rho_w) V g / A = (\rho_d + \theta_w \rho_w) g h \quad (17)$$

Based on Eq.(15), the normal stress at a depth of 40 cm under different moisture contents can be calculated. According to Eq.(11), the actual additional cohesion provided by roots can be determined $s_r = s^* - \sigma \tan \varphi - c$. Using the shear strength data of the root-soil composite and the eluvial sandy clay soil shear strength under volumetric water contents ranging from 25% to 45%, the additional cohesion contributed by roots under varying moisture conditions can be derived. At the 40 cm depth, although the normal stress on the soil shear plane changes minimally with increasing moisture content, both the soil cohesion and root-induced additional cohesion decrease significantly. However, as shown in Fig. 15, due to differences in RAR (as seen in Fig. 13), it is difficult to quantify the effect of moisture content on root-induced additional cohesion. To address this, the modified Wu model (Eq.(12)) is employed to calculate the additional cohesion for different RAR values, representing the root-induced additional cohesion of the root-soil composite at natural moisture conditions prior to rainfall. This is then compared with the measured additional cohesion under varying moisture conditions. A correction factor for root-induced additional cohesion considering moisture content $k_{r\theta}$ is defined as the ratio between the root cohesion under moisture influence and that calculated by the modified Wu model at natural moisture content. In this study, the natural moisture content is taken as 25%. The calculation formula of $k_{r\theta}$ is as follows:

$$k_{r\theta} = a \theta_w^b \quad (18)$$

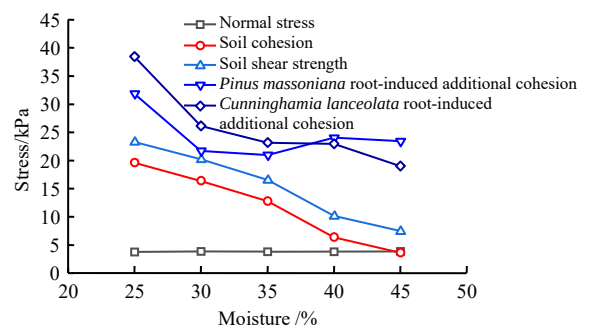


Fig. 15 Changes of mechanical index of water-root soil composite

where a and b are soil property parameters. The variation of the correction factor $k_{r\theta}$ with moisture content for *Pinus massoniana* and *Cunninghamia lanceolata* is shown in Fig.16. For *Pinus massoniana*, $k_{r\theta} = 10.67 \theta_w^{-0.74}$, $R^2 = 0.98$; and for *Cunninghamia lanceolata*, $k_{r\theta} = 62.10 \theta_w^{-1.30}$, $R^2 = 0.96$. The correction factor $k_{r\theta}$ essentially accounts for the reduction in root-soil interface friction during moisture infiltration, which leads to an increased likelihood of root slippage

and incomplete mobilization of root tensile strength. Therefore, $k_{r\theta}$ is used to correct this overestimated component of root reinforcement.

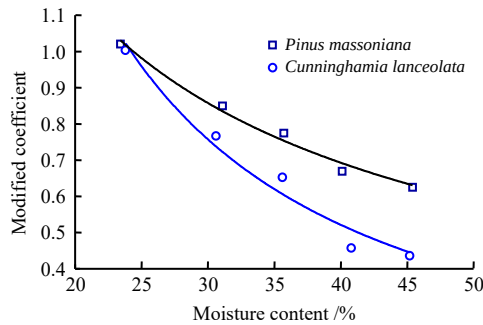


Fig. 16 Variation curves of moisture content–modified coefficient $k_{r\theta}$

Since the internal friction angle φ of the eluvial sandy clay soil varies only slightly with changes in moisture content (see Fig.14), the value of internal friction angle at natural moisture content or the corresponding moisture level can be used in the calculations. In contrast, soil cohesion decreases significantly with increasing moisture content; therefore, a moisture-dependent correction factor for soil cohesion $k_{s\theta}$ is introduced:

$$k_{s\theta} = c + d\theta_w \quad (19)$$

where c and d are both soil property parameters. For the eluvial sandy clay soil discussed in this study, $k_{s\theta} = 41.05 - 0.84\theta$, $R^2 = 0.98$.

Based on Eqs. (11), (12), and (17), along with the subsequent correction factors, the shear strength calculation formula for the root-soil composite considering variations in soil moisture content can be derived as

$$s_{\theta}^* = s + s_r = \sigma \tan \varphi + c + s_r = (\rho_d + \theta_w \rho_w) \cdot hg \tan \varphi + k_{s\theta} c + k_{r\theta} k' 1.2 T_r (A_s / A) \quad (20)$$

Taking *Pinus massoniana* as an example, the model was validated through in-situ direct shear tests on root-soil composites, with the results shown in Table 3. The validation indicates that the model predictions are reasonably accurate.

Table 3 Calculation table of modified model

RAR /%	Moisture content /%	Shear strength /kPa			Correction model deviation rate /%
		Correction model calculated value	Wu model calculated value	Tested value	
0.73	37.8	31.01	158.84	32.00	3.09
1.17	33.9	45.40	240.52	38.62	17.56

5 Discussion

5.1 Comparison between in-situ direct shear tests and laboratory direct shear tests

Due to the limited number of mechanical studies

on root-soil composites of *Cunninghamia lanceolata* and *Pinus massoniana*, this study compares the RAR and the corresponding root-provided additional cohesion s_r of root-soil composite reported in the works of Docker et al.^[1], Xia et al.^[9], with the results obtained in present study, as shown in Table 4.

As shown in Table 4, under similar RAR conditions, the additional cohesion provided by roots measured from the in-situ direct shear tests in this study is comparable to the results reported by Docker et al.^[1], and both are slightly higher than those obtained from laboratory direct shear tests. Although the principles behind in-situ and laboratory direct shear tests are fundamentally similar, their results differ to some extent, mainly due to the following reasons: (1) Laboratory direct shear tests are often conducted on remolded samples, in which the original soil structure and the biochemical bonding between soil particles and roots may be altered^[33]. (2) Due to the small size of laboratory samples, the root diameters used to prepare root-soil composites are limited, making it difficult to incorporate roots of various size classes. Furthermore, the root segments used are typically short due to equipment size constraints, and thus do not represent the complete root architecture or multi-directional root growth. In contrast, in-situ direct shear tests can capture realistic root behavior during shearing, including root breakage, frictional pull-out, and slippage. As a result, the root deformation and failure mechanisms observed in in-situ tests more accurately reflect actual conditions^[27, 33].

Table 4 Values of additional cohesion contributed by roots in root-soil complex obtained from in situ shear test and laboratory direct shear test

Data source	Test type	Tree species	RAR /%	s_r /kPa
Present study	In-situ direct shear test	<i>Cunninghamia lanceolata</i>	0.17	5.52
Present study	In-situ direct shear test	<i>Cunninghamia lanceolata</i>	0.28	8.83
Reference [9]	Laboratory direct shear test	<i>Cunninghamia lanceolata</i>	0.21	1.62
Reference [9]	Laboratory direct shear test	<i>Cunninghamia lanceolata</i>	0.42	3.15
Reference [1]	In-situ direct shear test	<i>Eucalyptus</i>	0.20	7.52
Reference [1]	In-situ direct shear test	<i>Eucalyptus</i>	0.29	10.19

5.2 Effects of root-soil mechanical properties on landslides in vegetated areas

Vegetation plays a crucial role in slope stability through a series of hydrological and mechanical processes^[34]. Although plant roots can provide additional cohesion to the soil through mechanical reinforcement, thereby enhancing its shear strength, the magnitude of this contribution is highly dependent on the spatial characteristics of the root system, particularly the root area ratio (RAR). As RAR decreases, the shear strength of the root-soil composite also declines

progressively^[1, 28], as indicated by Eqs. (11) and (20). Taking landslides in the study area as an example, Fig. 17 shows that for vegetated slopes in the Wuping region, both root number and total root cross-sectional area decrease with increasing depth. The RAR in the 60–80 cm depth interval is 0.67%, but drops sharply to only 0.005% at 160–180 cm. Although field surveys indicate that roots can extend to depths of approximately 2.3 m, RAR becomes nearly zero beyond a depth of 1.6 m, meaning the additional cohesion provided by roots becomes negligible. Once the soil depth exceeds the maximum rooting depth, the mechanical reinforcement effect of roots essentially disappears. Field investigations further reveal that in the study area, dominant tree species with DBH of 10–12 cm have maximum rooting depths typically between 1.5 and 2.0 m, closely corresponding to the depth of observed slip surfaces (1.5–2.5 m).

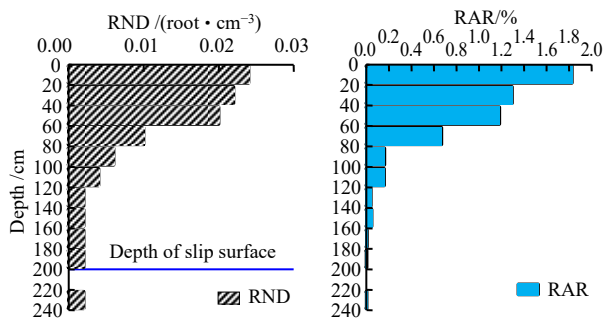


Fig. 17 Root characteristic distribution maps with root profile

Some studies have shown that plant roots can enhance the hydraulic conductivity of soil^[24]. In the case of shallow landslides during intense rainfall events, several processes may occur: (1) In the upper soil layers, preferential flow paths formed by roots accelerate water infiltration, which may reduce the additional cohesion provided by roots^[13]. (2) As infiltration progresses with depth, the infiltration rate decreases due to the reduced root density. At the root-soil interface, differences in hydraulic conductivity between rooted and non-rooted soils may lead to water accumulation along the interface, resulting in elevated pore water pressure^[35–36], which in turn reduces the shear strength of the soil. (3) With increasing depth, the root density decreases, and the additional cohesion provided by roots becomes negligible. Consequently, the shear strength of the soil at the root-soil interface is relatively low, making it a likely location for slip surface development^[24]. Therefore, although roots can reinforce the soil and improve shallow slope stability, their effectiveness is constrained by factors such as root depth and density. Under intense rainfall, the limited rooting depth, the root-induced enhancement of infiltration, and the sensitivity of root-soil composite shear strength to moisture content all limit the

stabilizing contribution of roots to shallow landslides.

6 Conclusion

This study conducted single-root tensile tests on the widely distributed roots of *Pinus massoniana* and *Cunninghamia lanceolata* in the landslide-prone study area, alongside in-situ direct shear tests on root-soil composites under varying moisture contents and root system investigations at the landslide site, leading to the following conclusions:

(1) Within diameter classes 1 to 7, the tensile force of *Pinus massoniana* and *Cunninghamia lanceolata* roots ranges from 12.45 to 673.09 N, exhibiting a positive power-law relationship with root diameter; their tensile strength ranges from 7.16 to 60.95 MPa, showing a negative power-law relationship with root diameter.

(2) The presence of roots significantly enhances the shear strength of the soil, and the additional cohesion provided by roots is significantly positively correlated with the root area intersecting the shear plane. The root architecture of *Cunninghamia lanceolata* is close to the R-type, while that of *Pinus massoniana* corresponds to the VH-type. Under similar root area ratios (RAR), the soil reinforcement effect of *Cunninghamia lanceolata* roots is superior to that of *Pinus massoniana*.

(3) With increasing moisture content, the shear strength of root-soil composites from trees with similar diameters at breast height shows a declining trend. As moisture increases, soil softening occurs, and both the root-soil interface friction and the tensile strength of roots decrease with rising moisture content, leading to a significant reduction in soil cohesion and the additional cohesion provided by roots.

(4) Based on the Wu model, an estimation model for the shear strength of root-soil composites considering the effect of moisture content on soil cohesion and the additional cohesion provided by roots was developed, which has been validated to exhibit high accuracy.

(5) While roots play a reinforcing role in shallow landslides, their effectiveness is constrained by factors such as root distribution depth, density, and rainfall. Under heavy rainfall conditions, the contribution of roots to the stability of shallow landslides is limited.

References

- [1] DOCKER B B, HUBBLE T C T. Quantifying root-reinforcement of river bank soils by four Australian tree species[J]. Geomorphology, 2008, 100: 401–418.
- [2] VANNOPPEN W, DE BAETS S, KEEBLE J, et al. How do root and soil characteristics affect the erosion-reducing potential of plant species?[J]. Ecological Engineering, 2017, 108(B): 186–195.
- [3] WANG X H, MA C, WANG Y Q, et al. Effect of root architecture on rainfall threshold for slope stability:

- variabilities in saturated hydraulic conductivity and strength of root-soil composite[J]. *Landslides*, 2020, 17: 1965–1977.
- [4] FAN C C, SU C F. Role of roots in the shear strength of root-reinforced soils with high moisture content[J]. *Ecological Engineering*, 2008, 33: 157–166.
 - [5] ZHANG C B, CHEN L H, LIU Y P, et al. Triaxial compression test of soil-root composites to evaluate influence of roots on soil shear strength[J]. *Ecological Engineering*, 2010, 36: 19–26.
 - [6] ZHANG C B, CHEN L H, JIANG J. Why fine tree roots are stronger than thicker roots: the role of cellulose and lignin in relation to slope stability[J]. *Geomorphology*, 2014, 206: 196–202.
 - [7] STOKES A, ATGER C, BENGOUGH A G, et al. Desirable plant root traits for protecting natural and engineered slopes against landslides[J]. *Plant and Soil*, 2009, 324(1/2): 130.
 - [8] MEIJER G J, BENGOUGH A G, KNAPPETT, J A, et al. New in situ techniques for measuring the properties of root-reinforced soil-laboratory evaluation[J]. *Geotechnique*, 2016, 66: 27–40.
 - [9] XIA Xin, JIANG Yuan-jun, SU Li-jun, et al. Estimation model of limit values of shear strength of root-bearing soil based on interface bonding[J]. *Rock and Soil Mechanics*, 2021, 42(8): 2173–2184.
 - [10] LOTFALIAN M, NASIRI M, MODARRES A, et al. Slope stability analysis considering weight of trees and root reinforcement[J]. *Journal of Environmental Engineering and Landscape Management*, 2019, 27(4): 201–208.
 - [11] VIROON K, ANTHONY K L, DAVID B, et al. Shearing behaviour of vegetated soils with growing and decaying roots[J]. *Canadian Geotechnical Journal*, 2022, 59: 2067–2084.
 - [12] CHEN Chang-fu, LIU Huai-xing, LI Ya-ping. Study on grassroots-reinforced soil by laboratory triaxial test[J]. *Rock and Soil Mechanics*, 2007, 28(10): 2041–2045.
 - [13] FU Jiang-tao, YU Dong-mei, LI Xiao-kang, et al. Statistical probability analysis of the physical index of rooted soil in Qiadam basin[J]. *Chinese Journal of Rock Mechanics and Engineering*, 2019, 39(8): 1696–1709.
 - [14] CHENG Lei. Experimental study on the effect of plant roots on slope reinforcement[D]. Beijing: China University of Geosciences (Beijing), 2018.
 - [15] LI Yue-zhou, FU Jiang-tao, HU Xia-song, et al. Experimental study of the influence of grain size on the shear strength of rooted soil[J]. *Chinese Journal of Rock Mechanics and Engineering*, 2016, 35(2): 403–412.
 - [16] WU T H, WATSON A. In situ shear tests of soil blocks with roots[J]. *Canadian Geotechnical Journal*, 1998, 35(4): 579–590.
 - [17] COMINO E, DRUETTA A. The effect of Poaceae roots on the shear strength of soils in the Italian alpine environment[J]. *Soil and Tillage Research*, 2010, 106(2): 194–201.
 - [18] RAI R, SHRIVASTVA B K. Biological stabilization of mine dumps: shear strength and numerical simulation approach with special reference to Sisam tree[J]. *Environmental Earth Sciences*, 2011, 63(1): 177–188.
 - [19] BISCHETTI G B, CHIARADIA E A, SIMONATO T, et al. Root strength and root area ratio of forest species in Lombardy (Northern Italy)[J]. *Plant and Soil*, 2005, 278: 11–22.
 - [20] LIN Y, JIAN W, ZHU Z, et al. Study on the mechanical properties of roots and friction characteristics of the root-soil interface of two tree species in the coastal region of southeastern China[J]. *Forests*, 2024, 15: 1285.
 - [21] General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China. GB/T 228—2002 Metallic materials—tensile testing at ambient temperature[S]. Beijing: China Planning Press, 2002.
 - [22] LÜ Chun-juan, CHEN Li-hua. Relationship between root tensile mechanical properties and its main chemical components of typical tree species in North China[J]. *Agricultural Engineering*, 2013, 29(23): 69–78.
 - [23] LU Hai-jing, WANG Lei, ZHAI Guo-liang, et al. Present status and progress of in-situ shearing test for root-soil composite system[J]. *Soil and Water Conservation in China*, 2013(7): 42–46, 77.
 - [24] QIN M, CUI P, JIANG Y, et al. Occurrence of shallow landslides triggered by increased hydraulic conductivity due to tree roots[J]. *Landslides*, 2022, 19: 2593–2604.
 - [25] Ministry of Water Resources of the People's Republic of China. GB/T 50123—2019 Standard for soil test method[S]. Beijing: China Planning Press, 2019.
 - [26] LI Y, WANG Y, MA C, et al. Influence of the spatial layout of plant roots on slope stability[J]. *Ecological Engineering*, 2016, 91: 477–486.
 - [27] FAN C C, CHEN Y W. The effect of root architecture on the shearing resistance of root-permeated soils[J]. *Ecological Engineering*, 2010, 36(6): 813–826.
 - [28] WU T H, MCKINNELLI W P, SWANSTON D N. Strength of tree roots and landslides on prince of wales Island, Alaska[J]. *Canadian Geotechnical Journal*, 1979, 16(1): 19–33.
 - [29] ZHANG C, ZHOU X, JIANG J, et al. Root moisture content influence on root tensile tests of herbaceous plants[J]. *Catena*, 2019, 172: 140–147.
 - [30] GERI Le, LIU Yan-qi, ZUO Zhi-yan, et al. Effect of soil moisture on the characteristics of root-soil interface Interaction[J]. *Journal of Soil and Water Conservation*, 2018, 32(1): 482–488.
 - [31] THOMAS R E, POLLEN-BANKHEAD N. Modeling root-reinforcement with a fiber-bundle model and Monte Carlo simulation[J]. *Ecological Engineering*, 2010, 36(1): 47–61.
 - [32] LÜ Chun-juan, CHEN Li-hua, CHEN Wei-guo, et al. Study on shear performance of soil-root composite[J]. *Journal of Irrigation and Drainage*, 2016, 35(3): 13–19.
 - [33] YU Qin-qin, HU Xia-song, LI Guo-rong, et al. Research on strength model test of shrub root-soil composite system in cold and arid environments[J]. *Chinese Journal of Rock Mechanics and Engineering*, 2013, 32(5): 1020–1031.
 - [34] FAN C C, CHEN Y W. The effect of root architecture on the shearing resistance of root-permeated soils[J]. *Ecological Engineering*, 2010, 36(6): 813–826.
 - [35] GHESTEM M, SIDLE R C, STOKES A. The influence of plant root systems on subsurface flow: implications for slope stability[J]. *Bioscience*, 2011, 61: 869–879.
 - [36] YAO Yun-qi, ZENG Run-qiang, MA Jian-hua, et al. Reliability analysis of slope under rainfall infiltration considering preferential flow model[J]. *Rock and Soil Mechanics*, 2022, 43(8): 2305–2316.