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A Study on Pullout Test of Root Subjected to Axial Load

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ABSTRACT

Vegetation can enhance the stability of slopes by increasing the shear resistance of the soil. Shear stress applied to the soil matrix is resisted by the pullout strength of the roots via the friction at contact points between the soil and the roots. The effectiveness of root reinforcement depends on interface friction between soil and roots. In this study, tests were carried out on *Indigofera amblyantha* Craib roots, by measuring resistance as they are pulled out of the soil where the soil has varying dry densities. The results reveal three phases in the relationship between the pullout force and the slippage of the roots, i.e. (1) steep rise, (2) steep fall, and (3) gradual decline. In the first phase, the pullout force is increasing sharply and linearly up to a maximum when the slippage is about 10mm. With continued slippage, the required pullout force decreases significantly and nonlinearly in up and down fluctuations. Eventually, the pullout force reaches zero. For soil with a given dry density, the maximum pullout force increases linearly with increasing root diameter, and the correlation coefficient is greater than 0.9. Further, for a root with a given diameter, the maximum pullout force increases with increasing soil dry density. When the root breaks on pulling, it is called tensile failure; when the root is fully pulled out, it is called friction failure. The mode of failure for all roots is friction failure, for soil with dry densities of 1.35 g/cm^3, 1.45 g/cm^3, and 1.55 g/cm^3. For soil with a dry density of 1.65 g/cm^3, and root diameter under 0.716 mm, the observed failure mode is generally tensile; for diameters over 0.716 mm, the failure mode changes to friction; that is, thin roots break, thick roots get pulled out.

INTRODUCTION

Over the past several decades, the rapidly expanding economy has led to a continuous increase in construction projects; this has caused large-scale disturbances in slopes, which require ecological restoration. Vegetation restoration techniques are widely accepted, effective, affordable, and environment-friendly to prevent soil erosion. Vegetation plays an important role in the slope stability by root reinforcement (Gray & Sotir 1996, Simon et al. 2000, Li & Eddleman 2002, Fan & Su 2008, Mickovski et al. 2009, Dazio et al. 2018)). Root systems in the soil change the mechanical properties of the soil consolidation (Mickovski et al. 2010, Yang et al. 2016). Plant roots can hold soil in the steep slopes depending on the advantage of extensive root proliferation and mechanical properties (Schwarz et al. 2010). Additionally, photosynthesis of plants can decrease soil moisture by root, and the matrix suction and mechanical strength were increased (Schwarz et al. 2010). As shown in Equation 1, these different mechanical effects were concentrated on a significant increase in soil cohesion as defined by the Mohr-Coulomb analysis (Genet et al. 2008).

$$\tau_{cr} = c_r + c_s + \sigma \tan(\phi) \quad \ldots(1)$$

τ_{cr} shear stress of the soil;

c_r: additional cohesion (in roots);

c_s : bare soil cohesion;

σ: effective normal stress (in the shear plane);

ϕ: bare soil friction angle.

The effect of root enhancement on the stability of a slope can be directly assessed by the additional shear strength provided by roots in the root-enhanced soil (Gray & Sotir 1996). Gray & Ohashi's (1983) laboratory experiments provide a useful interpretation of soil reinforcement by roots (Abernethy & Rutherfurd 2001). Root-soil is a fibre inclusion (Gray & Barker 2004), and it can be considered as a composite material (Gray & Ohashi, 1983, Abe & Ziemer

1991). Root fibre improves soil shear strength by transferring the shear stress in the soil matrix into the pullout strength of fibre inclusions through friction along with the points of contact between the fibre and the soil (Gray & Barker 2004, Cazzuffi et al. 2014a).

A large number of studies showed that the shear strength increase compared with no root-soil can result from many mechanisms, including pullout or breakage of individual roots (Wu et al. 1979) or composite action (Wu et al. 1988a) rely on root morphology and soil condition (e.g., soil density) (Mickovski et al. 2010, Comino & Marengo 2010). Soil root shear strength, the mechanical reinforcement effect of plant roots on slope stability, has been studied (Wu & Watson 1998). The pullout strength of roots can be measured by *in situ* root tests (Wu et al. 1979, Wu & Watson 1998, Comino & Marengo 2010) and laboratory root tensile tests (Abe & Ziemer 1991, Docker & Hubble 2008, Bischetti et al. 2009, Gray & Barker 2004, Liu et al. 2014). Wu et al. (1988b), Wu & Watson (1998) conducted an *in situ* shear test between the root-soil system and bare soil. The results show that the shear strength of the root-soil composite is higher than that of the bare soil, and the plant roots significantly enhance the cohesion of the soil; further, the stability of the slope is enhanced. The most critical parameters of root systems as soil reinforcement are root density, depth, and pullout strength. These papers provide a substantial introduction to the role of the root system in soil shear strength.

Previous studies involving root tensile tests have concluded that root destruction generally consists of the following processes: (1) root fibres slip, (2) root fibres stretch, and (3) root fibres break (Abe & Ziemer 1991, Gray & Barker 2004, Comino & Marengo 2010). Plant root response depends on plant species and plant growing conditions (Comino & Marengo 2010).

Waldron (1977) and Wu et al. (1979) assumed that the shear force generated in the soil when the soil layer (slope) moves was converted to the pullout force in the roots. Moreover, the shear stress can be decomposed into tangential and normal components, and that the soil friction was not affected, the additional cohesion coefficient ranges from 1.0 to 1.3 (Bischetti et al. 2009). Many researchers believe that the additional cohesion coefficient is a universal value of 1.2 (Waldron 1977, Wu et al. 1979, Wang et al. 2019). In particular, the mechanical characteristics (mean values of root pullout force and root diameter) of plant roots are very important.

From Fig. 1, the slope perspective of geotechnical engineering, the mechanical effect of the roots involves two significant actions: (i) Friction; the roots are resistant to axial tension and compression. When the roots touch and rub against the soil such that they serve as individual anchors, thereby preventing a pullout failure. (ii) Bearing, the roots are resistant to shear forces and bending moments. When the root-soil composite is subjected to external loading, the horizontal shearing force on the soil matrix is transferred into the pullout strength in the root fibre, enhancing the shear strength of the composite (Waldron 1977, Waldron & Dakessian 1981, Wästerlund 1989, Ennos 1989, Abe & Ziemer 1991, Cazzuffi et al. 2014b, Liang 2015). Therefore, plant roots need to strengthen the soil.

Pullout tests are a standard method to determine root pullout force in the laboratory (Shewbridge & Sitar 1996, Mickovski et al. 2005, Devkota et al. 2006, Stokes et al. 2007, Tosi 2007, Burylo et al. 2009).

In the process of ecological restoration, pioneer plant species are most relevant for a local application of these resource-saving, environment-friendly techniques. *Indigofera*

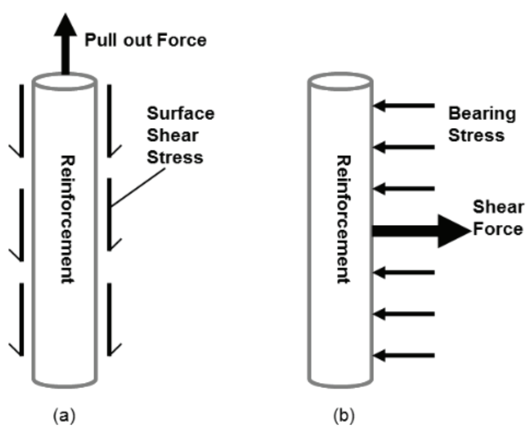


Fig. 1: Mechanism of soil inclusion interaction: The component force of force diagram: (a) Friction; (b) Bearing (Liang 2015).

amblyantha Craib (Fabaceae) is a shrub that is suitable for slope protection, especially because they have rapid growth, well-developed roots, drought resistance, disease resistance, and adaptability to bare soil (Chen et al. 2013, Zhao et al. 2018, Zhang et al. 2018). We selected the root of *Indigofera amblyopia* Craib as a research subject, investigating the root pullout force and its influential factors by pulling out test. Further, we developed a theoretical basis and foundation for root-soil interface friction.

MATERIALS AND METHODS

Study Area

A point at Yichang city in the Three Gorges Reservoir area in China was selected for collection of samples. As shown in Fig. 2, in this study area, the altitude is between 30-2057m; and more than 67.4% of the area is a low mountainous terrain; the climate is humid subtropical monsoon; the annual precipitation is 1100-1200mm; the annual average temperature is 16.9 °C; the average relative humidity is 70-80%; and the annual frost-free period is 340 days. Rainfall is unevenly distributed throughout the season, with the most rainfall in the period between May and September (Tang et al. 2014).

The purple soil developed from the Triassic to Tertiary is the dominant soil type in this study area, accounting for more than 70% of the area (He et al. 2009). It is characterized by low permeability, high hydrophobicity, and natural weathering (Zhang et al. 2016). It has been classified as a Regosols in FAO Taxonomy and Entisols in USDA Taxonomy (Tang et al. 2014). This purple sloping farmland is a vital cultivated land resource in the Three Gorges Reservoir area. It is also the primary source of soil erosion and sedimentation into the Three Gorges Reservoir; it is estimated that the annual soil erosion of the sloping farmland is 3,464-9,452 tons per square kilometre (Wei et al. 2018).

In restoration programs, the plant *Indigofera amblyopia* Craib has been used for slope vegetation protection. It is a deciduous perennial shrub of the genus *Magnolia* in the Leguminosae family and commonly grows at the edges of the forests, roadsides, barren slopes, and on the hillside below 1,200 m. It can hold the soil, improve soil permeability, effectively intercept precipitation, and has a good drought, cold resistance, and strong roots. As desirable vegetation for soil and water conservation and slope protection, *Indigofera amblyopia* Craib can prevent soil erosion, and it can be planted on both sides of a highway or railway slope along with grasses.

Sample Preparation

The purple soil with the experiment is widely distributed in the Three Gorges Reservoir area. The sampling site is located at Longkou Village (31°13'37''N, 110°41'16''E with a mean altitude of 110 m), Shuitianba Town, Zigui County, Yichang City in the Hubei Province in China. The samples are 0-20 cm, acquired from the surface soil in the middle of the slope, and they were collected in late June 2014. The soil samples were placed indoor and air-dried. Crumbled big clods, decomposed plant roots, residues of dead insects, stones, and other debris were removed. The air-dried soil samples were then sifted through 2 mm standard sieve to be used as standardized soil samples. The sieving method was

Fig. 2: Location of the study area and sampling sites.

used to measure the particle size distribution of the final soil samples. The stoving and cutting ring methods measured the natural water content and dry density of the final soil samples. Further, the pH of the final soil samples was measured using a potentiometer. The basic physical properties of the final purple soil sample are as follows: solid density, 1.33 g/cm^3; natural moisture content, 17.76 %; pH, 6.1; more than 2 mm, 28.49 %; 2-0.5 mm, 26.46 %; 0.5-0.25, 21.75%; 0.25-0.075, 11.89 %; 0.075-0.002, 6.54 %; less than 0.002, 4.87 %. As given in Tables 1 and 2, the range of shear stress is 47.65-85.23 kPa, the purple soil is clay, and liquid index, liquid limit, plastic limit, plasticity limit index are as follows: 0.28-0.74, 13.37-15.75%, 9.77-11.67%, and 3.15-4.33%, respectively (Hua et al. 2008).

In July 2014, we collected 38 well-grown and typical *Indigofera amblyopia* Craib as full plant samples. After collecting the samples, the soil off the plant was cleaned in still water and the plants were let to dry. We then used WinRHIZO to analyse the root diameters statistically. In some studies (Hales et al. 2009, Montagnoli et al. 2012), the root diameter is divided into four categories: very fine (< 0.5 mm), fine (0.5-1 mm), medium (1-2 mm), coarse (>2 mm). Extremely fine roots (0-0.5 mm) have been recognized in some studies; however, they have been questioned due to their rapid turnover (Adhikari et al. 2013). After using WinRHIZO to determine the average diameter of the samples with single roots, all roots were put into sealed bags and stored in a refrigerator. Hence, the pullout test was only performed on the roots with diameters between 0.5-1.0 mm. The root length is 100 mm, and the pullout tests of roots are completed within 24 h.

Pullout Test

Table 1 summarizes the basic parameters of the soil; the natural moisture content of the soil is 17.76%. We used a methodology of restoring the dry soil uniformly to that condition. The water content of the air-dried and screened soil, w_0, was determined. Since the natural water content is 17.76%, the design target moisture content of the soil samples, w_i, for the pullout test was set at 17.76%, and then the soil quantity was calculated. Using equations (2) and (3), the target is calculated under the condition of moisture content w_i, wherein water is added to the soil samples considering moisture content w_{wi} and soil quality, as follows:

$$m_{wi} = \frac{m}{1+0.01w_0} \times 0.01\left(w_i - w_0\right) \quad \ldots(2)$$

$$m_i = \left(1+0.01w_i\right)\rho_d V \quad \ldots(3)$$

Where, m: Soil mass

g: Mass unit

m_{wi} (g): Soil quality of the target water when preparing the soil samples

m(g): Soil quality of the air-dried soil when preparing the soil samples

m_i(g): Soil quality required for sample preparation

w_i(%): Target water content of the soil samples

w_0 (%): Water content of the air-dried soil

ρ_d(%) (g/cm^3): Dry density of the soil

V (cm^3): Volume of the soil

Table 1: Basic physical properties of the soils used in the study.

Soil	Index	Clay (< 0.002 mm) %	Organic matter content %	Natural moisture content %
Purple Soil	Maximum	15.31	1.48	13.76
	Minimum	11.08	1.16	11.08
	Average value	13.18	1.31	12.48
	Sample size	30.00	30.00	30.00

Table 2: Strength properties of the soils used in the study.

Soil	Index	Liquid index	Shear strength kPa	Liquid limit %	Plastic limit %	plasticity index %
Purple Soil	Maximum	0.74	85.23	15.75	11.67	4.33
	Minimum	0.28	47.65	13.37	9.77	3.15
	Average value	0.50	61.91	14.42	10.55	3.86
	Sample size	30.00	30.00	30.00	30	30.00

The soil sample was prepared as follows: (1) Mass m was measured for the air-dried soil sample, and mass m_{wi} was measured by adding water into a measuring cylinder. Then, water with mass m_{wi} was sprayed evenly on the soil sample with mass m. Next, the soil sample and water were mixed well, and the wetted soil sample was placed in a container. The soil sample was then left in the container until it reached the target moisture level at which point it was sealed with a tight cover. The sample was remoulded, and the initial dry density was controlled at ρ_d =1.35g/cm^3. We used equation (2) to calculate the soil mass m_i and prepared the sample of volume V to reach the target moisture content w_i. Then, as preparation for the soil sample to reach the target soil moisture, the soil sample was weighed; the mass of the soil was m_i. The container size of the test was 100×100×20mm. Before the test, the relationship between hitting times and the dry density was determined by the compaction method, and that increasing the hitting times was required for each 0.1g/cm^3 at the same height. When the test is conducted, the dry target density of the test is controlled by hitting times. By the soil mechanics test specification, the sample of pullout test is reconstituted by geotechnical test manual. A 100mm long single root of the *Indigofera amblyatha* Craib was embedded horizontally in the centre of a 100mm × 100mm × 200mm box packed with soil. The root-soil composite material is composed of an *Indigofera amblyatha* Craib single root and the soil.

A modified HANDPI's HP-50 digital tester of pullout force was then used to perform the pullout test on the single root-soil composite. The root protruding from the soil surface was clamped and pulled out of the soil at a constant rate of 10mm/min. During the test, the pullout force and the slippage were continually recorded. The device, HANDPI's HP-50, can record 60 data points per second. If the root in the soil with the initial dry density did not break, the dry density of the soil was increased by 0.1g/cm^3 until the single root pulled out or tensile failure occurred. In the test, the average diameter of the root was chosen between 0.50 and 1.00mm. Tests in which the position of the breakage is near the clamp were regarded as failures. The failure means that the root system is damaged by the clamp or because the root surface is damaged, it is pulled off by the action of the external force, and the value is not the actual test result. Because Zhang et al. (2014) said that when root breaking was caused by stress concentration near the clamp rather than by the pullout force, it is not like a natural break in the soil. The clamp is a fastening device made of a pair of steel blocks according to the diameter of the root. A circle of kraft paper was wrapped around the root system to improve the friction of the clamp and minimize breakage, caused by stress concentration near the clamp. In the test, one end of the root is in the soil, and the other end is in the clamp. Fig. 3 shows a schematic of the pullout test of a single root.

RESULTS

Pullout Tests

The pullout tests were performed on 38 root samples of *Indigofera amblyatha* Craib. Even if the root part is covered with kraft paper, it is easy to pinch the root, which causes the test to fail, and therefore, several trials had to be neglected. The roots of the pull test were pulled out of 38 roots, but only 14 of the 38 roots were properly pulled out or resulted in tensile failure. Table 3 lists the measured maximum pullout

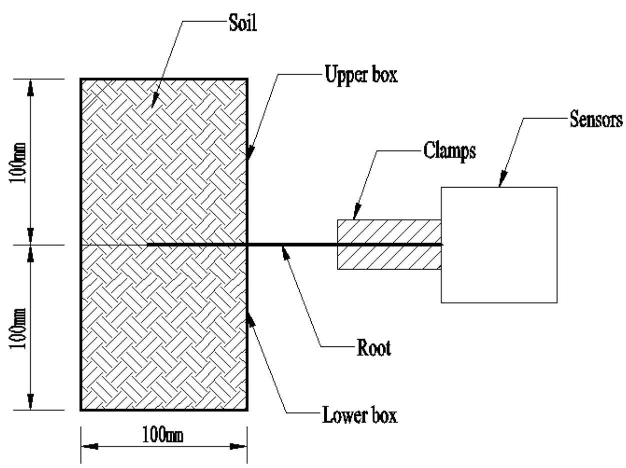


Fig. 3: Schematic plot for the pull-out test of a single root.

force, and maximum pullout strength with the corresponding root diameters.

From Table 3, there are 25 root systems in the table, and the results of two times are completed. The first pullout test has been performed on 38 root samples of *Indigofera amblyatha* Craib, and 14 roots have been pulled out by the device. In the second test, 22 roots pullout tests were completed, and 11 roots pulls were successful. From the two experiments, 25 roots were pulled successfully or experienced tensile failure it can be seen that for roots with an average diameter between 0.50-1.00 mm, the maximum pullout force varies between 4.39N and 13.51N. Further, the maximum pullout force increases with increasing average root diameter, as shown in Fig. 4; this relationship can be described by the power regression curve, which is also shown in Fig. 4.

Table 4 indicates that for the 14 *Indigofera amblyatha* Craib pulled out roots with the average diameter between 0.50-1.00 mm, the maximum pullout strength varies between 12.81 and 25.38 MPa. Further, the maximum pullout strength decreases with increasing average root diameter, as shown in Fig. 4. This relationship can be described by the power regression curve, also shown in Fig. 4.

Relationship Between Pullout Force and Slippage of Roots

Fig. 5 shows the measured pullout force and slippage of single roots of *Indigofera Amblyantha* Craib with diameters between 0.50-1.00 mm in the pullout tests for soils with four dry densities. Fig. 5(a) shows the pullout force and the slippage of the single root for the initial soil dry density $\Delta\rho_d = 1.35g / cm^3$. The results show that the failure mode is friction, and there is no tensile failure. The dry density of the soil was then increased by $\Delta\rho_d = 0.1g / cm^3$ until the dry soil density reached $\Delta\rho_d = 1.65g / cm^3$. The roots with diameters of 0.59

Table 3: Measured maximum pullout force, maximum pullout strength with corresponding root diameters from pullout tests.

N	D1 (mm)	D2 (mm)	D3 (mm)	Average diameter D (mm)	Maximum pullout force (N)	Maximum pullout strength (MPa)
1	0.73	0.52	0.32	0.52	4.40	20.46
2	0.63	0.56	0.43	0.54	4.97	21.70
3	0.42	0.46	0.84	0.57	5.00	19.37
4	0.76	0.48	0.46	0.57	6.40	25.38
5	0.56	0.59	0.61	0.59	5.82	21.51
6	0.66	0.51	0.61	0.59	5.91	21.47
7	0.76	0.50	0.56	0.61	6.47	22.28
8	0.78	0.68	0.43	0.63	5.80	18.61
9	0.84	0.70	0.35	0.63	6.70	21.49
10	0.92	0.62	0.42	0.65	6.90	20.58
11	0.61	0.71	0.65	0.66	7.20	21.26
12	0.48	0.72	0.82	0.67	6.75	19.03
13	0.59	0.61	1.16	0.79	8.46	17.48
14	0.83	0.70	0.81	0.78	8.06	16.87
15	0.88	0.79	0.72	0.80	7.30	14.64
16	0.93	0.76	0.83	0.84	7.82	14.14
17	1.07	0.84	0.61	0.84	8.90	16.06
18	0.75	0.82	0.96	0.84	8.13	14.53
19	0.84	0.89	0.97	0.90	10.59	16.68
20	0.86	0.91	0.94	0.90	11.11	17.34
21	1.01	0.92	0.83	0.92	10.50	15.80
22	0.89	0.92	0.99	0.93	8.87	13.00
23	0.89	0.92	1.03	0.95	9.04	12.81
24	1.10	0.93	0.87	0.97	11.41	15.55
25	1.20	0.91	0.88	1.00	13.51	17.32

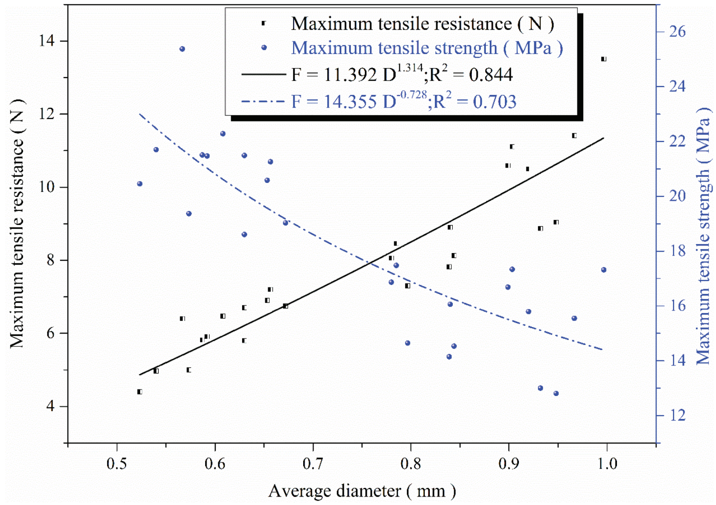


Fig. 4: Relationship between the maximum pullout force, the maximum pullout strength and the average root diameter.

mm and 0.63 mm must be broken, and the larger diameter roots (0.79 mm, 0.90 m, and 0.93 mm) may be completely pulled out or exhibit tensile failure, as shown in Figs. 5(b), 5(c) and 5(d), respectively.

As shown in Fig. 5(d), the change in the single root pullout force with increasing slippage can be divided into three phases, i.e. from A to B, which is the steep rise; from B to C, which is the steep fall; and from C to D, which is the gradual decline. With increasing slippage, the pullout force of the single root is linear upwards and reaches a maximum in the first phase. The pullout force is at its maximum when the slippage is about 10 mm. After reaching the maximum, the pullout force declines rapidly and nonlinearly in the second phase. The pullout force then fluctuates up and down and reaches zero eventually in the third phase. At the beginning of the test when the root is pulled, the slippage is almost zero due to the elastic modulus of the root in the soil. It is assumed that the root-soil complex is a homogeneous specimen. When the root system is pulled or broken by an external force (pullout force), the volume of the specimen is changed (Fig. 1). The root-soil contact surface of the soil particles with the pullout force enhances dislocation and rotation of the root, which is accompanied by the change in the soil volume. This process needs to use an external force to complete, and thus, pullout force rapidly reaches a maximum in the early stage of the test. Then, the pullout process continues, the movement and rearrangement of the soil particles around the roots make the root-soil interface smoother. The friction between the root and the soil particles decreases gradually and then reaches a constant. The drawing force also decreases and eventually reaches zero. These findings are consistent with those in the earlier study (Liu et al. 2012).

From Fig. 5(d), although the single root failure curve of tensile failure mode is similar to that of friction failure, there is a difference. The following two points can be seen from Fig. 5(d). (1) When tensile failure occurs, the pullout force reaches the maximum value; thereafter, the pullout force of the tensile failure decreases sharply and linearly. (2) When the pullout force is close to zero, the corresponding pulling resistance slippage decreases.

De Baets et al. (2008) reported that when the pullout test occurs the root fibre deforms. As shown in Fig. 1, the root fibre is stretched as long as there is enough interfacial friction, confining stress, and anchoring length to lock the fibres and prevent slippage or pullout. As the pullout force increases, the root system will have a tensile failure or be pulled out. The root reinforcement model assumes that the pullout strength of the roots is fully mobilized during failure.

The following two differences cause the tensile failure and the friction damage of the roots:

(1) Roots intersect with soil to improve the bond force between the roots and soil matrix. When tensile failure occurs, the bond force decreases as well as pullout force. (2) When the root system is broken, which is equivalent to the reduction of the effective length of the root system, the force of the root system being pulled out is small, and the root pullout time is shorter.

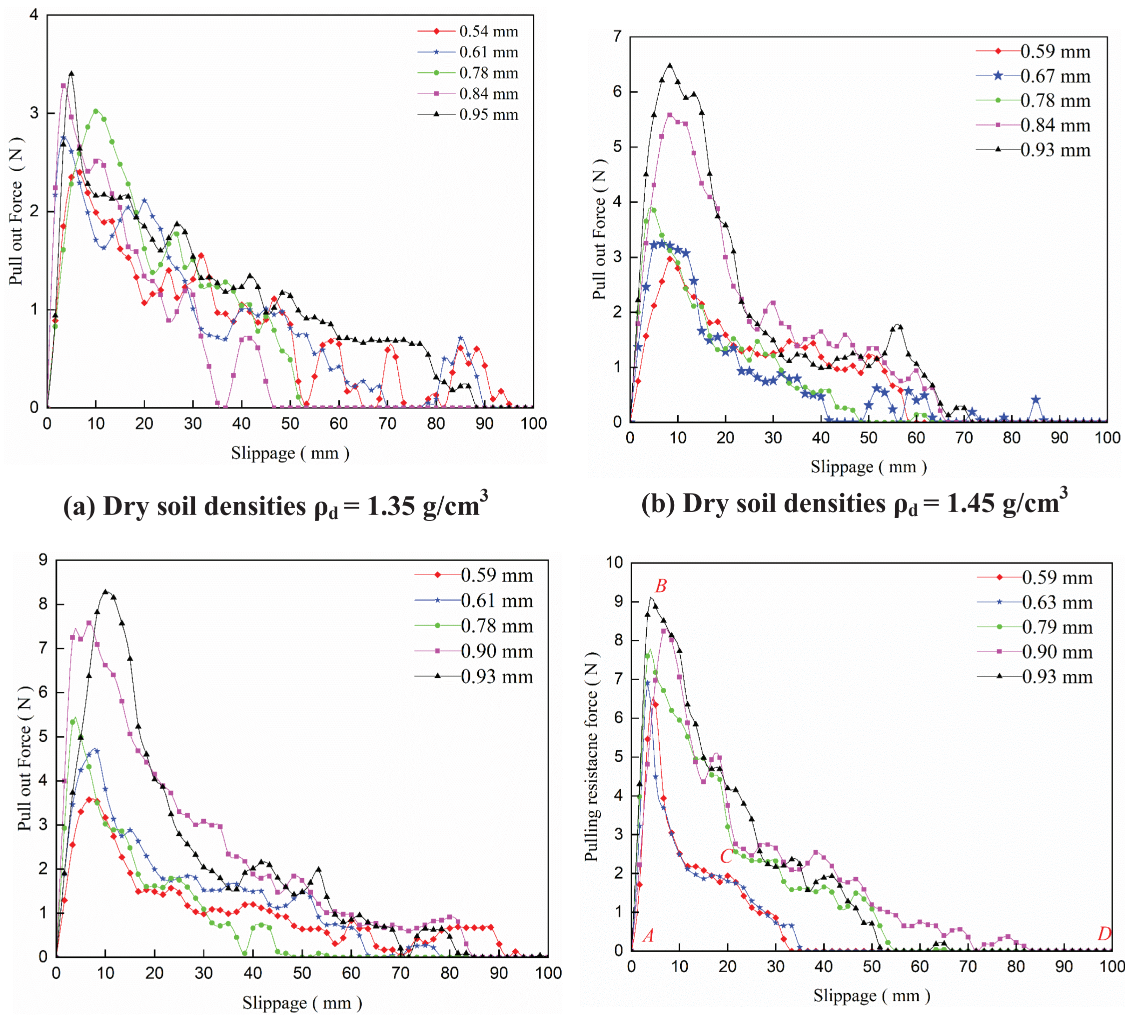
In the other case, when the root is pulled, the length of the root in contact with the soil decreases. Therefore, the length of the non-extracted root becomes shorter, and the pulling resistance slippage is reduced. Therefore, the slippage decreases more rapidly when the pullout force is close to zero.

Maximum Pullout Force

Fig. 4 shows the maximum pullout force of the root of *Indigofera Amblyantha* Craib with an average root diameter between 0.50-1.00 mm. The maximum pullout force increases significantly with the increasing average diameter of the root. The relationship between the maximum pullout force of the root of *Indigofera amblyantha* Craib and the average root diameter is power growth. Fig. 4 shows the fitted equation to the data.

Effect of Dry Soil Density on the Maximum Pullout Force

Table. 4 shows the relationships between the maximum pullout force and the average root diameter for four dry soil densities. Equations have been fitted to the data, and the smallest correlation coefficient is more significant than 0.9 from Table 4, it can be seen that for each dry soil density, the maximum pullout force of the single root increases with increasing average root diameter. This shows that the larger the root diameter, the larger the contact area between the root and the soil, resulting in more friction at the root-soil interface. Hence, the pullout force of the single root is also larger. For a given root diameter, the maximum pullout force of the single *Indigofera Amblyantha* Craib root increases with the increase of dry soil density. This result is consistent with that obtained from the earlier study (Song et al. 2006). For soil with lower dry density, the soil particles are looser.



(a) Dry soil densities $\rho_d = 1.35$ g/cm^3

(b) Dry soil densities $\rho_d = 1.45$ g/cm^3

(c) Dry soil densities $\rho_d = 1.55$ g/cm^3

(d) Soil dry density $\rho_d = 1.65$ g/cm^3

Fig. 5: Relationships between pullout force and slippage for four dry soil densities.

Table. 4: Relationships between maximum pullout force and average root diameter for four dry soil densities.

Dry soil densities	Fitting equation	R^2
$\rho_d = 1.35 g/cm^3$	$F = 3.572\ D^{0.731}$	0.932
$\rho_d = 1.45 g/cm^3$	$F = 6.952\ D^{1.752}$	0.958
$\rho_d = 1.55 g/cm^3$	$F = 8.909D^{1.732}$	0.940
$\rho_d = 1.65 g/cm^3$	$F = 9.142\ D^{0.662}$	0.957

Hence, there is less contact between the soil particles and the root surface, resulting in a smaller friction force between the root and the soil. For soil with higher dry density, there is more contact between the soil particles and the root surface, resulting in more friction at the root-soil interface. Hence, the pullout force of the root is larger.

In Fig. 6, the relationships between the maximum pull-out force and maximum pullout strength with average root diameter for $\rho_d = 1.65$ g/cm^3 are fitted with power equations, with $R^2 = 0.854$ and 0.959, respectively.

When the dry soil density is $\Delta\rho_d = 1.65 g/cm^3$, the *Indigofera amblyantha* Craib root undergoes a pullout failure. From Fig. 6, the maximum pullout force increases with increasing average root diameter. Further, at the average root diameter of $r = 0.716$ mm, the maximum pullout force equals the maximum pullout strength. This is an indication that $r = 0.716$ mm is a critical diameter of the single root of *Indigofera Amblyantha* Craib in which the pulling resistance failure mode changes from friction to tensile failure. Therefore, for $D < 0.716$ mm, the pullout failure mode is expressed as breaking mode, and for $D > 0.716$ mm, the pullout failure mode of the single root is expressed as friction damage. Hence, the pulling resistance of a plant is greatly dependent on the friction at the root-soil interface (Abe & Ziemer 1991, Anderson & Richards 1987, Leung et al. 2018).

DISCUSSION

Based on measured data from the pullout tests, Fig. 5 shows for the average root diameter between 0.5-1.0 mm and the pullout force increases with increasing average root diameters. After the load peaks, the pullout force decreases as the friction between root and soil lessens owing to the slippage of the roots and because of the decreasing interface area between the root and soil when the root is extracted from the soil. As can be seen from Fig. 5 (d), the pullout force is 0 when the slippage is about 40 mm, and this means that the contact area between the root system and the soil becomes smaller. These results are similar to those in the study of the extraction of sunflower taproot seedlings by Ennos (1989). After the load peaks, it fluctuates significantly, and there are further slippages.

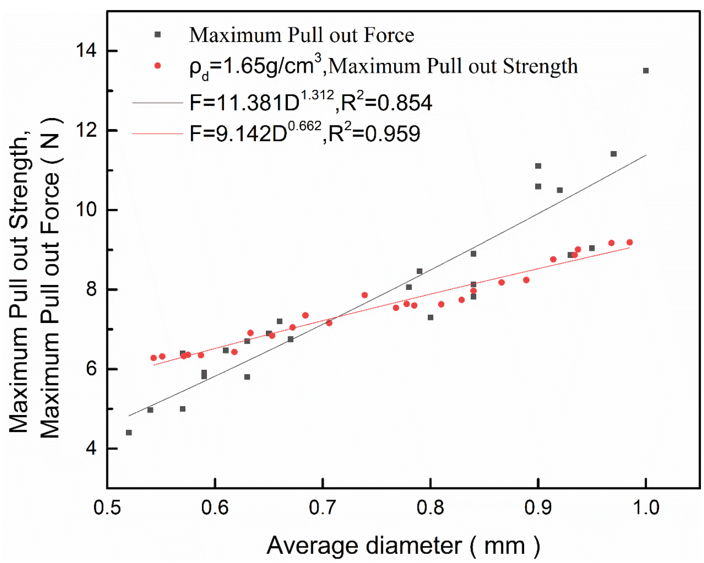


Fig. 6: Relationship between maximum pullout force and maximum pullout strength with average root diameter for $\rho_d = 1.65$ g/cm^3.

Fig. 5(a) shows that for a smaller root diameter, the pullout strength is greater. Further, the pullout strength first increases sharply and reaches a maximum when the slippage is about 10mm. As the test continues, the pullout strength decreases gradually with increasing slippage. The pullout strength eventually reaches zero.

The results of this study show a positive power function correlation between the root diameter and the stress, which is consistent with the results of earlier studies (Stokes et al. 2008, ChunJuan et al. 2011, Zhang et al. 2012, Zhang et al. 2014). The effect of the root diameter on the tensile properties of the root can be explained from the perspective of chemical composition, as follows:

The percentage of cellulose increases with a decreasing percentage of lignin. Therefore, for a larger root diameter, the lignin-cellulose ratio is smaller. As the lignin-cellulose ratio is positively correlated with the pullout strength, the pullout strength decreases with increasing root diameter (Genet et al. 2005, Hales et al. 2009, Lü & Chen 2013, Zhang et al. 2014). Using a power function, earlier studies have confirmed the negative correlation between the root diameter and the pullout strength (Nilaweera & Nutalaya 1999, Bischetti et al. 2005, Genet et al. 2007, ChunJuan et al. 2011). In this study, the results also show that the root pulls out strength decreases with increasing root diameter. However, the effect of the root diameter on the pullout strength is not always significant. This can be explained by the autocorrelation between the pullout strength and the diameter, i.e.

$$\sigma = \frac{F}{S} = \frac{4F}{\pi D^2} \quad \ldots(4)$$

Where σ is the pullout strength of the root, F is the pullout force of the root, S is a cross-sectional area of the root, and D is the diameter of the root. Equation 3 shows that the pullout strength of the root system is opposite to the root diameter (D). It can be seen from Equation 3 that the root diameter (D) is the denominator, which is opposite to the pullout force (F).

CONCLUSIONS

The study was conducted under conditions of the natural water content of soil = 17.76%, soil depth = 50 mm, and embedding root length = 100 mm. The pullout tests were carried out on single roots of *Indigofera amblyantha* Craib by the axial load method. The pullout force of *Indigofera amblyantha* Craib was investigated. The test results showed that:

(1) The relationship between the pullout force and the slippage of *Indigofera amblyantha* Craib roots can be summarized in three phases: (1) steep rise, (2) steep fall, and (3) gradual decline. During the first phase, the pullout force increases sharply and linearly up to a maximum when the slippage is about 10 mm. With the increase in slippage, the pullout force decreases significantly and nonlinearly, with up and down fluctuations. Eventually, the pullout force reaches zero.

(2) For soil with a given dry density, the maximum pullout force increases linearly with increasing root diameter, and the coefficient of correlation is greater than 0.9. This is an indication that the larger the root diameter, the longer is the embedded root length in the soil, and the greater is the friction at the root-soil interface. Hence, the force required to pull out the root is greater.

(3) For a root with a given diameter, the maximum pullout force increases with increasing soil dry density. The mode of pulling resistance failure of all roots is friction failure for soil with dry densities of 1.35 g/cm^3, 1.45 g/cm^3, and 1.55 g/cm^3. For soil with a dry density of 1.65 g/cm^3, the failure mode changes from friction to tensile failure when the root diameter is 0.716 mm (i.e., the pullout failure mode is a tensile failure when the root diameter is smaller than 0.716 mm; it is friction failure when the root diameter is larger than 0.716 mm).

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