Journal of Soil Science and Plant Nutrition (2023) 23:2893–2912
https://doi.org/10.1007/s42729-023-01330-3

REVIEW

Methods for Studying the Effect of Plant Roots on Soil Mechanical Reinforcement: a Review

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Received: 2 February 2023 / Accepted: 30 May 2023 / Published online: 13 June 2023

Abstract

Due to the need for engineering construction, a large number of man-made slopes are formed, which easy to induce soil erosion and shallow landslide. The root mechanical reinforcement effect of plants plays an important role in the reinforcement of slopes, and this paper discusses the research methods on it. The root mechanical reinforcement can be divided into main root anchorage and lateral root reinforcement, and experimental research, theoretical calculation model, and numerical simulation are used to quantify the root mechanical reinforcement effect. Different methods should be chosen according to different root growth morphology. The direct shear test is a good research method for shallow root growth depth. For deeper roots, theoretical calculation model is usually used to quantify the root mechanical reinforcement effect. The theoretical calculation model mainly depends on the tensile properties of roots and the distribution characteristics of roots. Therefore, to reduce the error of the theoretical calculation model, it is necessary to obtain high-precision experimental data measured in the field in the future. The theoretical calculation model has been widely used and can be applied to any species. Even if there is still a small amount of error between the quantified actual mechanical reinforcement effect, the error is accepted. At the same time, the theoretical calculation model can compare the root mechanical reinforcement effect of different plants, which is very beneficial for the selection of slope-reinforcing plants. Numerical simulation can be used as an auxiliary means in the research, but there are still challenges in how to deal with the relationship between root and soil and establish the actual root morphology.

Keywords Root mechanical reinforcement effect · Ecological engineering · Root additional cohesion · Soil erosion · Shallow landslides

1 Introduction

With the progress of production and construction (Banerjee et al. 2020; Srinivasu and Rao 2013), a large number of slopes are formed on the surface, and soil erosion and shallow landslides are prone to occur in the natural environment (Burger. 2011). According to statistics, approximately 1/5 of the world's land area is affected by shallow landslides under rainfall, causing approximately 4500 deaths and $3.2 billion in property damage each year (Kim et al. 2017).

Slope can be divided into two categories according to the formation type: man-made slope and earth slope. A large number of man-made slopes are formed in production and construction, and the soil is artificially disturbed. For example, in the process of mining, the mineral soil mined from underground was piled up to the surface to form the slope. These soils are loose, so the cohesion is small, if no protective measures are applied, geological disasters on the slope are bound to occur.

A major form of hazard in slope geological hazards is shallow failure (Cui et al. 2019; Gasser et al. 2019; Löbmann et al. 2020a; Sun et al. 2019; Yu et al. 2020). The shallow failure occurs on the slope surface and takes the form of soil erosion and shallow landslides (Pollen-Bankhead et al. 2013). Soil erosion is considered to be a form of hydrogeological instability in which the soil is stripped, transported, and deposited by external forces, such as hydraulic and wind forces, on the surface of soil particles (Vergani et al. 2017a). Shallow landslides are landslides with a sliding surface depth of less than 2 m (Bordoni et al. 2016), and

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the specific form is that the surface soil mass moves down as a whole. Shallow landslides are widely distributed and easy to occur in the world, especially under rainfall conditions, the infiltration of rainwater leads to the increase of pore water pressure inside the soil body (Sun et al. 2009). Soil erosion and shallow landslides can cause damage to soil resources, ecological degradation, river obstruction, and in severe cases, damage to living infrastructure and even threaten human lives (Löbmann et al. 2020a).

To reduce soil erosion and shallow landslides, appropriate management measures are needed. Civil engineering slope stabilization is a major management tool (Fang et al. 2010). Civil engineering reinforcement is mainly based on anti-slip piles, anchors, and grouting measures, which close the plant growth environment during the construction process and prevent the plant from growing and developing. However, under the erosion of rainwater, the engineering facilities are easy to age, which makes the civil engineering slope protection reduce the effect or even completely fail, and in serious cases, it may cause secondary disasters (Wang 2013). At the same time, civil engineering slope protection does not reflect the concept of coordinated development of engineering construction and ecological environment. Therefore, the management measures of ecological engineering slope protection have gradually emerged.

In eco-engineered slope protection, plants are effective barriers to inhibit and control soil erosion and shallow landslides (Stokes et al. 2009). After being reinforced by plants, the stability of the slope surface soil can be significantly enhanced. As shown in Fig. 1, the north side of the Haizhou open-pit mine dumpsite located in Fuxin City, Liaoning Province, China, the plant growth state obviously controls the stability of the slope surface soil. The role of plants is mainly divided into mechanical reinforcement and hydrological regulation (Löbmann et al. 2020a; Pollen-Bankhead et al. 2013). Mechanical reinforcement of plants plays a more important role in preventing and controlling slope hazards (Sidle and Bogaard 2016). The plant relies on the root mechanical reinforcement effect, which can effectively improve the shear strength of the soil. The root system of the plant expands in the soil and adheres to the soil. When the soil is subjected to external force, part of the external force is borne by the root system, thereby enhancing the strength of the soil matrix (Ennos 1990; Waldron 1977). If one wants to reinforce another material, the two materials must have different mechanical properties. The mechanical properties of soil are strong compressive capacity and weak tensile capacity, and its compressive strength is 10–20 times that of tensile strength, while the mechanical properties of plant roots are the opposite, with strong tensile capacity and almost no compressive capacity. There is a mutually reinforcing relationship between root and soil connections (Pollen-Bankhead et al. 2013).

The root system is the basic unit of slope reinforcement, and the mechanical reinforcement of the root is the basis for the study of plant reinforcement slope. The accurate quantification of plant root mechanical reinforcement plays a crucial role in ecological engineering slope protection and has a guiding value for the initial construction and later maintenance of ecological engineering. Therefore, this paper focuses on the research method of the root mechanical reinforcement effect. The structure of this paper is as follows: firstly, it introduces the root mechanical reinforcement (reinforcement theory and anchoring theory) (Sect. 3), then summarizes the research methods of root mechanical reinforcement (Sect. 4), and finally discusses the existing research results of root mechanical reinforcement and the future research was prospected (Sect. 5).

2 Materials and Methods

Relevant research work on quantitative methods for soil reinforcement by root was retrieved. The databases used in the search process included “ScienceDirect (Elsevier) (https://www.sciencedirect.com),” “SciELO (http://www.scielo.org/php/index.php),” “Springer Link (https://link.springer.com/),” “Wiley Online Library (https://onlinelibrary.wiley.com/),” and CNKI (https://www.cnki.net/), the search and

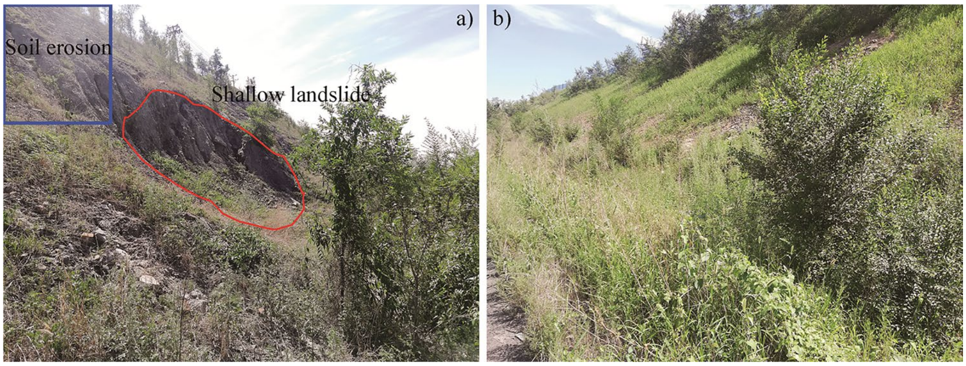


Fig. 1 Comparison of the reinforcement effect of the plant on slopes, **a**) Slopes with poor plant growth are prone to soil erosion and shallow landslides, **b**) slopes with good plant growth have stable surface soil after root reinforcement

management tool website (https://researchrabbitapp.com/) is used. The keywords used in the reference search process are "plant or vegetation and root reinforcement," "root reinforcement and WWM or FBM or RBMW," "root reinforcement and test," "root reinforcement and direct shear test or triaxial test or unconfined compressive test," "root reinforcement and numerical simulation," and "root and hydro-mechanical reinforcement." After the search, all works of literature were classified and screened.

3 Root Mechanical Reinforcement Effect

The plants species used for slope reinforcement can be divided into herbs, woody, and shrubs, and the plant root mechanical reinforcement effect is different (Fig. 2). The soil is assumed to consist of topsoil and a stabilized soil layer, and stabilized soil layer is assumed to do not occur shallow landslides. The shape of the sliding surface of shallow landslides is mostly circular, so an arc-like sliding surface is assumed between the topsoil and the stabilized soil layer in Fig. 2. Herbs have shallow root growth depth, and most of them are located at 10–20 cm of the surface soil, so herbs mainly reinforce the surface layer of soil, and shrubs and woody are used to reinforce deeper soil. Some of the woody have main roots growing at a depth of up to 5 m and lateral roots growing on the main root, and both the main root and lateral roots have reinforcement.

A lot of research work has been done on plant root systems to reinforce soil (Centenaro et al. 2018; Cislaghi et al. 2018; Ye et al. 2017). In the current study, most scholars believe that woody roots have a better mechanical reinforcement effect than herbs roots, and there are more landslides where herbs grow (Meusburger and Alewell 2008; Rickli and Graf 2009). This results in less research on slope mechanical reinforcement by herbs in current ecological engineering. Löbmann et al. (2020b) summarized the existing research and found that the number of landslides in herbs areas is one-sided because landslides in forests are easily ignored. By comparing the mechanical reinforcement effects of herbs and woody, it is found that herbs can also play a good mechanical reinforcement feature, especially for the soil surface. At present, to ensure the reinforcement effect in ecological engineering, herbs are usually used as pioneer species. Therefore, herbs occupy an important position in ecological engineering, and it is necessary to pay enough attention to the mechanical reinforcement effect of herbs.

The current research on the root mechanical reinforcement effect can be divided into mechanical reinforcement theory and anchoring theory. The mechanical reinforcement theory is mainly applied to the reinforcement of lateral roots of plants, such as the mechanical reinforcement of herb roots and the mechanical reinforcement of shallow scattered roots of shrubs and woody. Its root system is characterized by a large number of roots and mainly fine roots, which form a root-soil composite with the surrounding soil. The effect of the plant root system is similar to that of fiber. Therefore, the relevant research results of fiber mechanical reinforcement can be used to study the herb root mechanical reinforcement effect. The anchoring theory is mainly applied to the taproot of woody, and its mechanical reinforcement effect is similar to that of bolts and soil nails in geotechnical engineering. The taproot anchors the soil surface to the deep stable soil, thereby preventing the topsoil from falling off and slipping.

When using the mechanical reinforcement theory to determine the root mechanical reinforcement effect, the root mechanical reinforcement effect can be regarded as the root additional cohesion on the soil, as shown in Fig. 3. For unrooted soil, its shear strength can be expressed by the Mohr–Coulomb criterion, namely:

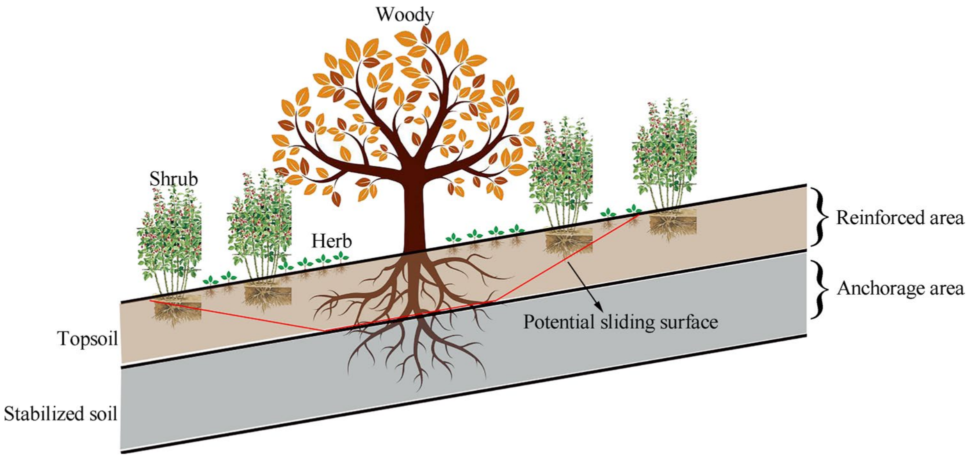


Fig. 2 Schematic diagram of the mechanical reinforcement effect of plants

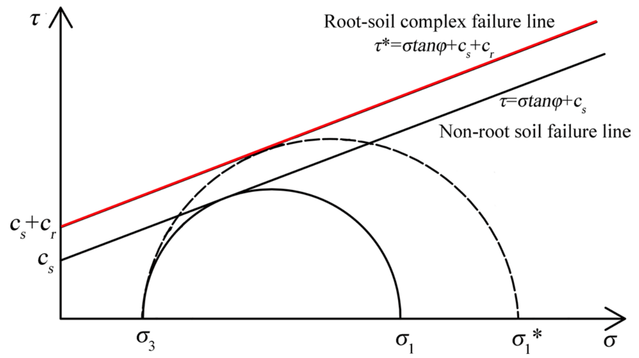


Fig. 3 Reinforcement theory of plant roots

$$\tau = \sigma \tan\varphi + c_s \tag{1}$$

where τ is the shear strength of the soil; σ is the effective normal stress; c_s is the cohesion of the soil; and φ is the friction angle of the soil. When the soil contains roots, a root-soil composite is formed, and the shear strength of the root-soil composite is:

$$\tau^* = \sigma \tan\varphi + c_s + c_r \tag{2}$$

where τ^* is the shear strength of the root-soil composite, and c_r is the root additional cohesion.

When the root system of the plant grows to the position of the stable soil layer, the root mechanical reinforcement effect is the anchoring effect. The anchoring force of the root can be determined by the bonding force between the root and the soil and can be expressed by the Eq. 3:

$$\tau_s(z) = \tau_d(z) + C \tag{3}$$

where z is the depth; $\tau_s(z)$ is the bonding force between the root and the soil; $\tau_d(z)$ is the friction force between the root and the soil; C is the cohesion between the root and the soil. When the friction coefficient between the root and the soil is μ, the maximum static friction force between the root and the soil is:

$$\tau_d(z)_{\max} = \mu \gamma z \tag{4}$$

where γ is the soil bulk density. Then, the maximum bonding force (*df*) of the root segment length (*dl*) is:

$$df = 2\pi r dl(\mu \gamma z + C) \tag{5}$$

where *r* is the radius of the root segment. The vertical component of *df is*:

$$df_z = df \cdot \cos\theta = 2\pi r(\mu \gamma z + C)dz \tag{6}$$

For the mechanical reinforcement of the entire root system, the average radius in the root structure is a function of $P(z)$ along the vertical direction, and the function of root density along the vertical direction is $Q(z)$, then the anchoring force of the root system is:

$$T = 2\pi \mu \gamma \int_0^\infty P(z)Q(z)z dz + 2\pi C \int_0^\infty \int_0^\infty P(z)Q(z)dz \tag{7}$$

In Eq. 7, $P(z)$ and $Q(z)$ were obtained from the field experimental data and the fitting results of the data.

The plant root mechanical reinforcement effect directly reflects the success of ecological engineering construction, so it is necessary to master the research methods of the root mechanical reinforcement effect. In the next section, we summarize the existing research methods of root mechanical reinforcement effect.

4 Research Method of Root Mechanical Reinforcement Effect

4.1 Experimental Research of Root Mechanical Reinforcement Effect

Experimental research is one of the main means to study the root mechanical reinforcement effect, which directly obtains the quantitative results of the root mechanical reinforcement effect through data collection and observation of experimental phenomena. Current experimental research methods include the direct shear test, triaxial shear test, unconfined compressive strength test, and centrifuge test.

4.1.1 Direct Shear Test

The direct shear test is one of the very important research tools in the current study of geotechnical engineering. The direct shear test is simple, economical, effective, and reliable (Zhu et al. 2014). The direct shear test was used to quantify the root mechanical reinforcement effect mainly by shearing the root-soil composite and the unrooted soil under the same experimental conditions to compare the shear strength of the two materials.

Many scholars (Comino and Druetta 2010; Comino et al. 2010; Hao et al. 2021; Tan et al. 2019; Zhu et al. 2022) currently determine the shear effect of root-soil composite by direct shear tests and further investigate the influencing factors of the root mechanical reinforcement effect. On the one hand, the effect of root-soil interaction on the mechanical reinforcement effect was investigated by direct shear test. Endo (1980) analyzed the root-soil interaction, and the results showed that the enhancement of shear strength was closely related to the root density, root tensile force, and friction at the root-soil interface. When the root-soil composite was subjected to shear external force, the roots on the shear surface were subjected to tension, and different roots showed different failure modes. For coarse roots, the root can withstand a large tensile force, so the root-to-soil mechanical reinforcement relied mainly on the friction between the interfaces, while for fine roots because the root can withstand a small tensile force, the root-to-soil mechanical reinforcement relied on the maximum tensile force of the roots. When the root density in the soil increases, the combined force of root mechanical reinforcement on the soil increases, and the mechanical reinforcement effect is enhanced. On the other hand, Yachuan et al. (1996) considered soil and root system as one material, and regarded root-containing soil as a new type of composite, also found that the strength of the root mechanical reinforcement effect could be measured by the size of root content. Characterizing the reinforcement effect of plant roots is to characterize the effect of roots on the mechanical parameters of the soil, and the shear properties of the root-soil composite are also by Mohr–Coulomb law. Li et al. (2013) compared the shear strength of root-soil composite of different herbs and showed that the presence of a root system can increase both the cohesion and internal friction angle of the soil. Xiao et al. (2014) similarly observed this phenomenon, but this seems to be the result observed in only a few studies. Current research prefers that root mechanical reinforcement has a minor effect on the internal friction angle of the soil, and thus, the root mechanical reinforcement effect on the internal friction angle was negligibled (Gray 1974; Lian et al. 2019; Zhang et al. 2010). The root mechanical reinforcement effect is also manifested as an influence on the deformation characteristics of the root-soil composite. Under the action of external force, due to the presence of roots, the strain of the root-soil composite before failure increases compared with that of the unrooted soil (Comino and Druetta 2010; D'Souza et al. 2019; Fannin et al. 2005), which provides more lead time to prevent the occurrence of shallow landslides.

The character of the soil seems to play a more critical role in the shear strength of the root-soil composite. Zhang et al. (2015) found that soil dry density and soil water content influenced the shear strength of the root-soil composite to a greater extent than the role of roots. Although the increase in water content affects the overall strength of the root-soil composite, the amount of root contribution to the shear strength of the soil becomes increasingly important in soils with high water content. And Fan and Su (2008) found that when the root-soil composite reached 80–85% saturation, its shear strength increased by 100% compared to that of unrooted soils. This further confirms the reinforcement effect of plant roots under rainfall conditions.

The shrinkage effect of root mechanical reinforcement was also observed from the direct shear test. Roots are organic materials, and when plants are disturbed by the outside world, roots are prone to decay and fracture (Gehring et al. 2019; Kamchoom et al. 2022; Phan et al. 2022), which leads to the loss of root mechanical reinforcement effect. Zhu et al. (2020) showed that when plant stems were cut, the root mechanical reinforcement effect decreased by 85.9% after 12 months. Therefore, after the construction of ecological engineering, good management measures for plants are needed to prevent the failure of ecological engineering construction.

The direct shear test is easy to operate and is one of the most applied means to measure the root mechanical reinforcement effect. However, in the direct shear test, the shear surface is artificially determined, and there is a certain deviation from the actual damaged surface of the soil, thus resulting in a certain error in the measurement results.

4.1.2 Triaxial Test

Compared with the direct shear test, the triaxial test can strictly control the drainage conditions of the sample, obtain the pore water pressure and effective stress of the soil, and more objectively reflect the actual strength of the soil. The soil used in triaxial experiments is usually cylindrical, and the ratio of height to diameter is 2–2.5. Under the action of predetermined surrounding pressure, the axial load is gradually increased until the soil is sheared. Dynamometer readings, pore water pressure changes, and axial deformations are recorded. The stress corresponding to a 15% strain in the soil sample is usually taken as the maximum stress in the root-soil composite (Salazar & Coffman 2014).

Some current scholars use triaxial tests to study the mechanical properties of the root-soil composite, and the shear strength was increased after root mechanical reinforcement in all (Lian et al. 2019; Negadi et al. 2015). Chen et al. (2007) studied the shear characteristics of the root-soil composite, and with only an 11% change in internal friction angle, while the cohesion can be increased by 9 times, which is the same conclusion as the direct shear test. In the triaxial state, the root mechanical reinforcement effect is related to the distribution characteristics of roots in the soil and the morphology of the root system. Chen et al. (2007) used the method of reshaping root-soil composite, layering plant roots in soil samples, and studied the mechanical effects of the number of reinforcement layers of plant roots on the root-soil composite. There exists an optimal value of root content in the root-soil composite and the shear strength of the root-soil composite reaches the highest. Meanwhile, Lian et al. (2019) found that the mechanical reinforcement effect of cross-distribution is the best among three forms of root system: horizontal, vertical, and cross-distribution. Therefore, in the process of ecological engineering slope protection, the best slope protection effect can be achieved by adjusting the planting density and selecting the best species. But in the process of selecting species, plants suitable for local growing conditions must be selected to prevent plant death caused by the change in the growing environment.

Triaxial testing has many advantages, but it also has its drawbacks. The size of the specimens in the triaxial test is small, and the root distribution is not uniform during the growth of plants, so the measurement of the root mechanical reinforcement effect under the triaxial test may produce large deviations. To achieve the accuracy of the measurement, it is necessary to collect a larger number of samples, which requires a lot of time and experience. At the same time, it is difficult to collect in situ soil in the field for the specimens of triaxial tests. Most of the experiments are remodeled soils and the soil is disturbed, which cannot fully reflect the actual root mechanical reinforcement effect. Therefore, triaxial tests have not been widely used in the study of shear properties of the root-soil composite, and they are used less frequently compared to direct shear tests.

4.1.3 Unconfined Compressive Strength Test

The damage to the root-soil composite in the natural state is mainly caused by vertical loads. The root system of herbs grows in shallow soils where the soil confining pressure is negligible (Rickli and Graf 2009). At the same time, the root system in the root-soil composite exerts a lateral constraint on the soil (Huang et al. 2007). When an element body is removed from the root-soil composite, the lateral restraint of the root system inside the cell and the restraint of the root system outside the element body cancel each other out, which is equivalent to the 0-perimeter confining pressure in triaxial compressive tests. So the unconfined compressive strength test is suitable for determining the strength of the root-soil composite. In the unconfined compressive test, the root-soil composite is placed on the press table position and gradually loaded, and the relationship between force and displacement changes during the loading process is recorded. The plant roots can significantly improve the compressive strength of the root-soil composite through the unconfined compressive strength test (Hu et al. 2013), and the root content is a better parameter to characterize the root mechanical reinforcement effect (Yang et al. 2018). Kleinfelder et al. (1992) found that the unconfined compressive strength of herbs increased non-linearly with increasing root length density of roots less than 0.5 mm in diameter, again observing the importance of root morphology on the mechanical reinforcement effect.

Although the unconfined compressive test is simple to perform, it is still less used than the direct shear test in quantifying the root mechanical reinforcement effect. Because the samples are affected by the size and the accuracy of the quantification of the actual root mechanical reinforcement effect cannot be guaranteed for the main root mechanical reinforcement effect, which cannot be measured by the unconfined compressive test.

4.1.4 Centrifuge Test

Centrifuge tests are now widely used by geotechnical workers. The advantage of centrifuge tests is that the soil material is placed in a high-speed rotating centrifugal acceleration field, which raises the gravitational acceleration level and makes the physical model under the corresponding prototype stress state and the experimental data more reflective of engineering reality. With the recognition of plant root mechanical reinforcement, centrifuge tests have been applied to the study of root-reinforced soil (Wu 2013). The results of centrifuge tests show that the change in soil deformation is mainly caused by the root system increasing the shear strength of the slope. The presence of plant roots makes the transition from progressive block damage to complete sliding block damage (Sonnenberg et al. 2012). It was also observed in the experiments that the slope damage response is very similar for different root additional cohesion (Liang et al. 2017), this finding can provide new solutions for plant species selection and planting density adjustment of slopes. Although the geotechnical centrifuge test is the experimental means that can best reflect the real force state of the soil, the geotechnical centrifuge is a highly expendable test, which often requires a lot of research time for model fabrication and a lot of manpower in the process of model placement. Therefore, it is important to design scientific fabrication means in the model fabrication to avoid the possibility of test failure.

4.2 Theoretical Calculation Model of Root Mechanical Reinforcement Effect

To determine the root mechanical reinforcement effect, it is necessary to quantify the root additional cohesion. Many scholars currently use theoretical calculation model to calculate the magnitude of root additional cohesion, and the current calculation models include the Wu-Waldron model (WWM) (Waldron 1977; Wu et al. 1979), energy method model (Ekanayake and Phillips 1999, 2002), fiber bundle model (FBM) (Pollen and Simon 2005), root bundle model (RBM) (Schwarz et al. 2010), the analytical fiber bundle model (Cohen et al. 2011), RBM based on Weibull function (RBMW) (Schwarz et al. 2013), and energy-based fiber bundle model algorithms (Ji et al. 2020). With the deepening of research, Meijer et al. (2021) established a new constitutive framework, assigned different constitutive models to soil and roots, and obtained the comprehensive stress–strain relationship of root constituents. Since WWM, FBM, and RBMW are widely used in the current research compared with other models and the calculation process is simple, the quantitative process and results of the three models are discussed this time.

4.2.1 WWM

Under the action of shearing force, the soil body on the shearing surface is dislocated and moved, the root system is gradually deformed and pulled, and the tensile force of the root bears part of the shearing force. The quantitative equation of the mechanical reinforcement effect of a single root is:

$$c_r = \frac{F}{A}\left[\sin(90^\circ - \psi) + \cos(90^\circ - \psi)\tan\varphi\right] \tag{8}$$

$$\psi = \arctan\left[\frac{1}{k + \frac{1}{\arctan i}}\right] \tag{9}$$

where F is the tensile strength of the root. A is the shear surface area of the soil block. ψ is the deformation angle of the root relative to the vertical direction of the soil surface after deformation. i is the angle between the root before deformation and the horizontal direction of the shear plane. k ($k = x / H$, where x is the displacement of the root along the shear direction, and H is the height of the shear zone) is the shear deformation ratio.

When there are multiple roots on the shear surface of the soil block, the WWM assumes that the roots on the shear surface are broken at the same time, and its quantitative equation is:

$$c_r = \frac{\sum_{i=1}^{N} F_i}{A}\left[\sin(90^\circ - \psi) + \cos(90^\circ - \psi)\tan\varphi\right] \tag{10}$$

where F_i is the tensile force of the i-th root. N is the total number of roots on the shear plane, and the $\left[\sin(90^\circ - \psi) + \cos(90^\circ - \psi)\tan\varphi\right]$ terms are called root-direction factors, denoted as R_f. Equation 10 is abbreviated as:

$$c_r = R_f\frac{\sum_{i=1}^{N} F_i}{A} \tag{11}$$

The root-direction factor includes the parameter ψ, but under natural growth conditions, the measurement of the ψ value for each root cannot be achieved, especially for herbs, which have a large number of intricate root systems. Therefore, to simplify the WWM, many scholars have conducted experimental research on roots from different angles. The results are shown in Table 1. At present, many scholars use a constant value of 1.2 to replace the root-direction factor. However, Thomas and Pollen-Bankhead (2010) made a sensitivity analysis of the variables of the root-direction factor and found that when 1.2 was not fully applicable to the quantification of the root mechanical reinforcement effect. In the current study, some scholars use a constant value of 1.0 to replace this item (Bischetti et al. 2009; Comino et al. 2010; Hao et al. 2022) and simplify the quantitative results of the WWM to:

$$c_r = 1.0\frac{\sum_{i=1}^{N} F_i}{A} \tag{12}$$

When the root-soil composite is subjected to shear force, the roots on the shear plane are not simultaneously fractured (Pollen and Simon 2005), so the quantification result of the root mechanical reinforcement effect by the WWM is high. The degree of overestimation of the WWM is determined by the specific species, and the Docker and Hubble (2008) study found that the magnitude of the WWM overestimation is 50–215%. Although the WWM overestimates the root mechanical reinforcement effect, it is still widely used today due to its easily measured parameters required to quantify the root mechanical reinforcement effect (Löbmann et al. 2020b; Su et al. 2021; Zhang et al. 2019a). To reduce the quantification error of the WWM on the root additional cohesion, some scholars have introduced a correction factor k' into the WWM

Table 1 Statistics of root-direction factors

Internal friction angle (°)	Deformation angle (°)	Root-direction factors	References
20–40	40–70	0.92–1.31	(Wu et al. 1979)
20–40	40–70	1–1.3	(Gray and Leiser 1982)
> 35	50–60	1.2	(Greenway 1987)
16.0	43–66	1.00	(Abernethy and Rutherfurd 2001)
20–40	40–70	1.2	(Simon and Collison 2002)
27–39.6	1–25	0.62–0.98	(Docker and Hubble 2008)
5–45	10–90	The root factor is close to 1	(Thomas and Pollen-Bankhead 2010)

(Bischetti et al. 2009; Hao et al. 2021). The correction WWM is proposed:

$$c_r = 1.0k' \frac{\sum_{i=1}^{N} F_i}{A} \tag{13}$$

To determine the correction factor of the WWM, the results of root mechanical reinforcement effect (c_{r_o}) determined by experimental studies and more accurate model calculations are currently used to compare the results of root mechanical reinforcement effect (c_{r_WWM}) quantified by WWM:

$$k' = \frac{c_{r\_\mathrm{o}}}{c_{r\_\mathrm{WWM}}} \tag{14}$$

The correction factors in the statistical current study are shown in Table 2. It can be seen that the correction factors ranged from 0.17 to 0.85, and the correction factors varied depending on the plants. It was shown through subsequent studies that the error in the predicted values of root additional cohesion was significantly reduced after the correction factor was introduced into the WWM (Hao et al. 2021; Zhang et al. 2020).

4.2.2 FBM

Although the WWM gives valuable estimates of the root mechanical reinforcement effect, the actual root failure mechanism needs to be considered to obtain results more suitable for engineering applications. Pollen and Simon (2005) applied the FBM proposed by Peirce (1926) and Daniels (1945) to the quantification of the root mechanical reinforcement effect. The FBM considers that when the root-soil composite is subjected to the external load, part of the load is transferred to the plant root system. When the load continues to increase, one or more roots on the shear plane break due to reaching the ultimate tensile strength, and the tensile force borne by the broken roots is redistributed and borne by the unbroken roots. Until further fracture of the root and distribution of force, this process is repeated until all the roots on the shear plane are fractured. The maximum tensile force that the root system can bear during the loading process is the maximum external force that the root can bear, which determines the strength of the root mechanical reinforcement effect.

There are three distributions of forces in the FBM. They are distributed by root area (Hidalgo et al. 2001; Mickovski et al. 2009), root diameter (Pollen and Simon 2005), and root number (Daniels 1945). The calculation equations for the three distributions methods are as follows (Mao et al. 2012):

$$c_{rFBM,byrootCSA} = 1000R_f \times \max\left(T_{rj} \sum_{n=1}^{j} RAR_n\right) \tag{15}$$

$$c_{rFBM,byrootdiameter} = 1000R_f \times \max\left(T_{rj} RAR_j \sum_{n=1}^{j} d_n\right) \tag{16}$$

$$c_{rFBM,byrootnumber} = 1000R_f \times \max\left(T_{rj} RAR_j j\right) \tag{17}$$

where $c_{rFBM,byrootCSA}$, $c_{rFBM,byrootdiameter}$, and $c_{rFBM,byrootnumber}$ were the root mechanical reinforcement effect distributed by

Table 2 Statistics of WWM correction factors for different species

Species	Name	Correction factor	References
Herb	*Poa annua*	0.51 ± 0.07	(Hao et al. 2021)
Herb	*Suaeda glauca*	0.17 ± 0.08	(Hao et al. 2021)
Herb	*Digitaria sanguinalis*	0.52 ± 0.04	(Hao et al. 2021)
Herb	*Lotus corniculatus*	0.55	(Comino et al. 2010)
Herb	*Trifolium pratense*	0.4	(Comino et al. 2010)
Herb	*Medicago sativa*	0.68	(Comino et al. 2010)
Herb	*Festuca pratensis*	0.99	(Comino et al. 2010)
Herb	*Lolium*	0.85	(Comino et al. 2010)
Herb	*Switchgrass*	0.48	(Pollen and Simon 2005)
Shrub	*Magnolia multiflora*	0.50 ± 0.19	(Zhang et al. 2020)
Shrub	*Senna bicapsularis*	0.33 ± 0.14	(Zhang et al. 2020)
Woody	*Broussonetia papyrifera*	0.45	(Po et al. 2019)
Woody	*Cottonwood*	0.60–0.61	(Pollen and Simon 2005)
Woody	*Sycamore*	0.75–0.76	(Pollen and Simon 2005)
Woody	*River birch*	0.61–0.62	(Pollen and Simon 2005)
Woody	*Pine*	0.81–0.82	(Pollen and Simon 2005)
Woody	*Black willow*	0.75	(Pollen and Simon 2005)

root area, root diameter, and root number, respectively. The 1000 is the unit conversion from MPa to kPa, T_r is the tensile strength of the root, RAR is the root area ratio, and d is the diameter of the root. Mao et al. (2012) used WWM and FBM with three force distribution methods to quantify the root mechanical reinforcement effect of mixed forest roots, and the results showed that the four types of models had different quantification results of the root mechanical reinforcement effect. And the performance is $c_{r,FBM,byrootnumber} < c_{r,FBM,byrootdiameter} < c_{r,FBM,byrootCSA} < c_{r-WWM}$. Mickovski et al. (2009) observed that root fracture during the experiment was initiated by small-diameter roots. The FBM of the three distribution methods was studied and found that the root fracture started from the large-diameter root when distributed by root area. When the root diameter distribution is adopted, according to the different fitting parameters of the root tensile force in the FBM, some roots start to break from large-diameter roots, and some roots start to break from small-diameter roots. However, by the method of distribution according to the number of roots, the root fracture starts from the small-diameter root, which is more in line with the experimental results. Therefore, it is optimal to use the FBM allocated by the number of roots. The FBM gives more accurate quantitative results than the WWM, but Comino et al. (2010) found that the FBM underestimated the root mechanical reinforcement effect. This further indicates that the root mechanical reinforcement effect depends not only on root tensile strength and failure process but also on root structure and root-soil interaction (Loades et al. 2010). Although FBM quantified root mechanical reinforcement effect is not entirely accurate in some cases, the root mechanical reinforcement effect quantified using FBM in engineering is not necessarily unreliable. Because of its low quantitative results, it can better ensure the stability of the slope in the project.

4.2.3 RBMW

The RBMW was proposed by Schwarz et al. (2013). In the RBMW, the root failure characteristics in tension are represented by the Weibull survival function, which avoids the interference of factors such as the curvature of the root. Strain loading is used in the RBMW calculation so that the relationship between the force and the displacement of the root can be given. The premise of the RBMW is that the roots do not interfere with each other, and the quantification of the root mechanical reinforcement effect is based on the maximum tensile force and elastic coefficient of a single root (Hooke law) (Giadrossich et al. 2013). The relationship between the diameter of the root (ϕ), the maximum tensile force of the root ($F_{\max}$), and the modulus of elasticity (k) can be expressed as:

$$F_{\max}(\phi) = F_0\phi^{\alpha} \tag{18}$$

$$k(\phi) = k_0 + k_i\phi \tag{19}$$

where, F_0, α, k_0, and λ are the fitting parameters.

The total tensile force F_{tot} of the root on the section mainly depends on the diameter distribution of the root on the section, the displacement (Δx), and the Weibull survival function of the root ($S(\Delta x^*)$), and the relationship is:

$$F_{tot}(\Delta x) = \sum_{i=1}^{N} F\left(\phi_i, \Delta x\right)S(\Delta x^*) \tag{20}$$

where N is the number of roots on the soil profile. $F\left(\phi_i, \Delta x\right)$ is the tension function of a single root. About $S(\Delta x^*)$ is a function of normalized displacement (Δx^*):

$$S(\Delta x^*) = \exp\left[-\left(\frac{\Delta x^*}{\lambda^*}\right)^{\omega}\right] \tag{21}$$

$$\Delta x^* = \frac{\Delta x}{\Delta x^{fit}_{\max}(\phi)} \tag{22}$$

$$\Delta x^{fit}_{\max}(\phi) = \frac{F_0\phi^{\alpha}}{k_0 + k_i\phi} \tag{23}$$

where λ^* is the scale factor and ω is the Weibull exponent. RBMW is a comprehensive model considering parameters, and it is widely used at present. However, it is mainly used in the quantification of the root mechanical reinforcement effect of woody (Cislaghi et al. 2017; Dazio et al. 2018; Vergani et al. 2016, 2017b; Yamase et al. 2019). At the same time, the RBMW assumes that there is no mutual influence between roots and roots in the process of quantifying the root mechanical reinforcement effect. The roots of herbs are complex and intersect with each other, and the roots and roots affect each other. Therefore, the RBMW is not fully suitable for quantifying the root mechanical reinforcement effect of herbs, and the quantification accuracy of herbs needs to be verified.

4.3 Numerical Simulation Study of Root Mechanical Reinforcement

Experimental studies are characterized by high operational intensity, and numerical simulation methods are gradually applied to the calculation of the root mechanical reinforcement effect. Numerical simulation combines the concepts of finite elements and discrete elements to achieve the purpose of solving various problems in engineering using numerical simulation and image display. Numerical simulation has the characteristics of fast solution speed, low economic cost, intuitive results, simple data processing, easy data acquisition, etc., and is now widely used in practical engineering. In the numerical simulation, there is no clear limitation on the size of the model. Current scholars use numerical simulation methods to study root mechanical reinforcement, and the model range can be as small as the size of the test specimen and as large as the size of the whole slope.

The main research method for the root mechanical reinforcement effect is the direct shear test, so some scholars use numerical simulation to simulate the direct shear test of root-soil composites. Through the numerical simulation of direct shear tests by the finite element method, Sui et al. (2021) found that the shear force of the root-soil composite showed a trend of rapid initial growth and gradually stable change. The results of the direct shear test were compared, and it is found that the average error between the numerical simulation results and the experimental results is only 2.9%, which indicates that the numerical simulation can be applied to the study of the shear strength of the root-soil composite. Mao et al. (2014) also suggested numerical simulation as an auxiliary means to study the plant root mechanical reinforcement effect. At present, the numerical simulation methods of root mechanical reinforcement mainly include the finite element method and discrete element method. The finite element is a mathematical approximation method to simulate the real physical system, while the discrete element is a numerical simulation method specially used to solve the problem of discontinuous media. The main differences between finite elements and discrete elements are as follows: discrete element refers to the complementary continuity between each element and there is no limit on the number of elements, while the number of elements in the finite element can be counted. To compare the application effects of finite elements and discrete elements in the root mechanical reinforcement, Mao et al. (2014) simulated the three-dimensional direct shear test through the finite element and discrete element, and found that the two methods are relatively reliable, but the calculation time of discrete element is long and the parameters are difficult to obtain. Mickovski et al. (2011) simulated direct shear tests of root-soil composites and unrooted soils by finite element method, using roots as linear elastic material and soil as a plastic medium, and found that 2D and 3D models obtained similar results. The validity of 2D model modeling is illustrated so that the shortcomings of the 3D model such as long calculation time and complex model establishment can be solved.

In addition to simulations of direct shear tests, Yang et al. (2018) and Świtała (2020) simulated unconfined compressive tests and triaxial tests by the finite element method, respectively. The distribution pattern of roots has an important influence on the strength of the root-soil composite (Yang et al. 2018), and horizontal and lateral fine roots have a stronger effect on soil consolidation than vertical roots. The layered existence of roots can also induce the network development of shear zones, and the higher the root content, the more complex the network structure, and the existence of roots changes the stress pattern of the soil (Świtała 2020). In the numerical simulation study of the root mechanical reinforcement effect, it is necessary to consider the influence of the direction position of the root and the root type. However, due to the large variety of plants and the influence of root growth by the external environment, there are still challenges in the research of root mechanical reinforcement numerical simulation. The root morphological parameter that was ignored can bring significant deviations to the actual plant root mechanical reinforcement effect (Mao et al. 2014).

To test the slope stabilization effect of roots in ecological engineering, some scholars studied the influence of roots on soil stability in combination with practical engineering applications. Roots can effectively improve the stability of topsoil and reduce the damage range of topsoil (Shahriar et al. 2013; Tang and Xiong 2011). The shape of the slope will affect the slope protection effect of ecological engineering. Yang et al. (2018) conducted a numerical simulation on the slope reinforced by herbs roots by the finite element method and found that when the slope angle is 27–34°, the root mechanical reinforcement effect of the herb is the most significant. And the herbs root mechanical reinforcement effect on the upslope and middle slope of the slope is more significant than that on the downslope, so the appropriate plants can be selected according to the different reinforcement positions.

5 Discussion

Soil eco-engineering reinforcement is an environmentally friendly treatment measure, which is now widely studied and applied. This paper summarizes the research methods of root mechanical reinforcement in ecological engineering.

5.1 Quantification Results of Root Mechanical Reinforcement Effect

Table 3 presents the results of the current study using three research methods to quantify root additional cohesion. From the analysis in Table 3, it can be obtained that plant roots can play a significant role in reinforcing the surface soil. The in situ shear test is currently mainly applied among herbs, probably because the depth of the shear surface in the in situ shear test is usually small due to the limitation of the shear box size. And the root growth depth of herbs is shallow, so the in situ shear test can better characterize the mechanical reinforcement effect of herbs. While for larger woody and shrubs, the root growth depth is larger, so it is a troublesome

Table 3 Statistics of the results of root additional cohesion quantified by different research methods

Quantification methods	Species	Name	Root additional cohesion (kPa)	References	Remarks
In situ shear tests	Herb	*vetiver Ziznoides (L) Nash*	2.25; 3.58; 5.19; 8.02; 7.04	(Teerawattanasuk et al. 2014)	The quantitative results from left to right are the results of the root additional cohesion when the plants were grown for 2, 3, 4, 5, and 6 months, shear boxes were 300 mm × 300 mm with 100 mm in height
	Herb	*Brachiaria ruziziensis*	1.27; 1.96; 1.15; 1.56; 1.15	(Teerawattanasuk et al. 2014)	
	Herb	*vetiver Ziznoides (L) Nash and Brachiaria ruziziensis mixed planting*	2.71; 5.37; 4.38; 9.23; 6.98	(Teerawattanasuk et al. 2014)	
	Herb	*Lotus corniculatus*	10.2 ± 3.40	(Comino et al. 2010)	The shear box was 300 mm × 300 mm with 100 mm in height
	Herb	*Trifolium pratense*	7.60 ± 2.80	(Comino et al. 2010)	
	Herb	*Medicago sativa*	7.80 ± 2.30	(Comino et al. 2010)	
	Herb	*Festuca pratensis*	8.90 ± 1.90	(Comino et al. 2010)	
	Herb	*Lolium perenne*	8.60 ± 2.30	(Comino et al. 2010)	
Triaxial tests	Woody	*Robinia pseucdoacacia*	12.70; 30.10; 46.80	(Lian et al. 2019)	The quantified results are shown from left to right for the root mechanical reinforcement methods of horizontal reinforced, vertical reinforced, and crossed reinforced under soil moisture content of 16% (top) and saturated conditions (bottom). (Non-root natural growth form)
	Woody	*Robinia pseucdoacacia*	6.10; 10.80; 14.20	(Lian et al. 2019)	
Unconfined compressive strength test	Herb	*Setariaanceps Stapf ex Massey L*	3.93	(Duan et al. 2019)	The average value of root additional cohesion from 0 to 50 cm
	Herb	*Dactylisglomerata L*	3.18	(Duan et al. 2019)	
	Herb	*Medicago sativa L*	1.05	(Duan et al. 2019)	
WWM	Herb	*P. paspaeoides*	4.42	(Zhong et al. 2016)	The average value of root additional cohesion from 0 to 30 cm
	Herb	*C. dactylon*	3.16	(Zhong et al. 2016)	
	Herb	*H. compressa*	4.90	(Zhong et al. 2016)	
	Herb	*H. altissima*	4.69	(Zhong et al. 2016)	
	Shrub	*Cotoneaster dammeri*	1.56	(Comino and Marengo 2010)	The average value of root additional cohesion from 0 to 40 cm
	Shrub	*Rosa canina*	1.03	(Comino and Marengo 2010)	
	Shrub	*Juniperus horizontalis*	1.13	(Comino and Marengo 2010)	
	Woody	*P. tomentosa*	10.26	(Wang et al. 2019)	
	Woody	*R. pseudoacacia*	15.12	(Wang et al. 2019)	
	Woody	*O. Europaea*	3.76	(Wang et al. 2019)	
	Herb	*Lotus corniculatus*	7.10; 6.90; 6.00	(Comino et al. 2010)	From left to right WWM models with roots factors of 1.2/1.15 and 1.0, respectively
	Herb	*Trifolium pratense*	10.20; 9.80; 8.50	(Comino et al. 2010)	
	Herb	*Medicago sativa*	20.40; 19.60; 17.00	(Comino et al. 2010)	
	Herb	*Festuca pratensis*	12.00; 11.50; 10.00	(Comino et al. 2010)	
	Herb	*Lolium perenne*	17.20; 16.50; 14.30	(Comino et al. 2010)	
Corrected WWM	Woody	*Fagus sylvatica L*	21.32	(Bischetti et al. 2009)	The mean value of root additional cohesion from 0 to 130 cm with a correction factor of 0.5
	Woody	*Castanea sativa Mill*	11.31	(Bischetti et al. 2009)	
	Woody	*Ostrya carpinifolia Scop*	13.76	(Bischetti et al. 2009)	
	Woody	*Picea abies (L.) Karst*	19.44	(Bischetti et al. 2009)	
	Woody	*Larix decidua Mill*	23.16	(Bischetti et al. 2009)	

Table 3 (continued)

Quantification methods	Species	Name	Root additional cohesion (kPa)	References	Remarks
FBM	Woody	*Chestnut*	5–25	(Bassanelli et al. 2013)	10–20 cm root mechanical reinforcement effect
	Woody	*P. tomentosa*	6.19	(Wang et al. 2019)	
	Woody	*R. pseudoacacia*	10.35	(Wang et al. 2019)	
	Woody	*O. Europaea*	2.31	(Wang et al. 2019)	
	Herb	*Lotus corniculatus*	3.30	(Comino et al. 2010)	
	Herb	*Trifolium pratense*	3.40	(Comino et al. 2010)	
	Herb	*Medicago sativa*	11.60	(Comino et al. 2010)	
	Herb	*Festuca pratensis*	9.90	(Comino et al. 2010)	
	Herb	*Lolium perenne*	12.20	(Comino et al. 2010)	
	Shrub	*Cotoneaster dammeri*	0.98	(Comino and Marengo 2010)	The average value of root additional cohesion from 0 to 40 cm
	Shrub	*Rosa canina*	0.75	(Comino and Marengo 2010)	
	Shrub	*Juniperus horizontalis*	0.76	(Comino and Marengo 2010)	
Numerical simulation	–	–	0.09; 0.25; 0.31	(Mao et al. 2014)	The orientation of roots in the modeling process was divided into roots in the opposite direction of 45° relative to the shear direction, roots in the perpendicular direction to the shear direction, and roots in the same direction of 45° relative to the shear direction, 36 roots in 3 rows in the center of the boxes with an equal interval between rows of 0.1 m. The root admissibility characteristics were distinguished and different cell types were assigned, and the quantified results from left to right were in the order of root model as beam, truss, and cable. (non-root natural growth form)
	–	–	1.38; 1.69; 1.50	(Mao et al. 2014)	
	–	–	1.80; 1.78; 1.75	(Mao et al. 2014)	

process to make specimens that meet the requirements of the in situ shear test. Theoretical calculation model is still widely used and apply to any species, because the advent of theoretical calculation model has made it possible to quantify root additional cohesion without the need to conduct a large number of tedious tests, making the problem simpler to handle. Therefore, to better characterize the root mechanical reinforcement effect and maintain the stability of the soil, it is necessary to improve the calculation accuracy of the theoretical calculation model, and in the calculation process, the influence of external environment changes on the calculation effect should be taken into account. Numerical simulations are still relatively few and present great challenges, and the study of numerical simulations needs to consider good physical–mechanical parameters between the roots and the soil. At the same time, it is still a complex task to reasonably model the root system structure and apply it to numerical simulations. As can be seen from the results of root additional cohesion in Table 3, the root additional cohesion is affected by a variety of factors. These include differences in species (Comino and Marengo 2010; Comino et al. 2010), type of root growth (Lian et al. 2019), the direction of root growth (Lian et al. 2019; Mao et al. 2014), growth stage (Teerawattanasuk et al. 2014) and soil moisture content (Lian et al. 2019; Wang et al. 2019), etc. The natural growth pattern of the root system was considered, and the range of root additional cohesion of woody was the maximum, between 2.31 and 25 kPa. The same plant *Lolium perenne* was compared, and the minimum error between the quantification results of WWM and FBM for root additional cohesion and the quantification results of in situ shear test was 31.19% and 11.93%, respectively, again confirming that the FBM model gave more accurate quantification results than WWM.

5.2 Influencing Factors of Root Mechanical Reinforcement Effect

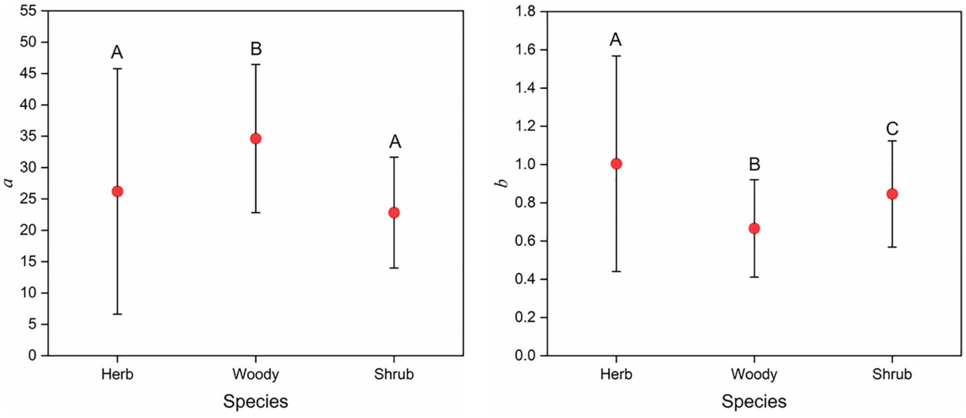
Combining the three methods for the study of root additional cohesion in Sect. 4, it can be seen that the magnitude of root additional cohesion depends on the mechanical properties of roots in the soil and root morphology, for which numerous scholars have done a lot of current measurements (Bischetti et al. 2009, 2005; Bordoni et al. 2016; Chiaradia et al. 2016; Cislaghi et al. 2017; Comino and Marengo 2010; Comino et al. 2010; Zhang et al. 2019b). The measurement of the mechanical properties of plant roots focused on the measurement of the tensile strength of the root system, characterized by the tensile strength, which is one of the necessary parameters in the model calculations. Most of the research results show that the tensile strength of the root system shows a power-law function law concerning diameter, and the results can be characterized by the equation $T = ad^{-b}$, where T is the tensile strength of the root and a and b are the fitting coefficients. Table 4 gives the results of the tensile strength measurements of roots in some of the current studies. The fitting accuracy between the tensile strength and diameter of plant roots is between 0.14 and 0.97, and there is a weak correlation between tensile strength and diameter, which also leads to a large error in quantifying the root additional cohesion using the theoretical calculation model. In the current study, most of the experimental data comes from laboratory measurements, and only a small portion of the data comes from the field. Laboratory measurements require roots to be collected in the field and brought back, which may also lead to errors, and how to obtain excellent field root tensile force data needs further study. The fitted coefficients of root tensile strength for different species in the statistical table are shown in Fig. 4, the fitted coefficients a and b of herbs have the largest standard deviations, indicating that the mechanical properties of roots may vary more significantly among different herbs. The mean values of a for herbs, woody, and shrubs are 26.21, 34.63, and 22.83, respectively, and the maximum a value exists for woody. The magnitude of b values was compared; the mean values of b for herbs, woody, and shrubs are 1.00, 0.67, and 0.85, respectively; and the smallest b value exists for woody; thus, it can be known that for the same diameter, the roots of woody exist greater tensile strength.

The root geometric parameters that are widely used in characterizing the root mechanical reinforcement effect are root density, root length density, root area ratio, and root growth depth. Root density is the dry weight (kg/m^3) of roots in a single volume of soil. Its measurement method is simple (Yang et al. 2018; Zhu and Zhang 2016), but it cannot characterize the diameter and number of roots. For example, taproot type plants may have lower root additional cohesion due to the existence of tap roots, while fibrous root plants have greater root additional cohesion due to the existence of a large number of fine roots. The root additional cohesion of taproot type plants and fibrous root plants from the root density was compared will lead to errors. To reflect the number and structure of roots, root length density was used. The root length density is the length of the root per unit volume of soil (km/m^3). It has been proved that root length density is directly related to the stability of surface soil (Hamidifar et al. 2018; Ola et al. 2015), and it is a good parameter to characterize the hydraulic reinforcement characteristics of roots (which is also an important role of roots in slope soil reinforcement, and it is further explained in Sect. 5.3 below) (Indraratna et al. 2006). Therefore, root length density may be a good root parameter to link the mechanical reinforcement and hydraulic reinforcement of roots. With the application of the section method in root morphology investigation, the root area ratio was used to characterize the effectiveness of root mechanical reinforcement (Ye et al.

Table 4 Plant root tensile strength coefficient statistics, tensile strength fitting equation is $T = ad^{-b}$, where a and b are fitting coefficients

Species	Name	Number of samples	a	b	R^2	Data source	References
Herb	*vetiver Ziznoides (L) Nash*	88	15.24	0.89	0.81	Laboratory	(Teerawattanasuk et al. 2014)
Herb	*Brachiaria ruziziensis*	39	16.71	0.44	0.90	Laboratory	(Teerawattanasuk et al. 2014)
Herb	*P. paspaeoides*	118	25.36	0.77	0.95	Laboratory	(Zhong et al. 2016)
Herb	*C. dactylon*	141	23.44	0.71	0.98	Laboratory	(Zhong et al. 2016)
Herb	*H. altissima*	102	8.75	1.47	0.97	Laboratory	(Zhong et al. 2016)
Herb	*H. compressa*	128	13.83	1.24	0.97	Laboratory	(Zhong et al. 2016)
Herb	*Lotus corniculatus*	70	3.52	1.41	0.40	Laboratory	(Comino et al. 2010)
Herb	*Trifolium pratense*	57	12.52	0.75	0.32	Laboratory	(Comino et al. 2010)
Herb	*Medicago sativa*	53	10.57	1.54	0.82	Laboratory	(Comino et al. 2010)
Herb	*Festuca pratensis*	53	2.58	2.01	0.94	Laboratory	(Comino et al. 2010)
Herb	*Lolium perenne*	35	1.93	2.10	0.91	Laboratory	(Comino et al. 2010)
Herb	*Tripsacum dactyloides*	76	43.10	1.00	0.39	Field	(Pollen and Simon 2005)
Herb	*Panicum virgatum*	72	35.20	1.78	0.71	Field	(Pollen and Simon 2005)
Herb	*L. perenne*	48	32.52	0.63	0.54	Laboratory	(Zhang et al. 2019a)
Herb	*V. zizanioides*	45	41.60	0.34	0.39	Laboratory	(Zhang et al. 2019a)
Herb	*P. notatum*	37	68.46	0.33	0.63	Laboratory	(Zhang et al. 2019a)
Herb	*Setariaanceps Stapf ex Massey L*	–	56.71	0.51	0.60	Laboratory	(Duan et al. 2019)
Herb	*Dactylisglomerata L*	–	53.09	0.53	0.65	Laboratory	(Duan et al. 2019)
Herb	*Medicago sativa L*	–	32.80	0.63	0.72	Laboratory	(Duan et al. 2019)
Woody	*Eucalyptus camaldulensis/Melaleuca ericifolia**	–	49.39	0.77	0.41	Laboratory	(Abernethy and Rutherfurd 2001)
Woody	*Fagus sylvatica L*	235	41.57	0.98	0.65	Laboratory	(Bischetti et al. 2009)
Woody	*Castanea sativa Mill*	47	17.86	0.53	0.49	Laboratory	(Bischetti et al. 2009)
Woody	*Ostrya carpinifolia Scop*	42	21.89	0.43	0.55	Laboratory	(Bischetti et al. 2009)
Woody	*Picea abies (L.) Karst*	92	28.10	0.72	0.52	Laboratory	(Bischetti et al. 2009)
Woody	*Larix decidua Mill*	43	33.45	0.75	0.56	Laboratory	(Bischetti et al. 2009)
Woody	*Platycladus orientalis*	–	21.94	0.48	0.48	Laboratory	(Ji et al. 2012)
Woody	*Robinia pseudoacacia*	–	50.20	0.28	0.36	Laboratory	(Ji et al. 2012)
Woody	*Salix nigra*	78	45.90	1.1	0.75	Field	(Pollen and Simon 2005)
Woody	*Populus fremontii*	90	18.90	0.64	0.29	Field	(Pollen and Simon 2005)
Woody	*Plantanus occidentalis*	36	50.50	0.94	0.58	Field	(Pollen and Simon 2005)
Woody	*Pinus palustris miller*	147	30.00	0.99	0.14	Field	(Pollen and Simon 2005)
Woody	*Fraxinus latifolia*	101	24.30	0.50	0.66	Field	(Pollen and Simon 2005)
Woody	*Betula nigra*	51	45.80	0.66	0.30	Field	(Pollen and Simon 2005)
Woody	*Salix exigua*	44	25.20	0.68	0.46	Field	(Pollen and Simon 2005)
Woody	*Liquidamber stryaciflua*	56	52.10	1.04	0.62	Field	(Pollen and Simon 2005)
Woody	*P. tomentosa*	–	27.42	0.39	0.44	Laboratory	(Wang et al. 2019)
Woody	*R. pseudoacacia*	–	40.31	0.28	0.45	Laboratory	(Wang et al. 2019)
Woody	*O. Europaea*	–	33.14	0.50	0.48	Laboratory	(Wang et al. 2019)
Shrub	*Rubus discolor*	30	19.50	0.69	0.17	Field	(Pollen and Simon 2005)
Shrub	*Spirea douglasii*	50	22.90	0.54	0.31	Field	(Pollen and Simon 2005)
Shrub	*Cotoneaster dammeri*	39	37.77	1.28	0.59	Laboratory	(Comino and Marengo 2010)
Shrub	*Rosa canina*	124	19.19	0.83	0.52	Laboratory	(Comino and Marengo 2010)
Shrub	*Juniperus horizontalis*	104	14.79	0.89	0.27	Laboratory	(Comino and Marengo 2010)

[*] The test results obtained no significant difference in tensile strength between the two woody, so two names are given in the name column



a) b)

Fig. 4 Tensile strength fitting coefficient statistics for different species of plant root, tensile strength fitting equation is $T=ad.^{-b}$, where a and b are fitting coefficients. (Capital letters represent significant differences between species, with a significance level of 0.01)

2017). The root area ratio is the root area per unit soil area (m^2/m^2). Current studies have shown that there is a good correlation between root area ratio and shear strength and slope soil stability, but root area ratio cannot reflect root diameter. Therefore, the mechanical reinforcement effect of herbs with a large number of fibrous roots may be underestimated. Root growth depth is an important parameter to describe the root mechanical reinforcement effect, and the maximum growth depth of roots varies with species. The lower the soil water content, the deeper the root growth depth of plants to obtain sufficient water, but the increase in soil hardness leads to an increase in resistance at the front end of root growth and therefore slow root growth (Bengough et al. 2011; Popova et al. 2016). Although the distribution characteristics of the root systems of different plants are different, 70% of the roots are often located at the 0 ~ 20 cm position in the soil profile (Ye et al. 2017).

In studying the plant root mechanical reinforcement effect, plant and soil are the basic constituent materials for studying the root mechanical reinforcement effect, and the two form a root-soil composite, and the properties of the two materials most directly reflect the stability of ecological engineering. During growth, plants are most susceptible to disturbances in the external environment, and changes in the external environment cause changes in the internal material content of roots, and the tensile strengths of roots are closely related to the cellulose content of roots (Genet et al. 2005; Zhang et al. 2014). When the external environment is not suitable for the natural growth and development of the plant, the root cellulose content decreases and thus, the root mechanical reinforcement effect decreases. Similarly, soil properties are also a key factor in the root mechanical reinforcement effect. The bonding force between different soils and roots is different, and when plant roots grow in moderately bonded soils, the roots are in full contact with the soil, thus making the root mechanical reinforcement effect higher. While in some gravelly soils with large pores, the roots are not in full contact with the soil, making the mechanical reinforcement effect lower. At the same time, the nature of the soil can change the growth structure of the root system, which indirectly affects the root mechanical reinforcement effect. When the soil is dense, the soil is stronger, and the root tip needs to penetrate the soil during growth and development, which makes the root tip subject to greater resistance (Bengough et al. 2011; Popova et al. 2016). This results in reduced root growth depth and extension, thus reducing the extent of root mechanical reinforcement.

Although most of the current findings indicate that plant roots have a significant reinforcement effect on soil air to improve surface soil stability, Guo et al. (2020) seem to observe a different result. The reinforcement effect of plants on top soil seems to fail or even play a negative role under rainfall conditions, probably because root decay forms a large number of pores inside the soil, which increases the infiltration rate and hydraulic conductivity of the soil (Feng et al. 2020) and the reinforcement effect of plant root was also reduced (Kamchoom et al. 2022). It is necessary to compare the positive effect of plant roots on soil reinforcement under rainfall conditions with the negative effect of rainwater infiltration on soil strength, to determine which effect plays a dominant role and thus ensure the rationality of ecological engineering construction.

5.3 Another Reinforcement Effect of the Plant — Hydraulic Reinforcement

This paper focuses on the mechanical reinforcement of plants root and introduces the research methods of the mechanical reinforcement effect. Existing research results show that plants can also bring a hydraulic reinforcement effect on soil (Gonzalez-Ollauri and Mickovski 2017; Ng 2017; Ng et al. 2016a, 2016b, 2013; Ni et al. 2018). To compare the characteristics of the two kinds of reinforcement effects, Table 5 summarizes the characteristics of the two kinds of reinforcement effects.

Table 5 Comparison of mechanical and hydraulic reinforcement characteristics of plant roots

Reinforcement type	Mechanism	Range of reinforcement	Remark
Mechanical reinforcement	The root has additional cohesion due to the mechanical action of roots	The plant root growth area provided an obvious mechanical reinforcement effect, but there was no mechanical reinforcement effect outside the growth area	Mechanical reinforcement always provides a reinforcement effect, but the reinforcement effect changes with the change of soil and root characteristics, such as the increase of soil moisture content, and the decrease of mechanical reinforcement effect
Hydraulic reinforcement	The change of soil matric suction due to transpiration affects the shear strength of the soil	The range of plant hydraulic reinforcement is larger than the growing area of plant roots	It is closely related to the change in the atmospheric environment. For example, in the process of rainfall, the hydraulic reinforcement effect is not obvious and can be ignored

The summary results in the table are under the premise of normal plant growth

Transpiration can lead to the production of a large amount of matric suction in the early period of rainfall. If transpiration is ignored in the early period of rainfall, the slope safety factor can be underestimated by up to 50%. Different plants cause different effects of hydraulic reinforcement; Boldrin et al. (2021) found that the water absorption of evergreen trees varied greatly, sometimes even exceeding that of deciduous trees. The difference in hydraulic reinforcement among different species is related to the growth morphology of plant roots. Based on root morphology, the root architectures are divided into four types: uniform root (Lynch 1995), triangular (Lynch 1995), exponential (Ghestem et al. 2011), and parabolic (Leung et al. 2015) root architectures. Among the four root forms, exponential root forms produced the largest suction, followed by triangular, uniform, and elliptic root forms (Ng et al. 2022). Therefore, it is very important to select suitable species according to the actual climatic conditions and geological conditions. Plant roots spread through the soil, changing the original soil structure. Soil is a three-phase material containing soil particles, water, and gas, and for root-soil composite, the root becomes the fourth-phase material.

To apply the root reinforcement effect to practical engineering, Switala et al. (2018) considered the coupling model of root mechanical reinforcement and hydraulic reinforcement, and obtained results consistent with the experimental process. Detailed knowledge of the root system and its parameters is not introduced in this model. Ng et al. (2021) established a three-dimensional theoretical calculation model that comprehensively considered root mechanical reinforcement and hydraulic reinforcement, and considered geotechnical engineering problems into three regions: primary root zone, secondary root zone, and soil zone, which solved the limitation of using the two-dimensional model to study the effect of plants root on slope reinforcement in the current research. It should be the focus of future research to study the reinforcement effect of plants on the soil by combining the root mechanical reinforcement effect with the hydraulic reinforcement effect.

6 Conclusion

The quantification of the plant root mechanical reinforcement effect is directly related to the slope reinforcement effect of ecological engineering. According to the type of mechanical reinforcement, plant roots are divided into the anchoring effect of main roots and the mechanical reinforcement effect of lateral roots, and different research methods are used for different types of root mechanical reinforcement.

The research method of root mechanical reinforcement effect mainly contains three methods: theoretical calculation model, experimental research, and numerical simulation. Among the three methods, the experimental research is the most direct method to quantify the root additional cohesion. The theoretical calculation model proposes to simplify the experimental process so that only the root tensile force and root geometric distribution characteristics need to be measured in the experiment. The numerical simulation method breaks the limitation of model size, which can be used as an auxiliary tool to characterize the root mechanical reinforcement effect by modeling the root mechanical reinforcement effect at various sizes.

At present, a lot of interesting research work has been done on the research methods of root mechanical reinforcement. In future research on the root mechanical reinforcement effect, the accuracy of quantitative results of plant roots should be improved first. Therefore, it is necessary to improve experimental means to measure good field experimental data, such as tensile strength data, elastic modulus, and strain of field roots, which can also provide favorable support for theoretical calculation model and numerical simulation. Secondly, the root mechanical reinforcement effect under more influencing factors should be studied, such as the growth process of plant roots, mixed planting, soil moisture content change, and other factors, and these factors should be taken into account in the theoretical calculation model and numerical simulation of the root mechanical reinforcement effect. To better guide the construction of ecological engineering, we propose to combine the existing research methods on the root mechanical reinforcement effect with the hydraulic reinforcement effect, which will be challenging research work.

Author Contribution Guoliang Hao: manuscript writing and revision. Laigui Wang: manuscript revision. Xiangfeng Liu: manuscript revision.

Funding This study was supported by the National Key R&D Projects (Grant No. 2017YFC1503102).

Data Availability The data used to support the findings of this study are available from the corresponding author.

Declarations

Conflict of Interest The authors declare no competing interests.

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