Heliyon 10 (2024) e37108

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

The root reinforcement on the slope under the condition of colonization of various herbaceous plants

Wanlei Yin [a,b,*], Yishan Pan [c], Miao Yang [d], Zhonghua Li [e]

[a] *School of mechanical machinery, Anyang Institute of technology, Anyang, 455000, China*
[b] *School of mechanical and power engineering, Henan Polytechnic University, Jiaozuo, 454150, China*
[c] *School of environment, Liaoning University, Shenyang, 110000, China*
[d] *School of civil engineering, Anyang Institute of technology, Anyang, 455000, China*
[e] *School of mechanics and engineering, Liaoning University of engineering and technology, Fuxin, 123000, China*

ARTICLE INFO

Keywords:
Root reinforcement
Herbaceous plants
Colonization
Slope stability
Shallow landslide

ABSTRACT

This study assessed root reinforcement on slopes influenced by various herbaceous species. The study examined the distribution, structural traits of these species, and their root systems, as well as their biomass. We established a quantitative model for evaluating root reinforcement at the soil interface influenced by different herbaceous colonizers. The focus was on a mining environment, specifically measuring root reinforcement at a dumpsite slope. The results showed that the herbaceous plants in the dumpsite included Candian fleabane (*Conyza canadensis*), Annual bluegrass (*Poa annua*), and Suaeda (*Suaeda glauca*), and the weights of the three herbaceous plants in descending order were Annual bluegrass, Candian fleabane, and Suaeda. Notably, the tensile strength of annual bluegrass roots peaked when diameters were less than 0.4 mm. Statistical analysis revealed significant variations in root tensile strength ($p < 0.05$, ANCOVA), root area ratio, and reinforcement (average values from 0 to 10 cm, $p < 0.05$, ANOVA) among the species. Canadian fleabane demonstrated the greatest root area ratio and reinforcement throughout the soil profiles. The integration of these herbaceous species increased the surface layer's stability of the slope by 21.6 % and marginally expanded the cross-sectional area of the landslide mass.

1. Introduction

Shallow landslide is a common natural disaster, mainly occurring in slope structures in forests, riverbanks and other areas [1–3]. Currently, soil bioengineering technology has been widely applied in controlling shallow slope landslides [4–7]. Plants play a key role in soil bioengineering technology. Plant roots can form complex network structures in the soil. These roots can anchor soil particles and prevent soil erosion and slope collapse. The role of pioneer species of herbaceous plants should be considered in soil bioengineering technology, which can achieve rapid land cover, good root development and can adapt to the environment. During the preliminary stages of ecological engineering aimed at slope restoration, herbs are selected as pioneer species for their swift growth and comprehensive coverage of the slope surface. It is crucial to conduct further investigations to verify the stabilizing contributions of these plants.

* Corresponding author. School of machinery, Anyang Institute of technology, West Section of Huanghe Avenue, Anyang City, Henan Province, China.

E-mail addresses: ywl696@126.com (W. Yin), panyish_cn@sina.com (Y. Pan), 1436557227@qq.com (M. Yang), 13941824411@139.com (Z. Li).

https://doi.org/10.1016/j.heliyon.2024.e37108
Received 8 May 2024; Received in revised form 26 August 2024; Accepted 27 August 2024
Available online 28 August 2024
2405-8440/

Current research shows that plants can improve slope stability in terms of both hydrological action and mechanical reinforcement. In hydrology, plants absorb and release water from the soil into the atmosphere through leaf transpiration, which helps regulate soil matric suction [5]. Plant roots can penetrate and occupy soil pore space, thereby improving soil hydraulic characteristics [8–10]. Above-ground parts of plants (such as trunks, leaves, etc.) can intercept precipitation and disperse its impact force, reducing the direct erosion and erosion of precipitation on the soil surface. The hydrologic reinforcement of plants plays a key role in maintaining slope stability, especially when the soil depth is greater than 1m [11].The main role of plants in suppressing shallow landslides is root reinforcement [12]. Root reinforcement is defined as "root reinforcement" added to soil cohesion. And many researchers have been devoted to accurately quantifying root reinforcement on the surface [13].

To measure root reinforcement, theoretical models are routinely applied. These frameworks are derived from the root's configuration at the shear plane and its dynamic interactions with the soil, enabling a detailed measurement of reinforcement. Presently, the dominant models are the Wu-Waldron model (WWM), the fibre bundle model (FBM), and the root bundle model (RBM). The WWM, formulated by Wu et al. [14] and Waldron [15], suggests that roots crossing the shear plane break simultaneously under external load. This assumption leads to an overestimation of reinforcement effects, as actual root breakage is staggered [16,17]. The FBM, employed by Pollen and Simon [16], operates as a progressive loading model where roots fracture incrementally, adjusting the distribution of tensile forces until the complete fracture of all roots. This approach provides enhanced accuracy over the WWM [18] and is broadly accepted [2,19,20]. Schwarz et al. [21] originally proposed the RBM, which was later augmented by the incorporation of the Weibull survival function, resulting in the RBMW [22]. This adaptation has established itself as the benchmark for evaluating woody plant reinforcement [23–25].

The quantification of root reinforcement is essential for the application of soil bioengineering methods in stabilizing slopes. In practical engineering, diverse herbaceous plants are planted on slopes to maintain their long-term stability. The stability of a slope cannot be linked exclusively to one type of root when evaluating the reinforcement offered by various herbaceous species. Slope stability is notably affected by species diversity [26], with different plants exhibiting varied effects on soil reinforcement. Therefore, precise prediction of root reinforcement is vital for improving slope stability and preventing shallow landslides. Zhang et al. [17] introduced the species importance value and formulated the concept of "relative root reinforcement." In a related study, Hao et al. [27] utilized this approach to evaluate root reinforcement resulting from the colonization by a range of herbaceous plants. This study leverages the interconnectedness of root reinforcement and root growth dynamics, integrating the distribution and growth traits of herbaceous plants to refine the method for quantifying root reinforcement [27]. The aims of this research include: (1) developing and validating a quantitative framework for root reinforcement amid various colonizing herbaceous species; (2) calculating the biomass of

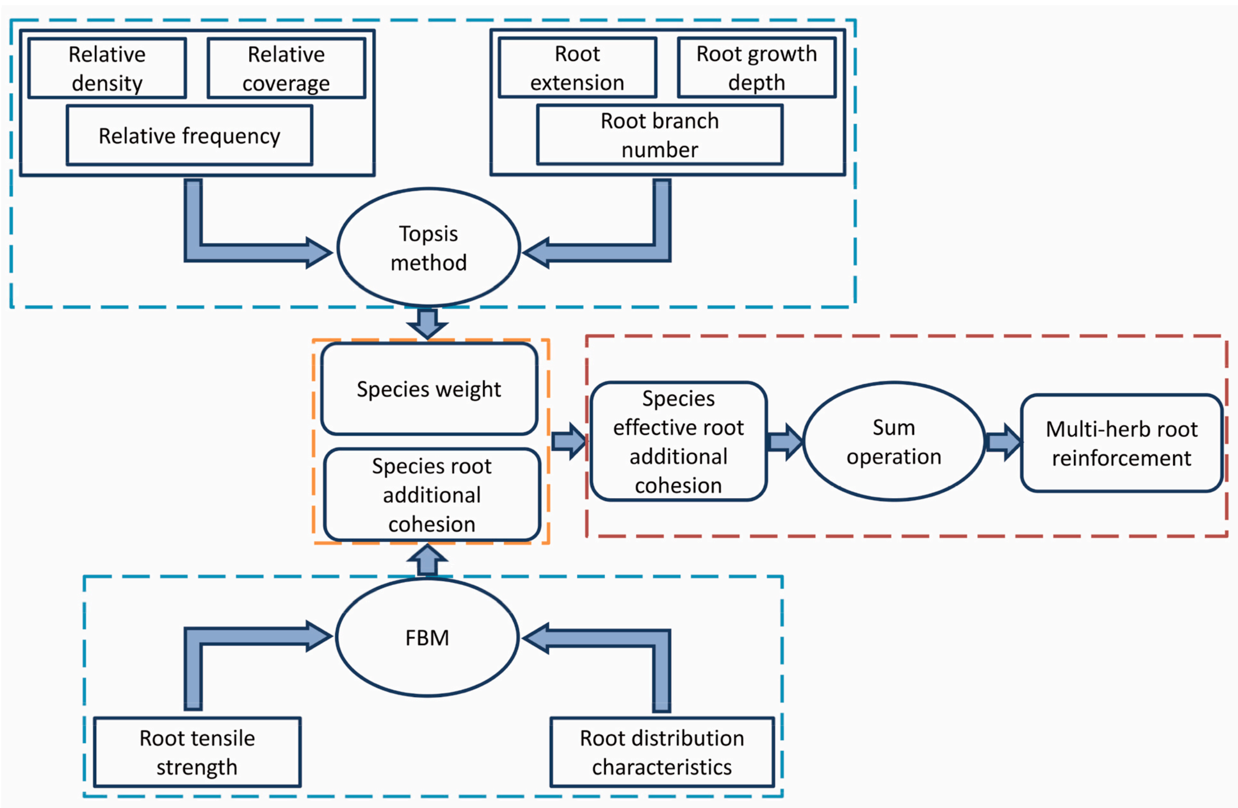

Fig. 1. Quantitative scheme for the root reinforcement on the soil surface under the condition of colonization of various herbaceous plants.

these plants, considering both plant distribution and root architecture; (3) detailing the distribution and reinforcement capacity of roots for each species; (4) evaluating root reinforcement in herbaceous colonization scenarios and examining the resultant stability improvements of the slope's surface layer. This investigation seeks to contribute valuable insights for subsequent research on root reinforcement within herbaceous plant-colonized slopes.

2. Materials and methods

2.1. Quantitative scheme of root reinforcement under the condition of colonization of various herbaceous plants

This study devised a framework to quantify root reinforcement, incorporating the distribution traits of plants alongside the geometric, distributive, and tensile biomechanical properties of roots, as shown in Fig. 1. The characterization of the local distribution of herbaceous plants involved metrics such as relative density, frequency, and coverage, whereas root geometry was defined through metrics of expansion, depth of growth, and branching. These parameters effectively discern the various types of root reinforcement and evaluate the capabilities of the herbs [17,28]. The biomass of the herbaceous plants was calculated using the TOPSIS method [29]. In parallel, the FBM was employed to determine root reinforcement [30]. The calculated weights and root reinforcement of the herbaceous plants were amalgamated to ascertain the effective reinforcement per species, culminating in a comprehensive assessment of the reinforcement impact on the topsoil under herbaceous colonization. The mining site was selected as the study site to validate the viability of the proposed framework. An exposition of the protocol for parameter collection and computation is provided subsequently.

2.2. Study sites and investigation of herbaceous plant growth indicators

The study site is Fuxin, Liaoning Province, China (42°01′17.83"N, 121°40′13.17"E). The dumpsite is located southwest of the mining area, covering an area of 13 km^2. This study selected a mixed planting area of herbaceous plants, including Candian fleabane (*Conyza canadensis*), Annual bluegrass (*Poa annua*), and Suaeda (*Suaeda glauca*) [27].

The sampling approach was utilized to evaluate the growth metrics of herbaceous plants, and the sampling distribution is shown in Fig. 2a. At each designated point, records were made of the number and coverage associated with each plant type. These data were used to compute the relative density, frequency, and coverage of three specific herbaceous species, aligning with the approach described by Zhang et al. [17]. Roots were extracted using the excavation technique, during which measurements of horizontal expansion, growth depth, and branching to the third tier were conducted. Each species was subjected to 5 rounds of sampling, as shown in Fig. 2b.

2.3. Calculation of herbaceous plant weights

The assessment of herbaceous plant mass is based on six indicators, as detailed in Section 2.2. The TOPSIS method, a ranking technique that aims for closeness to an ideal outcome, presumes that each utility function maintains monotonicity. This method is extensively applied for aggregate evaluations across groups, leveraging the entirety of the original dataset to precisely delineate distinctions among proposed evaluations. Within this framework, the aggregate distances to both the ideal positive and negative solutions are calculated for each scheme. A scheme is deemed superior if it approximates the ideal positive solution and deviates from the negative one. Here, the ideal positive solution embodies the condition wherein all index values are at their optimum, whereas the negative ideal solution represents the state where all indices are at their least advantageous. This investigation included three herbaceous plants and six evaluative indices, all of which are positive indicators (i.e., higher values signify enhanced outcomes). The weight calculation steps of herbaceous plants are as follows.

Step 1. The normalized initial matrix $A(a_{ij})$ was constructed, which is calculated by Equation (1).

$$A = \begin{pmatrix} a_{11} & \dots & a_{16} \\ \vdots & \ddots & \vdots \\ a_{31} & \cdots & a_{36} \end{pmatrix} \tag{1}$$

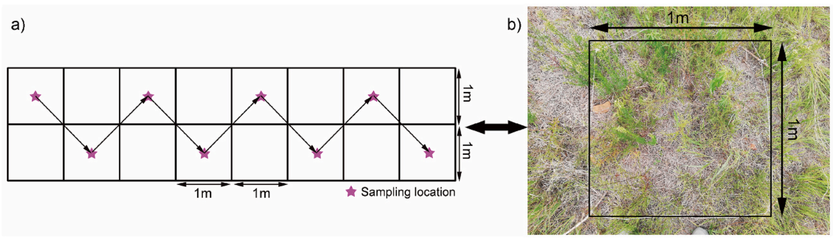

Fig. 2. a) Sampling distribution map of the herbaceous plant growth index survey. The sampling site is on the slope surface, the number of sample squares is 8, the size of each quadrat is 1 m × 1 m, and the interval between every two sample squares is 1 m. b) In situ sampling map.

The i represent the types of herbaceous plants,the value ranges from 1 to 3, corresponding to Candian fleabane, Annual bluegrass and Suaeda respectively; j is the 6 evaluation indicators, the value ranges from 1 to 6, in order of relative density, relative frequency, relative coverage, root expansion, root growth depth and number of root branches; for example, a_{11} represents the relative density value of Candian fleabane, and so on.

Step 2. A weighted norm matrix was constructed by initializing the matrix, and the attributes were vectorized, that is, which is calculated by Equation (2).

$$x_{ij} = \frac{a_{ij}}{\sqrt{\sum_{i=1}^{n} a_{ij}^2}} \tag{2}$$

x_{ij} is expressed as the vectorized value of each indicator of each herb. x_{ij} is arranged in order to finally get the normalized matrix X after normalization, which is calculated by Equation (3).

$$X = \begin{pmatrix} x_{11} & \cdots & x_{16} \\ \vdots & \ddots & \vdots \\ x_{31} & \cdots & x_{36} \end{pmatrix} \tag{3}$$

Step 3. The distance between the evaluation object and the optimal and inferior solutions was calculated (D_i^+ and D_i^-)

The optimal and worst solutions were identified by determining the maximum and minimum values of each column in matrix X, respectively. Distances from each evaluation object to these solutions were computed according to Equations (4) and (5).

$$D_i^+ = \sqrt{\sum_{i=1}^{6} \left(X_j^+ - x_{ij}\right)^2} \tag{4}$$

$$D_i^- = \sqrt{\sum_{i=1}^{6} \left(X_j^- - x_{ij}\right)^2} \tag{5}$$

Step 4. Herbaceous plant weight calculation (ω_i)

The weights of herbaceous plants were utilized to calculate each evaluation object's closeness to the optimal solution, as prescribed by Equation (6).

$$\omega_i = \frac{D_i^-}{D_i^+ + D_i^-} \tag{6}$$

In Equation (6), ω_i is the weight value of the herbaceous plant; the larger ω_i *is*, the better the evaluation object.

2.4. Root area ratio distribution and root tensile strength

The root area ratio, quantifying root distribution within the soil profile, is derived using the formula:

$$RAR = \sum_{i=1}^{N} \frac{\pi d_i^2}{4A} \tag{7}$$

N indicates the total number of roots; d_i denotes the diameter of the *i-th* root; and A signifies the soil profile area. The excavation method facilitated measurements of the root area ratio across soil profiles at depths ranging from 2 to 12 cm, at 2 cm intervals. The diameter of one root on each soil profile was recorded, and the root diameter was measured using a Vernier calliper with an accuracy of ± 0.01 mm. Images were captured with a 64-megapixel camera, and diameters were determined through pixel conversion.

The mechanical impact of plant roots was assessed by their tensile strength, providing more accurate insights than prior methodologies [31]. Roots were harvested, cleaned of surface soil, and immersed in a 15 % alcohol solution for preservation and viability maintenance [32], then stored at 4 °C in an incubator. Their biomechanical properties were analyzed using an electronic tension meter. Segments of roots, precisely 5 cm in length, were prepared, with surface moisture removed by absorbent paper. Diameters were similarly measured using a Vernier caliper. To guarantee the precision of experimental data, measurements were taken within 3 days post-collection, focusing exclusively on data from root fractures occurring in the middle 1/3. Extensive research has established a power-law relationship between root tensile strength and diameter [23,33–35], expressed as:

$$F = ad^b \tag{8}$$

where F is the tensile strength; and a and b are the respective fitting coefficients, with d representing the diameter of the root.

2.5. FBM quantifies root reinforcement

The FBM was used to calculate the root reinforcement [36]. FBM model is more accurate in predicting root reinforcement. In addition, the implementation of this model is simple and only a few parameters need to be calculated [34]. Assuming that there are N roots on a soil profile, the roots are sorted according to the strength of the roots, that is, the strongest root is recorded as number 1, and the weakest root is recorded as number N. For roots with root number n $(1 < n < N)$. When partial roots fail, the force exerted on the soil profile is borne by the remaining roots. When the j-th root fails, the root reinforcement is:

$$\Delta s = R_f \frac{F}{\sum_{n=1}^{j}\left((\pi/4)d_n^2\right)} \sum_{n=1}^{j} RAR_n \tag{9}$$

In the equation, R_f is the root-direction factor; when the root is broken, the force is distributed according to the number of roots, that is,

$$\frac{\pi}{4} d_j^2 T_{rj} = \frac{F}{j} \tag{10}$$

Therefore, the root reinforcement of herbaceous quantified by the FBM is:

$$\Delta s = R_f \times \max\left(T_{rj} RAR_j j\right) \tag{11}$$

Wu et al. [14] determined that the root factor ranges from 0.92 to 1.31. For this study, a constant value of 1.2, commonly employed in root reinforcement quantification, was adopted:

$$\Delta s = 1.2 \times \max\left(T_{rj} RAR_j j\right) \tag{12}$$

Based on Equations (6)–(10), a mathematical model using the FBM was developed to calculate the additional cohesion contributed by each herbaceous root to the soil profile, incorporating both the tensile strength of the roots and their distribution within the soil profile.

2.6. Root reinforcement under the condition of colonization of various herbaceous plants

To assess the extent of root reinforcement under various herbaceous colonization conditions, this study incorporates the weights of herbaceous plants to derive the effective root reinforcement for each species, where:

$$\Delta Es_z = \frac{\omega_i}{\sum_{i=1}^{m} \omega_i} \Delta s_z \tag{13}$$

$$\bar{c} = \sum_{i=1}^{m} \Delta Es_z \tag{14}$$

ΔEs_z is the effective root reinforcement of the z-th grass species. Δs_z is the root reinforcement of the z-th grass calculated by FBM, m is the number of grass species, and $\bar{c}$ is the root reinforcement of various herbaceous plants under colonization conditions.

2.7. Statistical analysis

The data's adherence to normal distribution was confirmed by the Kolmogorov-Smirnov test at a 1 % significance level, and

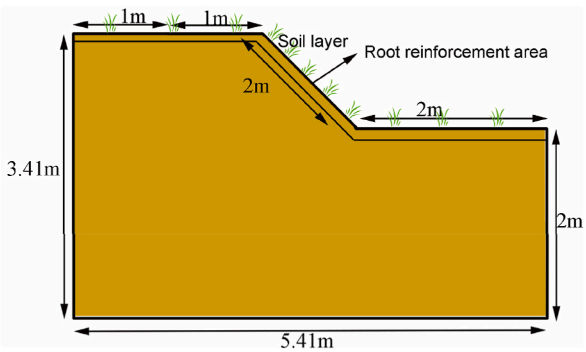

Fig. 3. The slope model diagram. The root reinforcement of herbaceous plants was mainly manifested in the surface layer of the slope. The slope angle is 45°.

variance homogeneity was verified using the Levene test. Variance analysis explored the disparities in root growth characteristics, root area ratios, and root reinforcement across species. Differences in root tensile strength among the three herbaceous plants were examined using ANCOVA, with root diameter serving as the covariate. The relationship between root tensile strength and diameter was modeled through power-law regression. All statistical analyses were executed in Python.

2.8. Slope surface stability analysis

The influence of plant roots on slope stability is primarily observed at the soil surface. A slope model was developed to investigate this effect, focusing on local slopes with an inclination of 45°, as identified in on-site engineering surveys, as shown in Fig. 3. Mechanical soil parameters were adopted from Hao et al. [27] (Table 1). The additional root cohesion calculated by the model in Section 2.6 was added to the surface of the model. Since the plant growth depth was only 10 cm below the surface, the reinforcement of plant roots was added to the surface 10 cm (the average value of 0–10 cm root reinforcement was added). In this calculation, the influence of root growth direction was ignored, and only a fixed value of 1.2 was used to replace the root growth direction factor when calculating root reinforcement in FBM model. The entire slope surface was fortified with roots, ensuring comprehensive reinforcement. Following model construction, the slope's safety factor was determined using the simplified Bishop method. A comparative analysis of the safety factors under conditions with and without root reinforcement was performed to evaluate their effectiveness.

3. Results

3.1. Indicator survey results and herbaceous plant weights

Table 2 presents the data for six indicators pertaining to three herbaceous species, with the normalized results displayed in Fig. 4. The survey showed that Annual bluegrass had the highest values in relative density, frequency, and coverage among the species examined. Distribution-wise, Annual bluegrass dominates, followed by Canadian fleabane and Suaeda. There were significant variations in root expansion, growth depth, and branch number across the species ($p < 0.05$, ANOVA). Annual bluegrass had the largest root growth in the horizontal direction, which was 8 0.89 and 7 0.36 cm larger than Candian fleabane and Suaeda. The root growth depth of Candian fleabane was the largest, and the number of branches was obviously dominant. Based on the analysis of the six indicators, it can be seen that Annual bluegrass has an obvious advantage in the local area, and its normalized results occupy the largest area, followed by Candian fleabane and Suaeda. After calculation by the TOPSIS method, the weights of the three herbaceous plants in descending order were Annual bluegrass (60.52 %) > Candian fleabane (28.72 %) > Suaeda (10.76 %).

3.2. Root tensile force

Fig. 5 demonstrates the relationship between root tensile strength and diameter for these species, showing that tensile force escalates with increasing diameter, adhering to a power-law dynamic. Employing Formula 8, the modeling of this relationship yielded results that underscore the varying tensile properties of the roots, differentiated by distinct fitting coefficients a and b. The fit quality for the species ranged between 0.8 and 0.9, with more scattered data points at smaller diameters. Specifically, within the 0.2–0.4 mm diameter range, Annual bluegrass exhibited the highest root tensile strength, outperforming Canadian fleabane and Suaeda. Significant disparities in root tensile strength were confirmed among these species ($P < 0.05$,ANCOVA).

3.3. Root area ratio and root reinforcement

During this study period, root growth depth was consistently 10 cm, and Fig. 6a illustrates the average root area ratio (RAR) within the 0–10 cm soil profile. Noteworthy differences in RAR were observed among the species ($p < 0.05$, ANOVA), with Canadian fleabane achieving the highest RAR, followed by Suaeda and Annual bluegrass. Fig. 6b details the average additional root cohesion within the same soil profile depth, highlighting significant variations ($p < 0.05$, ANOVA) in root cohesion, ranked as Canadian fleabane > Annual bluegrass > Suaeda. Contrary to the implications of the root-area ratio, this metric proved ineffective for comparing root cohesion between species; for example, although Suaeda's root-area ratio surpassed that of Annual bluegrass, its cohesion was comparatively lower.

3.4. Root reinforcement and stability of slope surface under the condition of colonization of various herbaceous plants

Fig. 7 illustrates the effective root reinforcement across three herb species, indicating substantial differences. Annual bluegrass demonstrates the highest relative root reinforcement at 6.47 kPa, while Suaeda exhibits the lowest at merely 0.5 kPa. Under the

Table 1
Soil properties of the study site.

Soil type	ρ (g cm $^{-3}$)	d_s	ω (%)	c(kPa)	φ (°)
Foreign soil	1.41 ± 0.13	2.7	8 ± 1	3.71	10

Table 2
Indicators survey results of *Candian fleabane*, *Annual bluegrass*, and *Suaeda*, the existence of root expansion, root growth depth, and root expansion among different species Significant difference ($p < 0.01$, ANOVA). (Capital letters represent ANOVA results at a significance level of 0.01).

Species	Relative frequency (%)	Relative density (%)	Relative coverage (%)	Root extension (cm)	Root growth depth (cm)	Root branches number (item)
Candian fleabane	30	8.8	21.4	10.33 ± 2.80^{A}	11.02 ± 0.84^{A}	$4\,0.8 \pm 3.82^{A}$
Annual bluegrass	40	86.1	66.5	$19.2\,2 \pm 2\,.88^{B}$	7.59 ± 0.91^{B}	15.4 ± 5.24^{B}
Suaeda	30	5.1	12.1	11.86 ± 2.17^{C}	8.79 ± 1.75^{C}	23.2 ± 2.86^{C}

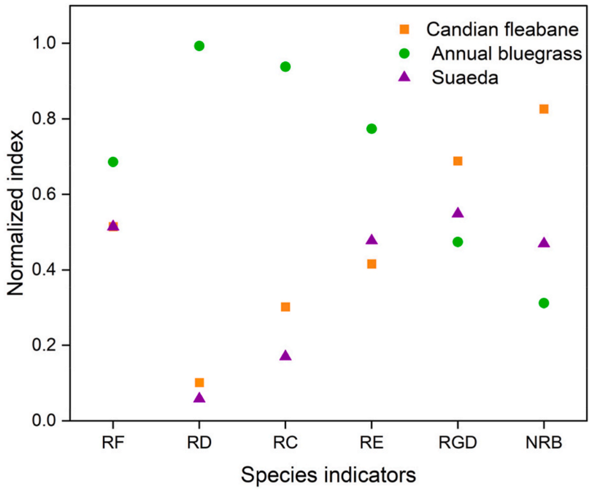

Fig. 4. The normalized distribution of growth indicators. RD: relative density, RF: relative frequency, RC: relative coverage, RE: root expansion, RGD: root growth depth, RBN: root branch number.

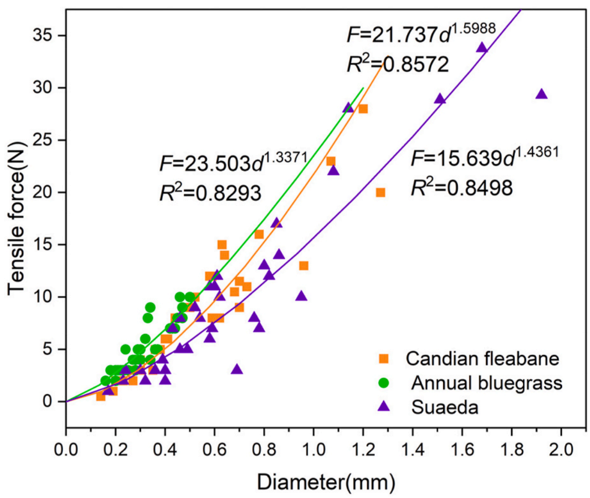

Fig. 5. The relationship between the tensile force (F) and diameter (d) of plant roots. Fitting with Equation $F = ad^{b}$, each set of data contains 34 test samples.

condition of multi-herbaceous plant colonization, the root reinforcement was 11.48 kPa, among which Annual bluegrass contributed the most to the root reinforcement (56.3 %), and the rest were Candian fleabane (39.27 %) and Suaeda (4.38 %). The surface stability of the slope reinforced by herbaceous plants is shown in Fig. 8. The safety factor of the bare soil slope is 1.522, and that of the slope reinforced by herbaceous plants is 1.851. Herb reinforcement improves slope stability by 21.6 %. Comparing the slope slip surface morphology under the two conditions, the slope slip surface depth and landslide area increase after the herb reinforcement.

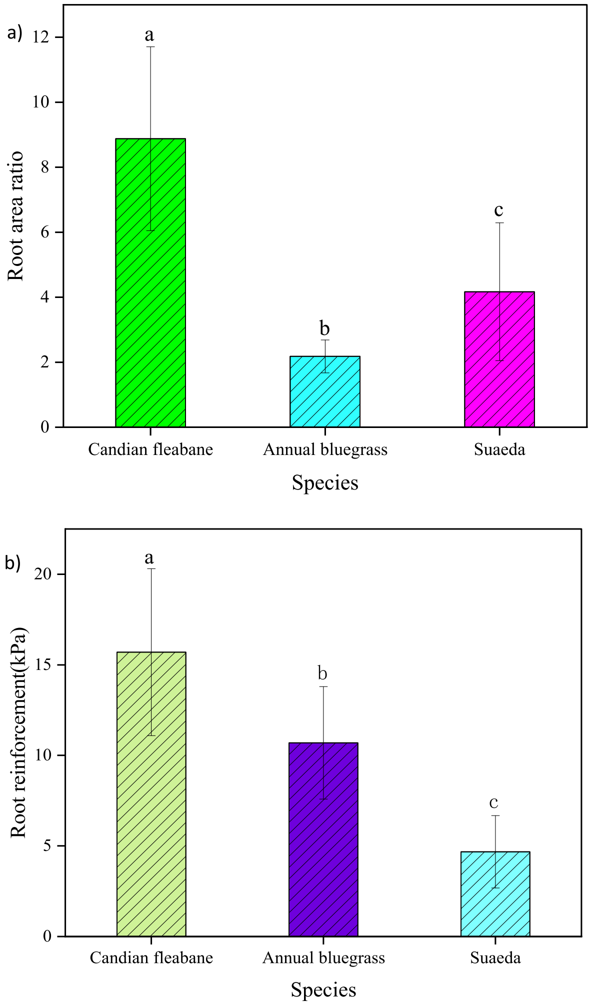

Fig. 6. a): The root area ratio of the three herbaceous plant; b): The root reinforcement of the three herbaceous plants.

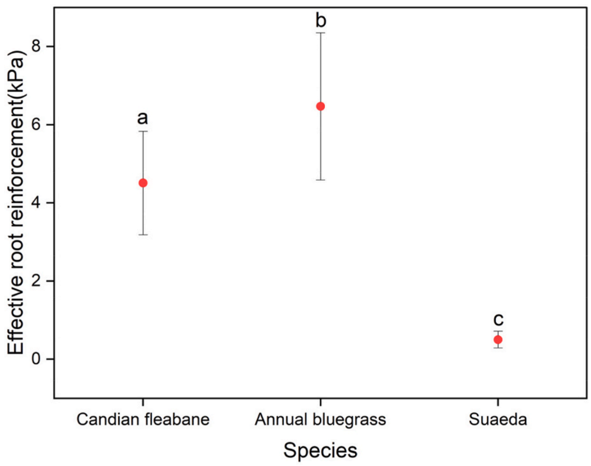

Fig. 7. The relationship between effective root reinforcement of three kinds of herbaceous plants.

4. Discussion

4.1. Species indicators

The composition and health of herbaceous plants are critical to their ability to reinforce slopes [26], and slope stability cannot be strictly classified based on particular vegetation types or root systems [37]. In contrast, slope stability is related to vegetation type and root structure type [26]. Therefore, in this study, relative density, relative frequency, and relative coverage were used to characterize local vegetation types, and root growth depth, root expansion, and root branch number were used to characterize root structural morphology. Annual bluegrass has good low-temperature resistance and can still maintain a green appearance at −5. Annual bluegrass has a developed root system and can maintain a good growth state in arid, poor soil, and thin soil areas [38], and it is a good species to reinforce slopes. In soil bioengineering techniques, considering the excellent slope stabilization characteristics of Annual bluegrass, an appropriate increase in the amount of Annual bluegrass planting is conducive to the reinforcement of the surface soil of the slope. Different herbaceous plants have different root morphologies due to their growth characteristics. Additionally, root morphology is also related to the external conditions of plant growth. Changes in soil temperature will affect root composition, starting direction, branching direction, and growth direction. If soil temperatures deviate significantly from a species' optimal range, this can modify the structure and function of their root systems [39]. Additionally, the mechanical characteristics of soil influence root development; dense, unyielding soils hinder root expansion by offering mechanical resistance [40].

In the study area of mine environment, only Candian fleabane, Annual bluegrass, and Suaeda had a large number of reproduction and co-growth, mainly because the three herbaceous plants could adapt to the local growth environment, and the difference in their growth weight value was mainly due to the species competition and plant evolution in the later stage. In the species competition, all kinds of herbs need external factors such as light and nutrients. The growth space required by the plants of Candian fleabane and Suaeda is large and the plants are tall, while the plants of Annual bluegrass are relatively small, which makes Annual bluegrass can grow widely between Candian fleabane and Suaeda, which may be the main factor for the higher weight of Annual bluegrass. In addition, the weight of herbaceous plants is also related to the evolution process of plants [41], and one of the main factors in the evolution process of plants is soil conditions [42]. However, due to the complex and changeable soil conditions and the wide variety of plants, the evolution process of plants in soil still needs more contributions from scientists.

4.2. Root tensile force

Results from tensile tests where roots slipped or fractured at the clip site were omitted, as these incidents may not accurately represent root tensile strength but rather damage from the clipping mechanism [33,43,44]. The trend observed, where root tensile force diminishes with increasing diameter, challenges the findings of numerous researchers [35,45–47] and is not fully explicable by the size effect in fracture mechanics. Analyzing the contents of cellulose and lignin within roots is essential for assessing root tensile strength [48], as environmental changes can affect cellulose levels [49]. A decrease in root diameter is associated with an increase in cellulose, which boosts tensile strength [50]. Conversely, root tensile force is inversely related to the lignin/cellulose ratio [51]. Furthermore, root tensile strength is connected to the water content within plant cell walls; an increase in water content weakens the bonds between cellular organic polymers by saturating the cell walls [52]. Variations in tensile strength among species are primarily shaped by distinct species traits that dictate the specific fitting coefficients a and b [3]. The differences in root tensile forces between species need to be further observed in the future in conjunction with root microstructure.

4.3. Root area ratio and root reinforcement

Root area ratio is an important metric for assessing the reinforcement abilities of herbaceous plants, with most species developing roots between 10 and 20 cm below the surface [51]. Variability in root area ratios across species can be attributed to genetic factors, local soil conditions, climatic influences, and land management practices [53]. Candian fleabane and Suaeda belong to taproot type plants, while Annual bluegrass belongs to fibrous root type plants, the taproot diameter is larger, so the root area ratio of Annual bluegrass is the smallest among the three herbaceous plants. In addition, because of the large root branch number of Candian fleabane, its root area ratio has obvious advantages over the other two herbaceous plants. Root reinforcement is dictated by the distribution and the tensile biomechanical characteristics of plant roots within the soil profile [54]. There are notable differences in root area ratio and tensile strength among species, which significantly influence root reinforcement effectiveness. Specifically, Annual bluegrass, which consists solely of fine roots (<0.25 mm), exhibits superior tensile strength and consequently more effective soil reinforcement [55]. The density of these fine roots within the root-soil matrix is directly linked to increased soil strength [34,56,57], although Annual bluegrass shows a smaller root area compared to Suaeda, its reinforcement capacity is significantly enhanced.

4.4. Slope stability under the condition of colonization various herbaceous plants

Extensive interactions between plant roots and soil modify the properties of the latter [58]. The interaction between roots and soil mechanically increases soil strength. Following plant reinforcement, the stability of the slope's surface improves, mainly due to the enhanced strength of the root-soil matrix. The biomechanical properties of roots enable them to resist both tensile and compressive stresses [33,59,60], while soil primarily exhibits compressive properties and lacks tensile strength [54]. When roots fortify a slope, they embed deeply into the soil, creating a root-soil complex that offers additional resistance to external forces [55]. This fortification

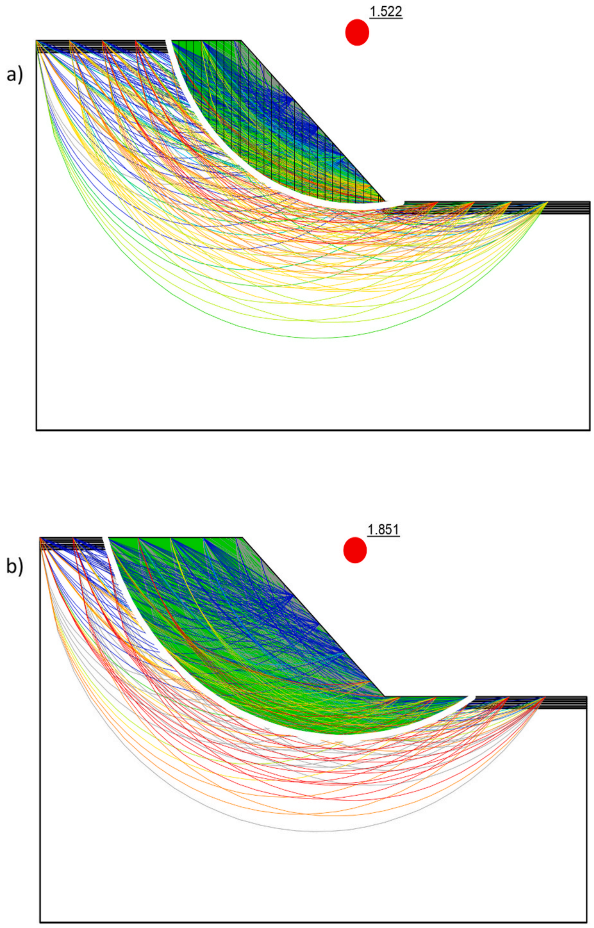

Fig. 8. Slope sliding surface and safety factor; a) Unrooted soil slope b) Plant root reinforced slope.

significantly bolsters the overall strength of the slope's soil, necessitating a higher sliding force to initiate landslides, thereby enlarging the cross-sectional area of the landslide mass. Post-herbaceous plant reinforcement, the safety factor of the slope is enhanced by 21.6 %. This study does not account for rainfall conditions; however, under normal precipitation scenarios, plant roots fortify the surface soil of slopes. With a slope height of 10m and a gradient of 1:1.5, under rainfall intensities of 5, 10, and 20 mm/h, the maximum soil displacement is reduced by 89.8 %, 80.3 %, and 71.8 %, respectively, in comparison to unprotected slopes [61]. In natural environments, slopes may be subject to severe rainfall, which significantly increases soil porosity through root penetration, thus accelerating the infiltration of rainwater. Differences in the root structures of various plants affect the morphology of these pores, which may influence the stability of slopes [62]. Consequently, the reinforcement effects of diverse herbs under extreme rainfall conditions require further investigation.

5. Conclusions

Slope stability is an important part of soil bioengineering techniques. Various herbaceous plants are usually planted on the surface of the slope. This study focused on the reinforcement effects of various herbaceous plants in colonization conditions. The principal findings are summarized as follows.

(1) Within a mining context, the biomass of three herbaceous species varied as follows: *Annual bluegrass* (60.52 %) > *Candian fleabane* (28.72 %) > *Suaeda* (10.76 %).
(2) The root tensile force of *Candian fleabane*, *Annual bluegrass*, and *Suaeda* increased with the increase of diameter. Specifically, between diameters of 0.2 and 0.4 mm, the tensile strength of Annual bluegrass significantly surpassed that of *Candian fleabane* and *Suaeda.*
(3) Significant variations were observed in the additional root cohesion across these species, ranked from highest to lowest as Candian fleabane > Annual bluegrass > Suaeda.

(4) Reinforcement efforts involving *Candian fleabane*, *Annual bluegrass*, and *Suaeda* augmented slope surface stability by 21.6 %. Post-reinforcement, there was an increase in the depth of the slip surface and an expansion in the cross-sectional area of the landslide mass.

CRediT authorship contribution statement

Wanlei Yin: Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Investigation, Funding acquisition. **Yishan Pan:** Writing – review & editing, Conceptualization. **Miao Yang:** Supervision, Project administration. **Zhonghua Li:** Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:Wanlei Yin reports financial support was provided by Scientific and Technological Project in Henan Province(24210230214). Wanlei Yin reports financial support was provided by Key Research Projects of Higher Education Institutions in Henan Province (22B44001). If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

NSFC National Natural Science Foundation Liaoning Joint Fund Key Project(U1908222),Key Research Projects of Higher Education Institutions in Henan Province (22B44001), Anyang Science and Technology Development Plan Project (2021C01SF029).

References

[1] E. Gasser, M. Schwarz, A. Simon, P. Perona, C. Phillips, J. Hübl, L. Dorren, A review of modeling the effects of vegetation on large wood recruitment processes in mountain catchments, Earth Sci. Rev. 194 (2019) 350–373.
[2] M. Bordoni, C. Meisina, A. Vercesi, G.B. Bischetti, E.A. Chiaradia, C. Vergani, S. Chersich, R. Valentino, M. Bittelli, R. Comolli, M.G. Persichillo, A. Cislaghi, Quantifying the contribution of grapevine roots to soil mechanical reinforcement in an area susceptible to shallow landslides, Soil Tillage Res. 163 (2016) 195–206.
[3] G.-A. Yu, Z. Li, H. Yang, J. Lu, H.Q. Huang, Y. Yi, Effects of riparian plant roots on the unconsolidated bank stability of meandering channels in the Tarim River, China, Geomorphology 351 (2020).
[4] J. Ni, Y. Xiao, J. Shi, J. He, Soil bioengineering using vegetation under climate change, Biogeotechnics 2 (2024) 100067.
[5] C.W.W. Ng, Q. Zhang, C. Zhou, J. Ni, Eco-geotechnics for human sustainability, Sci. China Technol. Sci. 65 (2022) 2809–2845.
[6] G.B. Bischetti, G. De Cesare, S.B. Mickovski, H.P. Rauch, M. Schwarz, R. Stangl, Design and temporal issues in Soil Bioengineering structures for the stabilisation of shallow soil movements, Ecol. Eng. 169 (2021) 106309.
[7] F. Rey, C. Bifulco, G.B. Bischetti, F. Bourrier, G. De Cesare, F. Florineth, F. Graf, M. Marden, S.B. Mickovski, C. Phillips, Soil and water bioengineering: practice and research needs for reconciling natural hazard control and ecological restoration, Science of the total environment 648 (2019) 1210–1218.
[8] C.W.W. Ng, J.J. Ni, A.K. Leung, Effects of plant growth and spacing on soil hydrological changes: a field study, Geotechnique 70 (2020) 867–881.
[9] J. Ni, A.K. Leung, C.W. Ng, Unsaturated hydraulic properties of vegetated soil under single and mixed planting conditions, Geotechnique 69 (2019) 554–559.
[10] Y. Wang, J. Gu, J. Ni, Influence of biochar on soil air permeability and greenhouse gas emissions in vegetated soil: a review, Biogeotechnics 1 (2023) 100040.
[11] J. Ni, A.K. Leung, C.W.W. Ng, W. Shao, Modelling hydro-mechanical reinforcements of plants to slope stability, Comput. Geotech. 95 (2018) 99–109.
[12] R.C. Sidle, T.A. Bogaard, Dynamic earth system and ecological controls of rainfall-initiated landslides, Earth Sci. Rev. 159 (2016) 275–291.
[13] B.B. Docker, T.C.T. Hubble, Quantifying root-reinforcement of river bank soils by four Australian tree species, Geomorphology 100 (2008) 401–418.
[14] T.H. Wu, Iii WP. McKinnell, D.N. Swanston, Strength of tree roots and landslides on prince of wales island, Alaska, Can. Geotech. J. 16 (1979) 19–33.
[15] L.J. Waldron, The shear resistance of root-permeated homogeneous and stratified soil, Soil Sci. Soc. Am. J. 41 (1977) 843–849.
[16] N. Pollen, A. Simon, Estimating the mechanical effects of riparian vegetation on stream bank stability using a fiber bundle model, Water Resour. Res. 41 (2005).
[17] C. Zhang, D. Li, J. Jiang, X. Zhou, X. Niu, Y. Wei, J. Ma, Evaluating the potential slope plants using new method for soil reinforcement program, Catena 180 (2019) 346–354.
[18] R.E. Thomas, N. Pollen-Bankhead, Modeling root-reinforcement with a fiber-bundle model and Monte Carlo simulation, Ecol. Eng. 36 (2010) 47–61.
[19] E. Comino, P. Marengo, V. Rolli, Root reinforcement effect of different grass species: a comparison between experimental and models results, Soil Tillage Res. 110 (2010) 60–68.
[20] X. Wang, M.-M. Hong, Z. Huang, Y.-F. Zhao, Y.-S. Ou, H.-X. Jia, J. Li, Biomechanical properties of plant root systems and their ability to stabilize slopes in geohazard-prone regions, Soil Tillage Res. 189 (2019) 148–157.
[21] M. Schwarz, D. Cohen, D. Or, Root-soil mechanical interactions during pullout and failure of root bundles, J. Geophys. Res. 115 (2010).
[22] M. Schwarz, F. Giadrossich, D. Cohen, Modeling root reinforcement using a root-failure Weibull survival function, Hydrol. Earth Syst. Sci. 17 (2013) 4367–4377.
[23] C. Vergani, M. Schwarz, M. Soldati, A. Corda, F. Giadrossich, E.A. Chiaradia, P. Morando, C. Bassanelli, Root reinforcement dynamics in subalpine spruce forests following timber harvest: a case study in Canton Schwyz, Switzerland, Catena 143 (2016) 275–288.
[24] E. Gehring, M. Conedera, J. Maringer, F. Giadrossich, E. Guastini, M. Schwarz, Shallow landslide disposition in burnt European beech (Fagus sylvatica L.) forests, Sci. Rep. 9 (2019) 8638.
[25] C. Vergani, M. Werlen, M. Conedera, D. Cohen, M. Schwarz, Investigation of root reinforcement decay after a forest fire in a Scots pine (Pinus sylvestris) protection forest, For. Ecol. Manag. 400 (2017) 339–352.
[26] M.T. Löbmann, C. Geitner, C. Wellstein, S. Zerbe, The influence of herbaceous vegetation on slope stability – a review, Earth Sci. Rev. 209 (2020).
[27] G. Hao, X. Liu, X. Li, Quantification of additional cohesion from roots of mixed planting of multi-herb in dumping site and its influence on slope stability, Arabian J. Geosci. 14 (2021) 1–15.
[28] G. Hao, X. Liu, Q. Zhang, L. Xiang, B. Yu, Optimum selection of soil-reinforced herbaceous plants considering plant growth and distribution characteristics, J. Soil Sci. Plant Nutr. (2022) 1–15.
[29] P. Chen, Effects of normalization on the entropy-based TOPSIS method, Expert Syst. Appl. 136 (2019) 33–41.
[30] G.J. Meijer, A generic form of fibre bundle models for root reinforcement of soil, Plant Soil 468 (2021) 45–65.
[31] C. Vergani, E. Chiaradia, G. Bischetti, Variability in the tensile resistance of roots in Alpine forest tree species, Ecol. Eng. 46 (2012) 43–56.
[32] G.B. Bischetti, E.A. Chiaradia, T. Simonato, B. Speziali, B. Vitali, P. Vullo, A. Zocco, Root strength and root area ratio of forest species in lombardy (northern Italy), Plant Soil 278 (2005) 11–22.

[33] F. Giadrossich, M. Schwarz, D. Cohen, A. Cislaghi, C. Vergani, T. Hubble, C. Phillips, A. Stokes, Methods to measure the mechanical behaviour of tree roots: a review, Ecol. Eng. 109 (2017) 256–271.
[34] F. Gilardelli, V. Chiara, G. Rodolfo, B. Anne, C. Pierre, C. Sandra, E.A. Chiaradia, Root characteristics of herbaceous species for topsoil stabilization in restoration Projects, Land Degrad. Dev. 28 (2017) 2074–2085.
[35] G. Hao, L. Wang, X. Liu, Y. Zhang, Geometric distribution characteristics and mechanical reinforcement effect of herbaceous plant roots at different growth periods, Soil Tillage Res. 229 (2023).
[36] Z. Mao, L. Saint-André, M. Genet, F.-X. Mine, C. Jourdan, H. Rey, B. Courbaud, A. Stokes, Engineering ecological protection against landslides in diverse mountain forests: choosing cohesion models, Ecol. Eng. 45 (2012) 55–69.
[37] M. Ghestem, K. Cao, W. Ma, N. Rowe, R. Leclerc, C. Gadenne, A. Stokes, A framework for identifying plant species to be used as 'ecological engineers' for fixing soil on unstable slopes, PLoS One 9 (2014) e95876.
[38] J. Beard, The plant characteristics, dissemination, environmental adaptation and cultural requirements of Poa annua L. Rosen, Turf, Gazon. 1 (1970) 33–35.
[39] M. Faget, S. Blossfeld, S. Jahnke, G. Huber, U. Schurr, K.A. Nagel, Temperature effects on root growth, in: A. Eshel, T. Beeckman (Eds.), Plant Roots: the Hidden Half, CRC Press, 2013.
[40] A.G. Bengough, B.M. McKenzie, P.D. Hallett, T.A. Valentine, Root elongation, water stress, and mechanical impedance: a review of limiting stresses and beneficial root tip traits, J. Exp. Bot. 62 (2011) 59–68.
[41] X. Ma, Y. Liu, Mohsen Zarebanadkouki, Bahar S. Razavi, Spatiotemporal patterns of enzyme activities in the rhizosphere: effects of plant growth and root morphology, Biol. Fertil. Soils 54 (2018) 819–828.
[42] L. Giupponi, G. Borgonovo, A. Giorgi, G.B. Bischetti, How to renew soil bioengineering for slope stabilization: some proposals, Landsc. Ecol. Eng. 15 (2019) 37–50.
[43] J. Ji, N. Kokutse, M. Genet, T. Fourcaud, Z. Zhang, Effect of spatial variation of tree root characteristics on slope stability. A case study on Black Locust (Robinia pseudoacacia) and Arborvitae (Platycladus orientalis) stands on the Loess Plateau, China, Catena 92 (2012) 139–154.
[44] B. Abernethy, I.D. Rutherfurd, The distribution and strength of riparian tree roots in relation to riverbank reinforcement, Hydrol. Process. 15 (1) (2001) 63–79.
[45] G. Hao, L. Wang, X. Liu, Methods for studying the effect of plant roots on soil mechanical reinforcement: a review, J. Soil Sci. Plant Nutr. 23 (2023) 2893–2912.
[46] C. Zhang, Y. Liu, P. Liu, J. Jiang, Q. Yang, Untangling the influence of soil moisture on root pullout property of alfafa plant, Journal of Arid Land 12 (2020) 666–675.
[47] C. Zhang, X. Zhou, J. Jiang, Y. Wei, J. Ma, P.D. Hallett, Root moisture content influence on root tensile tests of herbaceous plants, Catena 172 (2019) 140–147.
[48] C.-B. Zhang, L.-H. Chen, J. Jiang, Why fine tree roots are stronger than thicker roots: the role of cellulose and lignin in relation to slope stability, Geomorphology 206 (2014) 196–202.
[49] M. Schwarz, P. Lehmann, D. Or, Quantifying lateral root reinforcement in steep slopes - from a bundle of roots to tree stands, Earth Surf. Process. Landforms 35 (2010) 354–367.
[50] M. Genet, A. Stokes, F. Salin, S.B. Mickovski, T. Fourcaud, J.-F. Dumail, R. van Beek, The influence of cellulose content on tensile strength in tree roots, Plant Soil 278 (2005) 1–9.
[51] C. Ye, Z. Guo, Z. Li, C. Cai, The effect of Bahiagrass roots on soil erosion resistance of Aquults in subtropical China, Geomorphology 285 (2017) 82–93.
[52] T.C. Hales, C.F. Miniat, Soil moisture causes dynamic adjustments to root reinforcement that reduce slope stability, Earth Surf. Process. Landforms 42 (2017) 803–813.
[53] W.L. Wieder, S.A. Shoop, State of the knowledge of vegetation impact on soil strength and trafficability, J. Terramechanics 78 (2018) 1–14.
[54] N. Pollen-Bankhead, A. Simon, R.E. Thomas, 12.8 the reinforcement of soil by roots: recent advances and directions for future research, Treatise on Geomorphology (2013) 107–124.
[55] A.R. Ennos, The anchorage of leek seedlings: the effect of root length and soil strength, Ann. Bot. 65 (1990) 409–416.
[56] C. Caviezel, M. Hunziker, M. Schaffner, N.J. Kuhn, Soil–vegetation interaction on slopes with bush encroachment in the central Alps–adapting slope stability measurements to shifting process domains, Earth Surf. Process. Landforms 39 (2014) 509–521.
[57] S. De Baets, J. Poesen, B. Reubens, K. Wemans, J. De Baerdemaeker, B. Muys, Root tensile strength and root distribution of typical Mediterranean plant species and their contribution to soil shear strength, Plant Soil 305 (2008) 207–226.
[58] G. Centenaro, C. Hudek, A. Zanella, A. Crivellaro, Root-soil physical and biotic interactions with a focus on tree root systems: a review, Appl. Soil Ecol. 123 (2018) 318–327.
[59] A. Cislaghi, D. Cohen, E. Gasser, G.B. Bischetti, M. Schwarz, Field measurements of passive earth forces in steep, shallow, landslide-prone areas, J. Geophys. Res.: Earth Surf. 124 (2019) 838–866.
[60] M. Schwarz, A. Rist, D. Cohen, F. Giadrossich, P. Egorov, D. Büttner, M. Stolz, J.J. Thormann, Root reinforcement of soils under compression, J. Geophys. Res.: Earth Surf. 120 (2015) 2103–2120.
[61] X. Ji, P. Yang, The exploration of the slope displacement with vegetation protection under different rainfall intensity, J. For. Eng 5 (2020) 152–156.
[62] W.-Z. Guo, Z.-X. Chen, W.-L. Wang, W.-W. Gao, M.-M. Guo, H.-L. Kang, P.-F. Li, W.-X. Wang, M. Zhao, Telling a different story: the promote role of vegetation in the initiation of shallow landslides during rainfall on the Chinese Loess Plateau, Geomorphology 350 (2020) 106879.