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THE SHEAR STRENGTH PARAMETERS OF SOIL-ROOT SYSTEMS

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Abstract

The root systems of vegetation are fundamental in enhancing shallow slope stability, with the shear strength of soil-root systems serving as a critical parameter for its assessment. The role of roots in stabilizing shallow slopes has been extensively documented, and the use of vegetation for slope stabilization and soil erosion control is a well-established practice across many regions worldwide. This sustainable approach has even led to the emergence of new research disciplines focused on its development. This review article aims to synthesize and evaluate existing research on the shear strength parameters of soil-root systems across various plant species and soil types. Additionally, it examines how these parameters are affected when plant roots dry out due to hydric stress caused by recent climate change. The study provides insights into the impact of root desiccation on slope stability, highlighting the importance of understanding vegetation`s role in maintaining soil cohesion under changing conditions.

Key words*: shear strength, soil-roots, type of vegetation, age of vegetation.*

INTRODUCTION

Vegetation plays a crucial role in shallow slope stability and erosion control through both mechanical and hydrological mechanisms. Yen, as cited by Cazzuffi, classified root systems into five distinct categories based on their branching patterns: VH-type, H-type, V-type, R-type, and M-type. This classification, originally developed by Yen and later illustrated in Figure 1, highlights the varying effectiveness of root structures in stabilizing slopes (Cazzuffi et al., 2014). Among these, H-type and VH-type roots are particularly effective in combating soil erosion and enhancing slope stability. These root systems extend horizontally and vertically across the soil surface, creating a dense network that provides superior protection against the loss of topsoil. In contrast, R-type and M-type roots, while still beneficial, offer comparatively less resistance to erosion due to their less extensive branching patterns. Yen's analysis underscores the importance of selecting vegetation with H-type and VH-type root systems for optimal erosion control and slope stabilization.

Root networks contribute to hillslope stability through two key mechanisms: root pull-out resistance and enhanced soil cohesion (Wu, 2013; Fan et al., 2021). Key factors modulating this reinforcement include root architecture, soil moisture content, and vegetation type (Olinic et al., 2024). Under climate change, drought-induced root desiccation dynamically alters shear strength parameters, demanding context-specific assessments (Boldrin et al., 2018).

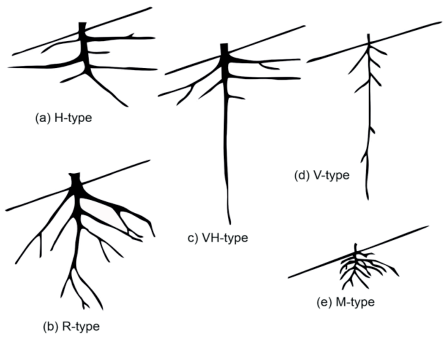

Figure 1. The root structure classified by Yen (recreated figure)

Optimal mitigation of land degradation requires detailed knowledge of site-specific soil materials, weather patterns, and terrain behaviour across diverse regions. Through laboratory testing and FEM simulations, Zhou et al. (2023) assessed how root-soil composite shear resistance varies across plant developmental stages and influences slope reinforcement mechanisms.

This work aims to: synthesize practical insights on plant species selection for erosion control and slope stability; to evaluate species-specific efficacy in improving mechanical shear strength parameters, and to demonstrate that slope reinforcement by root systems is strongly governed by soil moisture dynamics.

MATERIALS AND METHODS

A systematic literature review was conducted from June 2022 to present, using Web of Science and Scopus databases, covering publications written in English. Primary search terms ('soil-roots system', 'soil erosion', 'shear strength' and 'shallow slope stability') identified candidate studies. Subsequent screening eliminated duplicates and prioritized research aligned with sustainable development principles. This process yielded 3 review articles addressing shear strength parameters of soil-roots applications for soil erosion control and shallow slope stability.

RESULTS AND DISCUSSIONS

Type of vegetation

Based on the critical role of vegetation type in determining erosion control efficacy and slope stabilization performance, key species analyzed in this review - including grasses (*Chrysopogon zizanioides, Elytrigia elongata, Panicum virgatum*) and threes/shrubs (alder - *Alnus* spp., paper Mulberry - *Broussonetia papyrifera*). They demonstrate how root biomechanics, soil adaptability, and hydrological resilience govern their suitability for geoenvironmental applications (Francis et al., 2005; Bischetti et al., 2005; Cazzuffi et al., 2006; Cazzuffi et al., 2014; Fan et al., 2021).

Table 1. The core strengths of various vegetation species, emphasizing their biomechanical properties, environmental adaptability, and erosion control performance (Francis et al., 2005; Bischetti et al., 2005; Cazzuffi et al., 2006; Cazzuffi et al., 2014; Fan et al., 2021)

Plant Species	Key strengths	Tensile strength (MPa)	Root depth	Environmental adaptability	Performance in erosion control
Chrysopogon zizanioides	Highest root density; deep vertical roots; tolerates pollutants/saline soils	25–60	4–5 m	pH 4–11; drought/flood/saline-tolerant	Very good: cohesion gain: ≤15 kPa; rapid stabilization
Cortaderia selloana	Drought-resistant; forms dense root mats; thrives in poor soils	15–23	3–4 m	Sandy/rocky substrates; full sun	Good: 90% survival in drought season; reduces surface erosion
Corylus avellana	Exceptional tensile strength; deep anchoring	≤60	>2 m	Temperate forests; well-drained soils	Good: superior slope reinforcement; high RAR in topsoil
Elytrigia elongata	Robust fibrous roots; high tensile strength per diameter	38–55	3–4 m	Dry, nutrient-poor soils; heat-tolerant	Medium: Good for arid slopes; moderate cohesion gain
Alnus alnobetula	Nitrogen-fixing; improves soil fertility; cold-adapted	~35	1–2 m	Alpine/subalpine zones; resists frost	Medium: enhances soil structure; moderate erosion reduction
Panicum virgatum	Evergreen; saline-tolerant; persistent ground cover	25–70	≤2 m	Coastal/arid regions; full sun	Medium: long-term resilience; slower initial growth
Broussonetia papyrifera	Pioneer species; fast-growing in disturbed soils	Depending on the diameter	≤1 m	Collapsed slopes; low-moisture soils	Low: limited use in saturated soils: strength drops to 64%

Shear strength

Depending on the soil types analysed and the plant species employed in stabilization techniques, an increase in shear strength parameters is consistently observed in root-reinforced soils compared to those without vegetation. Most commonly, stabilization is applied to soils with inherently low cohesion - such as sandy or silty soils, where the contribution of roots to improved cohesion is particularly evident.

A study conducted by Zhou et al. (2023) confirms that the presence of plant roots substantially increases shear resistance. Direct shear tests on unrooted soil (bare soil) indicated a cohesion (c) of 33.2 kPa and an internal friction angle (φ) of 23.8°. In contrast, the soil-root composite with various plant types - namely *Cynodon dactylon* (Cd), *Magnolia multiflora* (Mm), and a grass-shrub mixture (Gs) recorded significantly higher values: cohesion ranged from 34.1-82.8 kPa (Cd), 49.5-72.9 kPa (Mm), and 36.8-99.8 kPa (Gs), while φ increased up to 39.1°. The maximum of 99.8 kPa (Gs, after 90 days) is three times higher than that of the bare soil, demonstrating the effective contribution of roots to the stabilization of the soil mass.

A study by Olinic & Olinic (2025) investigates the influence of plant roots on the shear strength parameters of sandy soils. Direct shear tests conducted on bare sand (BS) revealed a low cohesion value (c) of 1.24 kPa and an internal friction angle (φ) of 32.94°. They studied a root system composed of *Medicago sativa, Dactylis glomerata, Phleum pratense*, and *Trifolium* species which was growth in greenhouse conditions, cohesion increased to 23.43 kPa, representing a 1790% rise (because of the low value of unrooted soil), while the friction angle remained relatively stable at 32.35°, indicating a substantial reinforcement effect in sandy soils.

In the case of organic soil, a different behaviour was observed. Although the presence of roots reduced cohesion from 36.11 kPa (bare organic soil) to 29.72 kPa (approx. 18% decrease), the internal friction angle improved significantly, rising from 19.57° to 35.21°, an increase of nearly 80%. This pattern suggests that while roots may loosen compact soils, thereby reducing cohesion, they enhance internal friction through the mechanical interlocking effect of dense root networks.

The study further emphasizes that the reinforcement effect is most pronounced in the surface layer (0-5 cm), where root density is highest. For example, cohesion in sand drops to 10.65 kPa at 20-25 cm depth, indicating diminishing reinforcement with depth. These findings highlight the value of using dense-rooted vegetation as a sustainable and effective strategy for shallow slope stabilization and erosion control.

Growth period of vegetation

The type of vegetation and its temporal development dramatically influence reinforcement efficiency. In the study conducted by Zhou et al. (2023), the Gs mixture provided the best performance, owing to its complementary root structure: under a normal stress of 200 kPa, its shear strength was 15-30% higher than that of the other plant types. Furthermore, strength evolved nonlinearly over time, peaking at 90 days after germination (for both cohesion and shear resistance), followed by a slight decrease at 120 days. This pattern highlights the importance of species selection and optimal implementation timing. The effect depends on plant age and species: maximum performance is reached between 90-120 days, and Gs shows clear superiority over monoculture. These conclusions provide a scientific basis for designing ecological slope protection systems.

Also, stability analyses using the finite element method (FEM) validated the practical benefits of plant roots on the factor of safety (FS), resulting in an increase of 1.7-15.7% compared to slopes without vegetation (FS = 1.48).

Specifically, slopes planted with Gs had the highest value (FS = 1.72), followed by those with Mm (FS = 1.66), and those with Cd recorded the lowest value (FS = 1.60).

Hydric stress

Hydric stress (water deficiency or excess) influences plant physiology, root development, and ultimately, soil reinforcement capacity.

Roots improve slope stability via mechanical reinforcement (e.g., tensile strength, soil-root bond strength) and hydrological regulation (Wu et al., 2013; Fan et al., 2021).

Hydric stress significantly alters root architecture, directly impacting soil cohesion (c) and friction angle (ϕ). Under drought conditions, moderate water deficits can enhance deep-rooting in resilient species like *Salix elaeagnos*, increasing root tensile strength and soil cohesion by up to 25% due to adaptive root elongation, as demonstrated in cyclic drying experiments (Ghestem et al., 2011). Conversely, severe drought triggers root shrinkage and mortality, reducing root density by 50% and diminishing shear strength by 18-22% due to weakened root-soil interlocking, elevating landslide risks (Ng et al., 2016).

Waterlogging equally compromises shear strength through root degradation. Prolonged saturation depletes soil oxygen, causing root rot in sensitive species like *Alnus incana*, which exhibits 35% biomass loss and 40% tensile strength reduction (Francis et al., 2005). Saturated conditions also induce fiber slippage and diminish root-soil friction, leading to 30-50% cohesion loss in root-soil systems, as quantified by Ghestem et al. (2011). These biomechanical failures critically undermine slope stability during extreme hydric events.

Recent studies demonstrate that soil moisture dramatically influences root-soil resistance. Fan et al. (2021) observed a 63.9% decrease in pullout resistance under high moisture conditions (w = 30.6%), compared to low moisture conditions (w = 6.5%). This decline is attributed to reduced soil cohesion and the formation of water films at the root-soil interface. Furthermore, a critical root diameter threshold (3 mm in dry soil vs. 7 mm in wet soil) was identified, determining the transition between failure by breaking versus pullout. Field tests, which account for the intertwining of root hairs with soil, yield values 3-15 times greater than laboratory tests, underscoring the necessity of in situ evaluations. This integration highlights the impact of water stress on slope stabilization mechanisms, providing an empirical basis for risk management recommendations under extreme climatic conditions

Climate-induced hydric stress (drought/floods) compromises root functionality, escalating landslide risks (Boldrin et al., 2018; Francis et al., 2005).

The use of vegetation in sustainable soil stabilization and erosion control provides numerous benefits, but also presents certain challenges that require careful evaluation. As shown in Figure 2, root systems bind soil particles, increasing shear strength and reducing susceptibility to erosion (creating a natural reinforcement mechanism). As an eco-friendly and cost-effective solution is well known that vegetation-based methods are sustainable, require low maintenance once established, and are generally less expensive than hard engineering solutions (Stokes et al., 2014). Along with the other strengths, the use of vegetation in sustainable soil stabilization and erosion control enhances biodiversity, promotes carbon sequestration, improves soil structure, and regulates hydrological cycles.

The weaknesses of the use of vegetation in soil stabilization and erosion control depend on a required growth period needed for root systems to get mature and effectively stabilize the slope; effectiveness depends on local soil, climate and plant species and requires careful selection and site-specific planning. Also, drought of frost can weaken root systems, reducing stabilization capacity during critical periods (Lüscher et al., 2020).

The use of vegetation in soil stabilization and erosion control can be combined with bioengineering and nature-based solution making an opportunity in order to align with global and EU strategies on climate resilience, land reclamation and disaster risk reduction (Mickovski, 2021, Olinic & Olinic, 2025).

The threats are related to: climate change - increased frequency and intensity of rainfalls which may exceed root system capabilities, triggering shallow landslides (Noviandi et al., 2025), land-use conflicts - when the expansion of urban of agricultural land may limit vegetation-based slope interventions) and invasive species risk - non-native or poorly managed vegetation may disrupt local ecosystems or fail to provide stabilization (Sladonja and Poljuha, 2018).

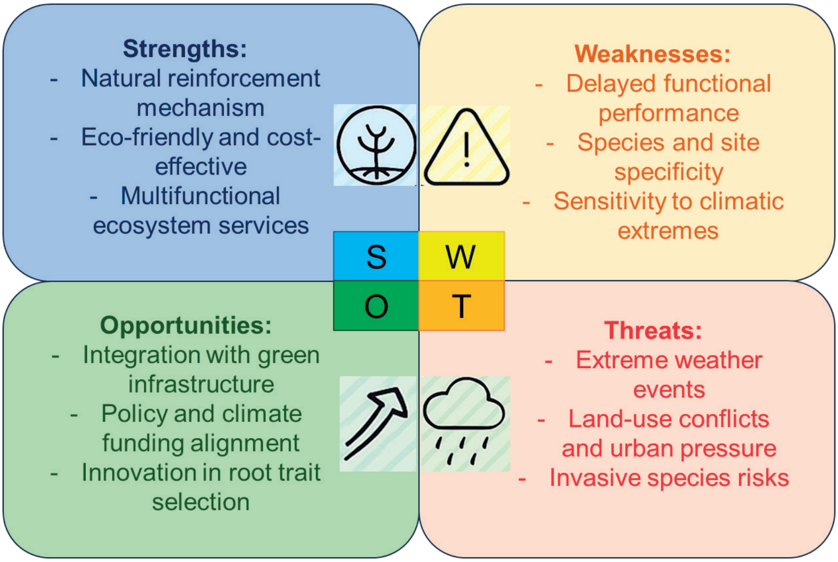

Figure 2. Vegetation for slope stabilization and surface erosion control

CONCLUSIONS

The shear strength parameters of soil-root systems are dynamic and highly sensitive to water stress. Effective slope stabilization strategies must incorporate (1) the selection of plant species based on their eco-physiological tolerance, and (2) the optimization of soil properties to mitigate the impacts of climate change.

Vegetation root systems significantly enhance slope stability through soil-root cohesion, with shear strength parameters serving as critical stability indicators. This review synthesizes global research on soil-root interactions across plant species and soil types, with emphasis on hydraulic stress impacts from climate change. Results demonstrate that root desiccation reduces shear strength by up to 64%, while interspecies variability in drought/flood tolerance dictates survival and reinforcement capacity. We argue that integrating root biomechanics with eco-physiological resilience is essential for sustainable slope management.

Plant roots, especially in the case of grass and shrub mixtures offer a sustainable solution for soil stabilization. Through the combined effect of deep roots (anchoring) and shallow roots (mechanical reinforcement), they reduce erosion and the risk of shallow landslides.

Vegetative root systems contribute to improving soil moisture regulation by facilitating water uptake and retention, thereby mitigating the likelihood of landslides triggered by slope saturation. In contrast to unsaturated, unvegetated slopes, analysing seepage and stability in vegetated terrains necessitates accounting for transpiration-induced variations in matric suction and the modified hydrological behaviour of soils influenced by plant activity.

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