

Analysis of bank slope stability considering vegetation hydro-mechanical reinforcement Abstract: Vegetation can effectively enhance the stability of bank slopes through mechanical reinforcement and hydrological effects. However, current research often focuses on a single aspect, lacking a compreh...

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Abstract

The banks in the middle and lower reaches of the Tarim River in China are weak in erosion resistance and prone to collapse. Vegetation, as a natural reinforcement material, can effectively improve slope stability and curb soil erosion. In March and July 2023, a field survey was conducted on the types and distribution characteristics of vegetation along both banks of a certain section in the lower reaches of the Tarim River. Taking COMSOL Multiphysics as the finite element numerical simulation platform, we investigated the variation law of bank slope stability in the middle and lower reaches of the Tarim River under different root morphologies, considering changes in transpiration time, rainfall, and water level under the action of hydro-mechanical reinforcement. The findings showed that vegetation transpiration has a significant effect on soil pore water pressure. Given the same transpiration rate, shorter root systems produced greater pore water pressure. For equal root lengths, the pore water pressures generated by roots in exponential and triangular morphologies were significantly greater than those generated by roots in uniformly distributed and parabolic morphologies. The water absorption capacity of the root system increased with transpiration rate. After 7 d of transpiration, the maximum safety factor of the bank slope reinforced by exponential roots was 1.568, which was a 9.88% improvement over that of the bare slope. After 24 h of rainfall, the effect of vegetation transpiration on soil pore water pressure weakened rapidly; the pore water pressure of the surface soil generated by transpiration from vegetation with different root morphologies was concentrated near -10.00 kPa. After rainfall, the displacement of

the exponential root reinforced slope was minimized to 0.137 m. The effect of transpiration-induced changes in substrate suction on slope stability was negligible during the rainfall period. Compared with that of the bare slope, the displacements of bank slopes reinforced by root systems significantly increased. The maximum displacement occurred when the water level changed by 1.5 m/d; the displacement of the bare slope was 0.554 m, whereas the displacements of bank slopes reinforced by roots in different morphologies were 0.260–0.273 m. The impact of vegetation transpiration on the safety factor of riverbanks under sudden water level drops was relatively minor, but it can enhance the stability of riverbanks to a certain extent. Among these, riverbanks reinforced by roots in triangular and exponential morphologies exhibited superior stability compared with those reinforced by uniformly distributed or parabolic root systems. The findings offer a theoretical basis and practical guidance for designing vegetation slope protection in the middle and lower reaches of the Tarim River.

Full Text

Preamble

J Arid Land (2026) 18(2): 280–303 doi: 10.1016/j.jaridl.2025.09.001; CSTR: 32276.14.JAL.20250205 Analysis of bank slope stability considering vegetation hydro-mechanical reinforcement TIAN Nianfeng^{1,2}, ZHANG Lingkai^{1,2*}, SUN Jin^{1,2} 1 College of Hydraulic and Civil Engineering, Xinjiang Agricultural University, Urumqi 830052, China; 2 Xinjiang Key Laboratory of Water Conservancy Engineering Safety and Water Disaster Prevention and Control, Urumqi 830052, China Abstract: The banks in the middle and lower reaches of the Tarim River in China are weak in erosion resistance and prone to collapse. Vegetation, as a natural reinforcement material, can effectively improve slope stability and curb soil erosion. In March and July 2023, a field survey was conducted on the types and distribution characteristics of vegetation along both banks of a certain section in the lower reaches of the Tarim River. Taking COMSOL Multiphysics as the finite element numerical simulation platform, we investigated the variation law of bank slope stability in the middle and lower reaches of the Tarim River under different root morphologies, considering changes in transpiration time, rainfall, and water level under the action of hydro-mechanical reinforcement. The findings showed that vegetation transpiration has a significant effect on soil pore water pressure. Given the same transpiration rate, shorter root systems produced greater pore water pressure. For equal root lengths, the pore water pressures generated by roots in exponential and triangular morphologies were significantly greater than those generated by roots in uniformly distributed and parabolic morphologies. The water absorption capacity of the root system increased with transpiration rate. After 7 d of transpiration, the maximum safety factor of the bank slope reinforced by exponential roots was 1.568, which was a 9.88% improvement over that of the bare slope.

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pressure weakened rapidly; the pore water pressure of the surface soil generated by transpiration from vegetation with different root morphologies was concentrated near -10.00 kPa. After rainfall, the displacement of the exponential root reinforced slope was minimized to 0.137 m. The effect of transpiration-induced changes in substrate suction on slope stability was negligible during the rainfall period. Compared with that of the bare slope, the displacements of bank slopes reinforced by root systems significantly increased. The maximum displacement occurred when the water level changed by 1.5 m/d; the displacement of the bare slope was 0.554 m, whereas the displacements of bank slopes reinforced by roots in different morphologies were 0.260 – 0.273 m. The impact of vegetation transpiration on the safety factor of riverbanks under sudden water level drops was relatively minor, but it can enhance the stability of riverbanks to a certain extent.

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Keywords: bank slope; slope stability; root morphologies; vegetation transpiration; COMSOL Multiphysics; Tarim River Citation: TIAN Nianfeng, ZHANG Lingkai, SUN Jin. 2026. Analysis of bank slope stability considering vegetation hydro-mechanical reinforcement. *Journal of Arid Land*, 18(2): 280–303. <https://doi.org/10.1016/j.jaridl.2025.09.001>; <https://cstr.cn/32276.14.JAL.20250205> *Corresponding author: ZHANG Lingkai (E-mail: xjauzhanglk@163.com) Received 2025-05-17; revised 2025-08-29; accepted 2025-09-03 © 2026 Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, and Science Press. Publishing services by Elsevier B.V. on behalf of KeAi Communications Co. Ltd.

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1 Introduction

The collapse of a riverbank is a phenomenon of collapse, landslide, and slumping caused by the destruction and erosion of the soil, or other components of the riverbank due to the hydraulic action of the river. The Tarim River is located at the edge of the arid Tarim Basin, China. As the longest inland river in China, the Tarim River is characterized by wind-deposited sandy soil-dominated riverbanks in its middle and lower reaches due to its special geographical location; such soils exhibit poor scour resistance and are highly prone to slumping and bank failure (Yu et al., 2017). Vegetation is widely used in bank slope protection projects because of its significant effects on bank slope reinforcement, resistance to water

scour, prevention of soil erosion, and protection of the ecological environment (Wiel and Darby, 2007; Shen et al., 2023; Zhang et al., 2024a).

The influence of vegetation on riverbank erosion is reflected mainly in the changes of soil characteristics caused by its roots and the hydrological effects on plant growth (Bischetti et al., 2009; Bordoni et al., 2016). Plants hold the soil and increase its resistance to erosion by interlocking and interspersing the root system. Moreover, plants increase the stability of riverbanks by changing the permeability, water content, and substrate suction of the soil during their growth. Soils usually have good compressive strength but weak tensile properties, and plant root systems have high tensile strength but low compressive strength, so the root system and the soil form a complex with good tensile and shear strengths (De Baets et al., 2008; Forster et al., 2022). Wu et al. (1979) combined a series of related experiments to establish a calculation model for the shear strength of a root-soil composite, and quantitatively analyzed the influence of vegetation roots on the shear strength of soil for the first time. Since then, many scholars have proposed other root-soil fixing models on this basis (e.g., Ekanayake and Phillips, 1999; Pollen and Simon, 2005), which further enriched the theory of vegetation soil fixation. At present, the mechanical effects of vegetation have been widely studied (Mickovski et al., 2009; Kokutse et al., 2016), but the hydrological effects of plants are often ignored (Stokes et al., 2014). Studies have shown that when calculating slope stability, ignoring the hydrological effects of vegetation will underestimate the safety factor of the slope (Pollen-Bankhead and Simon, 2010; Boldrin et al., 2017). In arid or semi-arid channels and rivers, the hydrological characteristics of riverbanks are particularly evident because they are usually unsaturated and are therefore sensitive to changes in water content. Many studies revealed that plant roots have significant effects on the soil suction distribution, water holding capacity, permeability, and pore water pressure (Leung et al., 2015a; Jotisankasa and Sirirattanachat, 2017). Indraratna et al. (2006) reported that vegetation roots can increase the strength of soil by enhancing matrix suction. Studies have shown that the decrease in shear strength caused by the loss of matric suction is one of the main reasons for the failure of bank slopes in incised river channels (Simon et al., 2000). Vegetation transpiration has a significant effect on soil matrix suction. The method by which vegetation generates suction through transpiration, thereby reducing the soil moisture content and pore water pressure and increasing the soil shear strength, is known as the hydrological effect of vegetation. Research has indicated that matric suction caused by transpiration can significantly enhance slope stability (Ni et al., 2018; Patil et al., 2021). In summary, vegetation roots can not only improve the slope stability via mechanical reinforcement, but also have an important effect on the distribution of water in slopes and the overall stability of slopes via transpiration (Leung et al., 2017; Zhu and Zhang, 2019). Therefore, in the analysis of bank slope stability, the establishment of a bank slope model considering hydro-mechanical reinforcement can more accurately reveal the influence mechanism of vegetation slope protection.

Based on the above conclusions, this study took the bank slopes in the middle and lower reaches of the Tarim River as the research object and used COMSOL Multiphysics as the finite element numerical simulation platform. We selected the typical riparian vegetation and simplified its root structures into four common morphological types representing natural conditions. By analyzing the hydro-mechanical effect of vegetation slope protection and using JOURNAL OF ARID LAND 2026 Vol. 18 No. 2 vegetation transpiration to quantify the hydrological effect of roots, we established a hydro-mechanical reinforcement model and verified the validity of the model using a root water uptake model. Finally, we evaluated the differences in the hydro-mechanical reinforcement of vegetation roots in different morphologies considering changes in transpiration time, rainfall, and water level, and analyzed the effects of different root morphologies on the stability of bank slopes. This study can provide a theoretical basis and guidance for vegetation slope protection projects and offer valuable references for enhancing ecological protection capacity, promoting soil and water conservation, and facilitating ecological restoration in the middle and lower reaches of the Tarim River Basin.

2.1 Regional overview and root simplification

The Tarim River originates from the Tianshan Mountains and Kunlun Mountains, with a drainage area of approximately 1,020,000 km² and a total length of about 2350 km. It is the longest inland river in China. Located in an arid inland region, the Tarim River experiences high evaporation rates and limited rainfall. In recent decades, due to the impact of climate change, the ecological problems such as bank slope collapse, river swing, and soil erosion of the Tarim River have become obvious. The present situation of riverbank collapse and riverbed shrinkage is shown in Figure 1 [Figure 1: see original paper].

Fig. 1 Schematic diagram of bank collapse (a and b) and riverbed shrinkage (c and d) of the Tarim River Vegetation is commonly employed as an effective revetment method. Trees, shrubs, and other plants are extensively distributed in the middle and lower reaches of the Tarim River, and primarily located along both riverbanks. In March and July 2023, the research team conducted a field survey on the types and distribution characteristics of vegetation along both banks of a certain section in the lower reaches of the Tarim River in Bayingol Mongolian Autonomous Prefecture by visiting and investigating. According to the field data, four plant species—*Populus euphratica*, *Tamarix ramosissima*, *Alhagi camelorum*, and *Haloxylon ammodendron*—are selected as the focus of this study, as shown in Figure 2 [Figure 2: see original paper].

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Fig. 2 Photos showing the four plant species selected in the study. (a), *Populus euphratica* and *Tamarix ramosissima*; (b), *Alhagi camelorum*; (c), *Haloxylon ammodendron*.

The root morphology of vegetation is an important parameter affecting the ef-

fect of slope protection. The root morphology of vegetation is mainly affected by the age, species, and genetic factors of vegetation. Some important environmental factors such as seasonal changes, soil conditions, and groundwater level depth will also affect the root morphology of vegetation (Dupuy et al., 2005; Zhang et al., 2024b). The roots growing in natural environments have complex shapes, which are influenced by a variety of factors. Based on the theory of root simplification (Ng et al., 2015), the root morphology can be simplified into four types: uniformly distributed, triangular, exponential, and parabolic, and described using root distribution functions (Eq. 2). This simplification is based on ideal conditions and ignores the influence of environmental and biological factors, which may cause differences in root morphology and water absorption capacity. In this study, we did not consider the factors such as the growth state and age of the root morphology of the vegetation. In the whole root system area, the root system was considered to be fully distributed (i.e., the slope protection difference caused by the spacing and density of the vegetation was not considered), and the water absorption property of the root system was only studied from the perspective of root morphology. For the convenience of comparison, the total root surface area was kept constant when root systems of different morphologies had the same length. The simplified root morphology of each plant is shown in Figure 3 [Figure 3: see original paper]. The uniform root zone was evenly distributed with depth, the triangular root zone decreased linearly with depth, the exponential root zone changed exponentially with depth, and the parabolic root zone changed parabolically.

2.2.1 Consideration of the seepage control equation for root water uptake

The hydrological effects of vegetation mainly refer to its ability to intercept rainfall and extract moisture from the soil. Studies have shown that the canopy retention rate of deciduous tree species generally ranges between 10.00% and 20.00% (Coppin and Richards, 1990). However, these data are annual average values under continuous closed conditions. In reality, canopy interception is affected by various factors such as tree height and wind speed. Under heavy rainfall conditions, the canopy interception rate is lower, making it difficult to quantify accurately. Therefore, this study did not consider the canopy retention capacity. The hydrological JOURNAL OF ARID LAND 2026 Vol. 18 No. 2 Fig. 3 Simplification of the four plant species effects in this study mainly refer to the process whereby vegetation reduces soil water content and pore water pressure and increases soil shear strength through the suction generated by transpiration. The mechanisms underlying soil-vegetation interactions and plant water stress responses are complex and involve numerous influencing factors, so they were not considered in this model. Most of the water absorbed by plant roots is used for transpiration, so the transpiration rate can be approximated by the root water uptake rate to study the hydrological effects of vegetation.

Currently, theoretical models of root water uptake are primarily classified into

micro-models and macro-models (Peddinti et al., 2020). Micro-models are rarely used in actual analysis due to their complex structure, numerous assumptions, and difficulty in measurement and parameter acquisition. Macro models treat the root system and soil as a whole, defining root water uptake as a source-sink term inserted into the Richards equation. This method has been proven to be feasible and effective. The expression for the water uptake rate $S(\psi, Z)$ of plant roots is as follows: where ψ is the matric suction in soil (kPa); Z indicates the root depth perpendicular to the slope (m); T_p refers to the potential transpiration rate of the plant (m/s); $\alpha(\psi)$ represents the reduction rate of root water uptake; and $\beta(Z)$ is the root shape function. Under natural conditions, the transpiration rate is low but occurs over a prolonged period. Based on the field measurement data on the main species in the arid regions of Northwest China obtained from Zhang et al. (2021), the average water consumption during the main growing season (April–September) of each species type was selected as the average transpiration rate (4.40 mm/d). The water consumption of *Tamarix ramosissima* was selected as the maximum transpiration rate (6.56 mm/d), and the water consumption of *Haloxylon ammodendron* was the minimum transpiration rate (1.61 mm/d). The $S(\psi, Z)$ is also influenced by the soil's matric potential. Feddes et al. (1974) introduced $\alpha(\psi)$ as a function dependent on the matric potential. Its expression is: 1 if $\psi > \psi_1$ where ψ_1 indicates the soil matric suction at the anaerobic point (kPa); ψ_2 represents the soil matric suction at the point when root water uptake is reduced (kPa); and ψ_3 is the soil matric suction at the wilting point (kPa). According to the research by Nyambayo and Potts (2010), ψ_1 , ψ_2 , and ψ_3 were typically set to 5.00, 100.00, and 1500.00 kPa, respectively. The expression of $\beta(Z)$ is shown in Equation 3:

TIAN Nianfeng et al.: Analysis of bank slope stability considering vegetation ... (Uniformly distributed) (Triangular) (Parabolic) (Exponential) where Z_r denotes the root depth (m). Considering the changes in root system characteristics caused by differences in vegetation species, root samples with root depths of 0.400, 0.700 and 1.000 m were selected for the four root morphology types to conduct computational analysis. The relationship between $\beta(Z)$ and root depth is illustrated in Figure 4 [Figure 4: see original paper].

Fig. 4 Root distribution function of different root morphology types. $\beta(Z)$ is the root shape function, where Z indicates the root depth perpendicular to the slope.

The Richards equation is generally employed to describe the infiltration process in unsaturated soils. By including $S(\psi, Z)$ as a sink term in the equation, the Richards equation that accounts for plant root water uptake can be formulated as follows: $\epsilon \rho \rho$ Substituting Equations 5 and 6 into Equation 4 yields: $+\nabla -$ where t is the time (s); ϵ is the porosity; ρ stands for the fluid density (kg/m³); ∇ is the gradient operator; u is the Darcy velocity (m/s); S_e is the effective saturation; S denotes the water storage coefficient (1/Pa); C_m is the specific water capacity (1/m); g represents the gravitational acceleration (m/s²); p is the pore water pressure (kPa); k_s is the saturated hydraulic conductivity

(1/m); k_r is the relative permeability (m/s); y refers to the coordinate in the y -direction.

Taking C_m as $\rho g(\partial\theta/\partial p)$ (where θ is the volumetric water content (cm³/cm³)), and neglecting the compressibility of soil and water (with $S=0$), the first term of Equation 7 was simplified as follows:

JOURNAL OF ARID LAND 2026 Vol. 18 No. 2 Then, by calculating the $H\nabla$ (where H is the total hydraulic head (m)) using the equation: the main and multiplying both sides by ρg yields: $\nabla = \nabla + \nabla = \nabla$ body of the second term in Equation 7 can be simplified as follows: $\nabla \cdot$ (9) Since the equation is for a two-dimensional flow (horizontal x and vertical y), the divergence operator ∇ can be expanded to:

Substituting the results of Equations 8-10 into Equation 7, the modified Richards equation can be expressed as:

The van Genuchten model is used for the soil-water characteristic curve and the permeability function curve in the model. The volumetric water content of the soil can be calculated using the equation as follows: θ_r where θ_r is the soil residual volumetric water content (cm³/cm³); θ_s is the soil saturated volumetric water content (cm³/cm³); h is the pressure head (m); and α , m , and n are the fitting parameters in the van Genuchten model, with $m=1-1/n$. The relative permeability coefficient of unsaturated soil can be calculated as:

2.2.2 Mechanical reinforcement model of vegetation

The shear strength of soil has an important influence on slope stability. The increase of soil shear strength caused by roots can be described as: where τ is the shear strength of the root soil (kPa); c' is the soil cohesion (kPa); c_r' is the cohesion provided by the root system (kPa); σ is the normal stress (kPa); u_w is the pore water pressure (kPa); and ϕ is the internal friction angle of the soil (°). \tan The contribution of roots to soil shear strength can be simplified as the increase of soil cohesion.

Schwarz et al. (2010) modified the root-soil reinforcement model, which can be simplified as: where ζ is the correction factor and equals 0.4 in the present study; T_r is the average tensile strength of the root system (MPa); R_f represents the root orientation factor and equals 1.2 in the present study; and RAR is the root area ratio (%). According to Zong et al. (2018) and Sun and Zhang (2024), the tensile strength of typical vegetation root systems in the Tarim River Basin is mainly concentrated in 10.0-30.0 MPa, so this study took a value of 25.0 MPa considering the influence of root diameter. Relevant studies show that RAR typically falls between 3.00% and 5.00% (Eab et al., 2015), so this study took 4.00% as the applied value. Because the root system TIAN Nianfeng et al.: Analysis of bank slope stability considering vegetation...mainly improves the shear strength by enhancing the cohesion of the soil, the change of the internal friction angle caused by the root system was not considered.

2.3 Validation of the root water uptake model and numerical simulation

The mechanism of mechanical reinforcement of vegetation roots has been fully verified in previous studies (e.g., Murgia et al., 2022). In this section, a root water uptake model was constructed using numerical simulation, and the rationality of the numerical model was verified through comparison with the laboratory experimental results reported by Ng et al. (2013). The experimental data from Ng et al. (2013) were used to verify the simulation results of the numerical model. The test device is shown in Figure 5 [Figure 5: see original paper]. The test soil was completely decomposed granite (CDG), which can be classified as silt according to the soil classification standard. The gravel, sand, silt, and clay contents of CDG were 19.00%, 42.00%, 27.00%, and 12.00%, respectively. Each test chamber was compacted with silt, the target weight water content was 12.00%, and the dry density was 1496 kg/m³. The plant used in the experiment was *Cynodon transvaalensis*, which is widely used in the construction of grassland and slope protection in China. *C. transvaalensis* is a typical herbaceous plant species. The root system has obvious vertical downward growth characteristics, so the water absorption distribution of the root system is the same as that of the uniformly distributed root. The relevant parameters of vegetation, soil, and environment are shown in Table 1.

Fig. 5 Schematic diagram of test device. (a), plan view; (b), section view. d , diameter.

Table 1 Main parameters in model test

Parameter	Zr (m)	ρ_d (kg/m ³)	ks (m/s)
Value	2.2	1.0×10^{-6}	Parameter θ_s (cm ³ /cm ³)
Parameter	Rh (%)	Φ (W/m ²)	Value 53.00
Parameter	θ_r (cm ³ /cm ³)	Ta (°C)	Note: Zr is the root depth; ρ_d is the dry density; ks is the saturated hydraulic conductivity; θ_s is the soil saturated volumetric water content; θ_r is the soil residual volumetric water content; Ta is the air temperature; Rh is the relative humidity; Φ is the light radiation.

Figure 6 [Figure 6: see original paper] shows the cloud diagram of negative pore water pressure in different periods of numerical simulation. With the transpiration of vegetation, the water in the soil was gradually absorbed. In the root zone, the water in the soil was gradually absorbed by the root system, and a 'crescent' shaped negative pore water pressure area was formed in the root zone. The pore water pressure of the soil gradually increased with the transpiration time, and reached its maximum (90.75 kPa) when the time reached 20 d. The simulation results showed that vegetation transpiration has a great influence on the pore water pressure of soil.

Figure 7 [Figure 7: see original paper] shows the comparison between the simulation results of the numerical model and the experimental measurements. The simulation results were basically the same as the experimental JOURNAL OF ARID LAND 2026 Vol. 18 No. 2 results. The maximum relative error was 14.64%. In engineering, the error range between the simulated value and the experimental value is usually within $\pm 20.00\%$ (Bracmort et al., 2006; Zhang et

al., 2007), which is considered acceptable. Therefore, it can be considered that the root water uptake model used in this study is reasonable. In addition, the matrix suction of the soil gradually increased with the transpiration of vegetation, and the matrix suction was linearly related to the depth; with the increase of transpiration time, the change of matrix suction gradually slowed down, and finally the matrix suction tended to be stable in the whole soil profile (Fig. 7).

Fig. 6 Pore water pressure diagrams when transpiration time was 0 d (a), 7 d (b), 14 d (c), and 20 (d). The black line in the figure represents the root zone.

Fig. 7 Comparison between simulation values and measurement values of soil matrix suction TIAN Nianfeng et al.: Analysis of bank slope stability considering vegetation...

2.4.1 Bank slope model and parameters

The research focused on the typical soil composition of the riverbank slopes in the middle and lower reaches of the Tarim River, which is characterized by silty sand. A representative riverbank was chosen to determine the dimensions and construct a bank slope model (Fig. 8 [Figure 8: see original paper]). The soil composition of the riverbank slope was silty sand. The slope had a height of 8.000 m, a top width of 4.000 m, a bottom length of 18.000 m, and an initial water level of 4.000 m, and the monitoring section was positioned at 8.000 m. Table 2 provides details of the main parameters in the bank slope model.

Fig. 8 Schematic of the bank slope model
 Parameter c' (kPa) ϕ ($^\circ$) k_s (m/s)
 Zr (m) Value 2.2×10^{-6} 0.400, 0.700, and 1.000
 Table 2 Model parameters
 Parameter Value θ_s (cm³/cm³) Parameter θ_r (cm³/cm³) ρ_{dmax} (g/cm³) Value
 Note: c' is the soil cohesion; ϕ is the internal friction angle; n, m, and α are the parameters of the van Genuchten model; ρ_{dmax} is the maximum dry density; v is the poisson' s ratio; e is the porosity ratio.

2.4.2 Boundary settings

A bank slope model was established using COMSOL Multiphysics. The model' s bottom was defined as a fixed no-flow boundary, and the sides were configured as roller supports. The left side was assigned a water pressure boundary corresponding to the initial river water level of 4.000 m, while the right side was set to a fixed no-flow water level of 4.200 m. The area above the water level was designated as a free boundary to allow for rainfall infiltration analysis. The initial conditions of each working condition were set with the steady-state calculation results as the initial values. The free triangular mesh was used for meshing. Because the change rule in the root zone was mainly studied, the mesh in the root zone was properly encrypted. Considering the limitations of the computational volume, the use of a refined mesh can better reflect the calculation results, so the root zone was divided using an ultra-refined mesh, and the remaining area was divided using a refined mesh. A total of 732 triangles were

created, including 406 mesh vertices. The mesh division and boundary settings are illustrated in Figure 9 [Figure 9: see original paper].

2.4.3 Calculation conditions

In the initial state, this study performed the steady-state seepage calculation on the bank slope and took the results as the initial values. The impact on slope stability was then assessed under four conditions: variations in root morphology, transpiration duration, rainfall effect, and water level fluctuation.

Plan group 1: 7-d transpiration analysis. We calculated the effect of root morphology on pore water pressure for three root depths (0.400, 0.700, and 1.000 m) at the same transpiration rate.

Then, we calculated the effect of different transpiration rates on pore water pressure at the same depth (1.000 m). Finally, we calculated the effect of 7-d transpiration on slope stability.

JOURNAL OF ARID LAND 2026 Vol. 18 No. 2 Fig. 9 Model grid and boundary setting diagram Plan group 2: Rainfall impact calculation. Using meteorological data, the historical maximum rainfall was determined as 96.00 mm/d. We then analyzed the variation pattern of pore water pressure in the bank slope under the influence of rainfall and employed the strength reduction method to evaluate slope stability.

Plan group 3: Water level change calculation. Starting with initial water levels, we considered the effect of a sudden water level drop. We set the water level changes to 0.5, 1.0, and 1.5 m/d, and compared stability variations of slopes reinforced by vegetation with different root morphologies under these rapid water level changes.

2.4.4 Initial permeation calculation

Figure 10 [Figure 10: see original paper] illustrates the initial pore water pressure and initial stress contour maps obtained from the seepage calculation under the starting conditions. The maximum initial pore water pressure was 41.18 kPa, and the minimum was -38.26 kPa. The maximum initial stress was 46.52 kPa, while the minimum was 3.11 kPa. The results from the initial state were used as the initial values for all subsequent working conditions.

Fig. 10 Initial pore water pressure (a) and initial stress (b) contour maps obtained from the seepage calculation under the starting conditions. The black line in the figure represents the root zone.

3.1.1 Effects of root transpiration on pore water pressure

Figures 11–13 show the distribution of pore water pressure generated by roots at depths of 0.400, 0.700, and 1.000 m under the same transpiration rate (4.40

mm/d). The pore water pressure gradually decreased as the root depth increased. The shorter the roots were, the more pronounced the change in suction at the surface of the slope. As the root depth increased, root water uptake affected pore water pressure over a more extensive area. The water absorption of the root system mainly affected the distribution of pore water pressure within the root zone. For uniformly distributed root morphology, the pore water pressures generated were -92.59, -75.26, and -62.54 kPa at root depths of 0.400, 0.700, and 1.000 m, respectively, which were 4.82, 3.91, and 2.83 times greater than the suction force of the bare slope at the corresponding depths. For triangular root morphology, the generated pore water pressures were -385.99, -135.73, and -119.96 kPa at TIAN Nianfeng et al.: Analysis of bank slope stability considering vegetation...Fig. 11 [Figure 11: see original paper] Distribution of pore water pressure generated by roots in different root morphologies at a root depth of 0.400 m under the average transpiration rate (4.40 mm/d). (a), uniformly distributed root; (b), triangular root; (c), exponential root; (d), parabolic root. root depths of 0.400, 0.700, and 1.000 m, respectively; these values were 20.10, 7.06, and 5.43 times greater than the suction force in the bare slope at the corresponding depths. For the exponential root morphology, the generated pore water pressures were -428.81, -160.03, -123.50 kPa at root depths of 0.400, 0.700, and 1.000 m, respectively, corresponding to suction forces approximately 22.33, 8.33, and 5.59 times greater than those in the bare slope. For parabolic root morphology, the pore water pressures generated were -90.45, -89.40, and -55.63 kPa at root depths of 0.400, 0.700, and 1.000 m, respectively, corresponding to suction forces approximately 4.71, 4.65, and 2.48 times greater than those in the bare slope. The exponential roots produced highest pore water pressures, followed by the triangular roots. The pore water pressures generated by the uniformly distributed and parabolic roots were relatively similar. The reason for this difference may be determined by the root system morphology function. For triangular and exponential root morphologies, the shorter the root system is, the greater the number of plant roots in the horizontal direction. As transpiration continues, these root systems absorb large amounts of water from the shallow soil layer, causing rapid water loss from the surface soil layer, forming a relatively large water potential gradient, and accelerating the speed at which water moves to the surface layer. This results in higher pore water pressures for triangular and exponential roots than for uniformly distributed and parabolic roots.

Figures 14 and 15 show the distribution of pore water pressure under different transpiration rates at a root depth of 1.000 m. Differences in transpiration rates strongly affected the water absorption capacity of root systems. The comparison revealed that exponential and triangular roots maintain high water absorption capacity at different transpiration rates. Given the maximum transpiration rate (6.56 mm/d), the pore water pressure generated by roots in uniformly distributed JOURNAL OF ARID LAND 2026 Vol. 18 No. 2 Fig. 12 [Figure 12: see original paper] Distribution of pore water pressure generated by roots in different root morphologies at a root depth of 0.700 m under the

average transpiration rate (4.40 mm/d). (a), uniformly distributed root; (b), triangular root; (c), exponential root; (d), parabolic root. morphology was -70.91 kPa, that generated by roots in triangular morphology was -282.98 kPa, that generated by roots in exponential morphology was -426.93 kPa, and that generated by roots in parabolic morphology was -130.46 kPa. Given the minimum transpiration rate (1.61 mm/d), the pore water pressure generated by roots in uniformly distributed morphology was -28.98 kPa, that generated by roots in triangular morphology was -38.28 kPa, that generated by roots in exponential morphology was -42.51 kPa, and that generated by roots in parabolic morphology was -30.95 kPa. The comparison revealed that under the same transpiration rate, difference in root morphology is the primary factor influencing root water absorption capacity. Under different transpiration rates, the root water absorption capacity increased as the transpiration rate increased.

In actual engineering protection, vegetation with a high transpiration rate can be selected for slope protection.

3.1.2 Impact of transpiration on the safety factor of bank slope

Figure 16 [Figure 16: see original paper] shows the safety factor of bare slope and bank slopes reinforced by roots in different root morphologies after 7 d of transpiration. Compared with the bare slope, slopes with vegetation transpiration had a significantly greater safety factor. The safety factors of the bare slope and bank slopes reinforced by roots in uniformly distributed, triangular, exponential, and parabolic morphologies were 1.427, 1.555, 1.567, 1.568, and 1.553, respectively. Considering the improvement in the safety factor of the slope under vegetation transpiration, the improvement range was about 8.82%–9.88%, with the most significant improvement of 9.88% observed for the exponential root morphology. As seen from the above analysis, exponential roots had a more significant water absorption capacity, and the water absorption function of root systems can TIAN Nianfeng et al.: Analysis of bank slope stability considering vegetation...Fig. 13 [Figure 13: see original paper] Distribution of pore water pressure generated by roots in different root morphologies at a root depth of 1.000 m under the average transpiration rate (4.40 mm/d). (a), uniformly distributed root; (b), triangular root; (c), exponential root; (d), parabolic root. significantly alter soil hydrological conditions. The root system absorbs water from within the soil, causing the degree of unsaturation of the soil to continuously increase, the pore water pressure to decrease, the matrix suction to increase, and the soil shear strength to increase, thereby increasing the safety factor of the bank slope.

3.2.1 Impact of rainfall on pore water pressure

Figure 17 [Figure 17: see original paper] shows the 24-h pore water pressure distribution of the bare slope and bank slopes reinforced by roots in different

morphologies under 96.00 mm/d rainfall condition. With the occurrence of rainfall, the pore water pressure in the soil gradually tended to be saturated, indicating that the difference between the soil matrix suction of root bank slopes and the soil matrix suction of bare slope decreased gradually with the rainfall. After 24 h of rainfall, the pore water pressure decreased sharply in all cases due to rainfall infiltration; the pore water pressure of the surface soil for the bare slope was -5.09 kPa, and the pore water pressure of the surface soil for root bank slopes was concentrated near -10.00 kPa. In spite of this, the root bank slopes still maintained a larger absolute value of negative pore water pressure compared with the bare slope.

The pore water pressure varied significantly within the root zone, yet it tended to converge to the same curve at a vertical depth of 1.500 m. Besides, the influence of root morphology on pore water pressure under rainfall was almost negligible, indicating that vegetation transpiration has little effect on pore water pressure under heavy rainfall. Rainwater infiltration caused by heavy rainfall is the main cause of soil matrix suction loss.

JOURNAL OF ARID LAND 2026 Vol. 18 No. 2 Fig. 14 [Figure 14: see original paper] Distribution of pore water pressure generated by roots in different root morphologies at a root depth of 1.000 m under the maximum transpiration rate (6.56 mm/d). (a), uniformly distributed root; (b), triangular root; (c), exponential root; (d), parabolic root.

3.2.2 Effect of rainfall on the safety factor of bank slope

Figure 18 [Figure 18: see original paper] shows the change in the safety factor of the bare slope and bank slopes reinforced by roots in different morphologies before and after rainfall. The safety factors of the bare slope and bank slopes reinforced by roots in different morphologies decreased by about 0.200 after rainfall, and the safety factors of root bank slopes were larger than those of the bare slope before and after rainfall. The safety factor of the bare slope after rainfall was 1.217. The safety factors of uniformly distributed, triangular, exponential, and parabolic root bank slopes were 1.352, 1.358, 1.360, and 1.351, respectively. The safety factor of the bare slope decreased by 14.71% after rainfall. The safety factors of uniformly distributed, triangular, exponential, and parabolic root bank slopes decreased by 13.05%, 13.33%, 13.26%, and 13.00%, respectively. There was little difference in the safety factor of slopes reinforced by roots in different morphologies after rainfall, and from the above analysis, we found that vegetation transpiration can be ignored during rainfall, indicating that the mechanical reinforcement of the root system is the main factor affecting the stability of the bank slope during rainfall.

Figure 19 [Figure 19: see original paper] shows the displacement of the bare slope and bank slopes reinforced by roots in different morphologies after rainfall. The maximum displacement of the slope occurred at the slope angle. Compared with the bare slope, slopes reinforced by vegetation roots showed a significant

reduction in displacement. However, slopes reinforced by roots in different root morphologies showed little difference in displacement changes after rainfall. The maximum displacement of the bare slope was 0.237 m, whereas the maximum displacements of the vegetation TIAN Nianfeng et al.: Analysis of bank slope stability considering vegetation...Fig. 15 [Figure 15: see original paper] Distribution of pore water pressure generated by roots in different root morphologies at a root depth of 1.000 m under the minimum transpiration rate (1.61 mm/d). (a), uniformly distributed root; (b), triangular root; (c), exponential root; (d), parabolic root.

Fig. 16 Safety factors of the bare slope and bank slopes reinforced by roots in different morphologies after 7 d of transpiration. A-E indicate bare slope, uniformly distributed root bank slope, triangular root bank slope, exponential root bank slope, and parabolic root bank slope, respectively.

JOURNAL OF ARID LAND 2026 Vol. 18 No. 2 Fig. 17 Distribution of 24-h pore water pressure of slopes reinforced by roots in different morphologies under 96.00 mm/d rainfall condition. (a), uniformly distributed root bank slope; (b), triangular root bank slope; (c), exponential root bank slope; (d), parabolic root bank slope.

Fig. 18 Variations in safety factor of the bare slope and bank slopes reinforced by roots in different morphologies before and after rainfall. A-E indicate bare slope, uniformly distributed root bank slope, triangular root bank slope, exponential root bank slope, and parabolic root bank slope, respectively. reinforced slopes were 0.152 m for uniformly distributed roots, 0.139 m for triangular roots, 0.137 m for exponential roots, and 0.156 m for parabolic roots. Among the four different root morphologies, triangular and exponential roots are more effective than uniformly distributed and parabolic roots in reducing slope displacement. In future engineering protection projects, root morphologies with triangular and exponential shapes can be selected for reinforcement.

TIAN Nianfeng et al.: Analysis of bank slope stability considering vegetation ...Fig. 19 Displacement diagram of the bare slope and bank slopes reinforced by roots in different morphologies after rainfall. (a), bare slope; (b), uniformly distributed root bank slope; (c), triangular root bank slope; (d), exponential root bank slope; (e), parabolic root bank slope.

3.3.1 Impact of water level changes on bank slope displacement

Figure 20 [Figure 20: see original paper] shows the displacement of the bare slope and bank slopes reinforced by roots in different morphologies following changes in water levels. The displacement of the slope steadily increased as the water level decreased, with the maximum displacement occurring at the slope's base. Initially, the maximum displacement of the bare slope was similar to the maximum displacement of the slopes reinforced by vegetation roots. However, as the water level continued to drop, the displacement of the bare

slope increased substantially. When the water level changed by 1.5 m/d, the maximum displacement of the bare slope reached 0.554 m, and the maximum displacements of uniformly distributed, triangular, exponential, and parabolic root bank slopes were 0.271, 0.263, 0.260, and 0.273, respectively. It can be found that the effect of different root morphologies on the displacement of bank slope is not obvious under the condition of sudden change of water level. Nevertheless, the presence of vegetation roots noticeably reduced the displacement compared to the bare slope. When the water level changed by 1.5 m/d, the displacements in vegetated slopes were reduced by 0.284–0.294 m compared to the bare slope, indicating that plant roots play an important role in controlling slope displacement.

3.3.2 Impact of water level changes on the safety factor of bank slope

The safety factor of bank slopes reinforced by vegetation roots gradually decreased with the JOURNAL OF ARID LAND 2026 Vol. 18 No. 2 Fig. 20 Displacement diagram of the bare slope and bank slopes reinforced by roots in different morphologies following declines in water level. (a1-a4), bare slope; (b1-b4), uniformly distributed root bank slope; (c1-c4), triangular root bank slope; (d1-d4), exponential root bank slope; (e1-e4), parabolic root bank slope. decrease of water level (Fig. 21 [Figure 21: see original paper]). The reinforcement effect of different root morphologies on bank slope decreased in the following order: triangular>exponential>uniformly distributed>parabolic.

When the water level changed by 0.5 m/d, the safety factor of the bare slope decreased by 5.32% compared to its initial value. The safety factors of the slopes reinforced by roots in four morphologies (uniformly distributed, triangular, exponential, and parabolic) decreased by 4.69%, 4.78%, 4.91%, and 4.63%, respectively. When the water level changed by 1.5 m/d, the safety factor of the bare slope was 1.195, representing a decrease of 16.25% from the initial value. The safety factors of the four root-reinforced slopes (uniformly distributed, triangular, exponential, and parabolic) were 1.331, 1.337, 1.336, and 1.327, respectively, showing corresponding decreases of 14.40%, 14.67%, 14.79%, and 14.55% from the initial safety factor. Comparing the safety factors of the root-reinforced slopes to the bare slope, it was observed that under conditions of sudden water level changes, the safety factors of the slopes reinforced by roots in different morphologies shows minimal differences, with the triangular and exponential roots performing slightly better than the uniformly distributed and parabolic roots. The effect of vegetation transpiration on the safety factor of bank slope under sudden water level drops was relatively modest, but it can improve the slope's stability to some degree.

4.1 Study on hydrological effects of vegetation roots

The hydrological effect of vegetation mainly refers to the effect of changes in soil matric suction caused by plant evapotranspiration. The transpiration of plants absorbs water through roots, reduces the pore water pressure in the soil (Cao et al., 2018), changes the permeability of the soil, and increases the shear strength (Chen et al., 2019), thereby improving the bank slope stability. TIAN Nianfeng et al.: Analysis of bank slope stability considering vegetation... Fig. 21 Safety factor diagram of the bare slope and bank slopes reinforced by roots in different morphologies following declines in water level. A-E indicate bare slope, uniformly distributed root bank slope, triangular root bank slope, exponential root bank slope, and parabolic root bank slope, respectively. Studies have shown that vegetative root systems can directly alter the hydraulic properties of soils and that roots cause structural changes in soils by occupying the pore space between soils (Scholl et al., 2014), which in turn alters the pore sizes and soil-water characteristic curves of soils (Romero et al., 1999; Ng and Leung, 2012). Therefore, soil with vegetation coverage has lower water permeability and higher water retention capacity than bare land (Huat et al., 2006; Aravena et al., 2011). Through simulation, this study revealed that root depth is an important factor affecting the strength of substrate suction, with shorter roots resulting in greater substrate suction. However, shorter roots also had a smaller range of influence. Under the same transpiration rate, root morphology was the main factor affecting the water absorption capacity of the root system. At relatively low transpiration rates, root morphology had no significant effect on the water absorption capacity of the root system. The magnitude of soil matrix suction varied under different root morphologies. The simulation results indicated that triangular and exponential roots result in the most significant soil matrix suction. The root distribution function showed that the triangular and exponential root zones decrease linearly with depth, and most of the roots are distributed near the shallow surface; thus, these two root systems can produce greater suction forces through root water absorption, which reduces the infiltration coefficient, increases the unsaturated shear strength of the soil, and thereby improves the stability of slopes more effectively (Zhu et al., 2018). Studies have shown that soil matric suction caused by vegetation transpiration is 1.5-2.0 times greater than that caused by bare land (Liu et al., 2019). Moreover, the existence of vegetation can effectively reduce rainwater infiltration and matrix suction loss, playing a positive role in maintaining slope stability. Zaini et al. (2020) reported that trees located at the top of a slope can increase the safety factor of the slope by 57.00% through root water uptake. The simulation in this study revealed that the matric suction of soil affected by transpiration of roots in different morphologies under rainfall is basically the same and greater than that of the bare slope, and the difference is about 5.00 kPa. Rainfall is usually short and intense; in contrast, the transpiration of vegetation and the loss of soil moisture are long and slow processes. When rainfall occurs, the rate of rainwater infiltration is much greater than the rate of loss, indicating that vegetation transpiration can be ignored during rainfall. Therefore, the mechanical anchoring effect of plant

roots during rainfall is the main factor maintaining slope stability (Arnone et al., 2016). In addition, the numerical simulations agreed with the experimental data, both demonstrating that vegetation transpiration can effectively increase soil matric suction during relatively dry periods, thereby affecting the slope stability. Changes in the JOURNAL OF ARID LAND 2026 Vol. 18 No. 2 river water level can strongly influence the slope stability. Vegetation transpiration under sudden drops in the water level can improve the slope stability to a certain extent. Recent study has shown that under the regulation of vegetation transpiration, a decline in the infiltration line on a slope has a lag effect relative to a decline in the river water level, and the distribution of the infiltration line on a slope with vegetation is more uniform (Qiu et al., 2024). The reinforcement of the bank slope by vegetation can be reflected in the improvement in the safety factor and the reduction in displacement. The protection performance of bank slopes reinforced with triangular and exponential roots was found to be better than those reinforced with uniformly distributed and parabolic roots under the condition of a sudden drop in the water level. This also proves that triangular and exponential roots, with their strong water absorption capacity, can significantly alter the water field and matrix suction of the bank slope soil, thus improving the slope stability from the perspective of hydrological effects. The faster the decline rate of water level, the stronger the lag effect of drainage in the root-soil composite system. However, the negative impact of drainage lag in the root-soil composite system is much weaker than its positive impact (Liu et al., 2024).

4.2 Shortcomings and prospects

This study simulated the mechanism of hydro-mechanical effects of vegetation with different root morphologies on slope stability and compared their reinforcement effects. However, there are several limitations. We treated the vegetation root systems as ideal models, and only compared the effects of root morphology on water absorption capacity. However, in reality, plant species and environmental factors also affect the ability of root systems to absorb water. As temperatures rise, soil evaporation and shrinkage cracking accelerate. The cracks formed by soil cracking serve as new pathways for water exchange between the soil and the atmosphere, increasing the soil evaporation area and evaporation rate. Cracks are the preferred pathways for rainfall infiltration, leading to faster and deeper infiltration, which reduces slope stability (Sun et al., 2022; Barciela-Rial et al., 2023). Factors such as evapotranspiration, stomatal conductance, surface area, root biomass, and plant growth duration are also important parameters influencing root water uptake (Leung et al., 2015b; Gadi et al., 2019). Soil type and compaction can also alter the magnitude of substrate suction (Ng et al., 2014). In addition, considering that vegetation growth is a dynamic process, root systems can invade soil pores and cause changes in soil porosity, leading to changes in soil permeability. As vegetation ages, root decay can create large voids, leading to the formation of preferential flow paths that alter soil permeability. Changes in saturated hydraulic conductivity caused by root

decay may affect slope stability at depths of 1.000-2.000 m.

Therefore, the hydrological effects of vegetation will also change continuously as vegetation grows (Liu et al., 2021). Future studies may employ experimental methods to investigate the changes in soil water retention curve and saturated hydraulic conductivity caused by root systems, which can more accurately simulate the hydrological effects of vegetation. Moreover, in studies on slope stability, the impact of vegetation on soil erosion resistance is also an important consideration.

Given that this study focused primarily on the hydrological effects of vegetation and that it is difficult to simulate the influence of root systems on soil erosion resistance using finite element methods, subsequent simulation studies may employ discrete element methods to investigate the mechanisms by which root systems affect soil erosion resistance. In summary, future research should comprehensively consider factors such as vegetation, soil, and the environment, taking into account the coupled effects of multiple factors. The interactions among these factors constitute the theory of vegetation slope protection.

5 Conclusions

Based on the research background of the middle and lower reaches of the Tarim River, considering the hydro-mechanical reinforcing effect of vegetation, this study investigated the variation characteristics of bank slope stability under the combined actions of vegetation TIAN Nianfeng et al.: Analysis of bank slope stability considering vegetation transpiration, rainfall infiltration, and water level fluctuations. Water absorption by the root systems affected the pore water pressure in the root zone. Under the same transpiration rate, shorter root systems produced greater pore water pressure. Under the same root depth, exponential and triangular roots produced significantly higher pore water pressures than do uniformly distributed and parabolic roots. Considering the impact of vegetation transpiration on slope stability, the exponential root system has the most significant effect, with a safety factor of 1.568 and an improvement of 9.88% compared to the bare slope. The influence range of root water absorption was about 1.5 times greater than the length of the root system. The slope reinforced by exponential roots had the smallest displacement of 0.137 m after rainfall. The displacement of the slope increased gradually with increasing decline rate of water level. The maximum displacement occurred when the water level changed by 1.5 m/d, with a displacement of 0.554 m for the bare slope and 0.260-0.273 m for the slopes reinforced with by roots in the four morphologies. The impact of vegetation transpiration on the safety factor of bank slope under sudden water level drops was relatively minor. However, triangular and exponential roots exerted a more significant influence on riverbank displacement through enhanced hydrological reinforcement than do uniformly distributed and parabolic roots. This study can provide a valuable theoretical basis and practical guidance for the design, implementation, and maintenance of vegetation-based slope protection projects in the middle and lower reaches of

the Tarim River Basin.

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

- Aravena J E, Berli M, Ghezzehei T A, et al. 2011. Effects of root-induced compaction on rhizosphere hydraulic properties—X-ray microtomography imaging and numerical simulations. *Environmental Science & Technology*, 45(2):
- Arnone E, Caracciolo D, Noto L V, et al. 2016. Modeling the hydrological and mechanical effect of roots on shallow landslides. *Water Resources Research*, 52(11): 8590–8612.
- Barciela-Rial M, Saaltink R M, van Kessel T, et al. 2023. A new setup to study the influence of plant growth on the consolidation of dredged cohesive sediment. *Frontiers in Earth Science*, 11: 952845, doi: 10.3389/feart.2023.952845.
- Bischetti G B, Chiaradia E A, Epis T, et al. 2009. Root cohesion of forest species in the Italian Alps. *Plant and Soil*, 324: 71–89.
- Boldrin D, Leung A K, Bengough A G. 2017. Correlating hydrologic reinforcement of vegetated soil with plant traits during establishment of woody perennials. *Plant and Soil*, 416: 437–451.
- Bordoni M, Meisina C, Vercesi A, et al. 2016. Quantifying the contribution of grapevine roots to soil mechanical reinforcement in an area susceptible to shallow landslides. *Soil and Tillage Research*, 163: 195–206.
- Bracmort K S, Arabi M, Frankenberger J R, et al. 2006. Modeling long-term water quality impact of structural BMPs. *JOURNAL OF ARID LAND* 2026 Vol. 18 No. 2 Transactions of the ASABE, 49(2): 367–374.

- Cao X Q, Yang P L, Engel B A, et al. 2018. The effects of rainfall and irrigation on cherry root water uptake under drip irrigation. *Agricultural Water Management*, 197: 9-18.
- Chen R, Huang J W, Chen Z K, et al. 2019. Effect of root density of wheat and okra on hydraulic properties of an unsaturated compacted loam. *European Journal of Soil Science*, 70(3): 493-506.
- Coppin N J, Richards I G. 1990. *Use of Vegetation in Civil Engineering*. London: Butterworths, 23-36.
- De Baets S, Poesen J, Reubens B, et al. 2008. Root tensile strength and root distribution of typical Mediterranean plant species and their contribution to soil shear strength. *Plant and Soil*, 305: 207-226.
- Dupuy L, Fourcaud T, Stokes A. 2005. A numerical investigation into the influence of soil type and root architecture on tree anchorage. *Plant and Soil*, 278: 119-134.
- Eab K H, Likitlersuang S, Takahashi A. 2015. Laboratory and modelling investigation of root-reinforced system for slope stabilisation. *Soils and Foundations*, 55(5): 1270-1281.
- Ekanayake J C, Phillips C J. 1999. A method for stability analysis of vegetated hillslopes: an energy approach. *Canadian Geotechnical Journal*, 36(6): 1172-1184.
- Feddes R A, Bresler E, Neuman S P. 1974. Field test of a modified numerical model for water uptake by root systems. *Water Resources Research*, 10(6): 1199-1206.
- Forster M, Ugarte C, Lamandé M, et al. 2022. Root traits of crop species contributing to soil shear strength. *Geoderma*, 409: 115642, doi: 10.1016/j.geoderma.2021.115642.
- Gadi V K, Hussain R, Bordoloi S, et al. 2019. Relating stomatal conductance and surface area with evapotranspiration induced suction in a heterogeneous grass cover. *Journal of Hydrology*, 568: 867-876.
- Huat B B, Ali F H, Low T H. 2006. Water infiltration characteristics of unsaturated soil slope and its effect on suction and stability. *Geotechnical & Geological Engineering*, 24: 1293-1306.
- Indraratna B, Fatahi B, Khabbaz H. 2006. Numerical analysis of matric suction effects of tree roots. *Geotechnical Engineering*, 159(GE2): 77-90.
- Jotisankasa A, Sirirattanachat T. 2017. Effects of grass roots on soil-water retention curve and permeability function. *Canadian Geotechnical Journal*, 54(11): 1612-1622.
- Kokutse N K, Temgoua A G T, Kavazović Z. 2016. Slope stability and vegetation: Conceptual and numerical investigation of mechanical effects. *Ecological*

Engineering, 86: 146-153.

Leung A K, Garg A, Ng C W W. 2015a. Effects of plant roots on soil-water retention and induced suction in vegetated soil.

Engineering Geology, 193: 183-197. Leung A K, Garg A, Coo J L, et al. 2015b. Effects of the roots of *Cynodon dactylon* and *Schefflera heptaphylla* on water infiltration rate and soil hydraulic conductivity. Hydrological Processes, 29(15): 3342-3354.

Leung A K, Kamchoom V, Ng C W W. 2017. Influences of root-induced soil suction and root geometry on slope stability: a centrifuge study. Canadian Geotechnical Journal, 54(3): 291-303.

Liu H X, Mao Z, Wang Y, et al. 2021. Slow recovery from soil disturbance increases susceptibility of high elevation forests to landslides. Forest Ecology and Management, 485: 118891, doi: 10.1016/j.foreco.2020.118891.

Liu Q, Su L J, Xia Z Y, et al. 2019. Effects of soil properties and illumination intensities on matric suction of vegetated soil.

Sustainability, 11(22): 6475, doi: 10.3390/su11226475.

Liu R, Zhou C, Chen Y, et al. 2024. Numerical simulation of seepage and stability in root-soil composite slopes. Hydro-Science and Engineering, 4: 47-59. (in Chinese) Mickovski S B, Hallett P D, Bransby M F, et al. 2009. Mechanical reinforcement of soil by willow roots: impacts of root properties and root failure mechanism. Soil Science Society of America Journal, 73(4): 1276-1285.

Murgia I, Giadrossich F, Mao Z, et al. 2022. Modeling shallow landslides and root reinforcement: A review. Ecological Engineering, 181: 106671, doi: 10.1016/j.ecoleng.2022.106671.

Ng C W W, Leung A K. 2012. Measurements of drying and wetting permeability functions using a new stress-controllable soil column. Journal of Geotechnical and Geoenvironmental Engineering, 138(1): 58-68.

Ng C W W, Woon K X, Leung A K, et al. 2013. Experimental investigation of induced suction distribution in a grass-covered soil. Ecological Engineering, 52: 219-223.

Ng C W W, Leung A K, Woon K X. 2014. Effects of soil density on grass-induced suction distributions in compacted soil subjected to rainfall. Canadian Geotechnical Journal, 51(3): 311-321.

Ng C W W, Liu H W, Feng S. 2015. Analytical solutions for calculating pore-water pressure in an infinite unsaturated slope with different root architectures. Canadian Geotechnical Journal, 52(12): 1981-1992.

Ni J J, Leung A K, Ng C W W, et al. 2018. Modelling hydro-mechanical reinforcements of plants to slope stability. Computers TIAN Nianfeng et al.:

Analysis of bank slope stability considering vegetation...and Geotechnics, 95: 99-109.

Nyambayo V P, Potts D M. 2010. Numerical simulation of evapotranspiration using a root water uptake model. *Computers and Geotechnics*, 37(1-2): 175-186.

Patil U D, Shelton III A J, Aquino E. 2021. Bioengineering solution to prevent rainfall-induced slope failures in tropical soil.

Land, 10(3): 299, doi: 10.3390/land10030299. Peddinti S R, Kambhammettu B V N P, Lad R S, et al. 2020. A macroscopic soil-water transport model to simulate root water uptake in the presence of water and disease stress. *Journal of Hydrology*, 587: 124940, doi: 10.1016/j.jhydrol.2020.124940.

Pollen N, Simon A. 2005. Estimating the mechanical effects of riparian vegetation on stream bank stability using a fiber bundle model. *Water Resources Research*, 41(7): W07025, doi: 10.1029/2004WR003801.

Pollen-Bankhead N, Simon A. 2010. Hydrologic and hydraulic effects of riparian root networks on streambank stability: Is mechanical root-reinforcement the whole story? *Geomorphology*, 116(3-4): 353-362.

Qiu J Q, Yu M H, Li Q. 2024. Analysis of the influence of vegetation on the riverbank stability in the Lower Jingjiang Reach under water level change. *Journal of Hydraulic Engineering*, 55(1): 60-70. (in Chinese) Romero E, Gens A, Lloret A. 1999. Water permeability, water retention and microstructure of unsaturated compacted Boom clay. *Engineering Geology*, 54(1-2): 117-127.

Scholl P, Leitner D, Kammerer G, et al. 2014. Root induced changes of effective 1D hydraulic properties in a soil column. *Plant and Soil*, 381: 193-213.

Schwarz M, Preti F, Giadrossich F, et al. 2010. Quantifying the role of vegetation in slope stability: A case study in Tuscany (Italy). *Ecological Engineering*, 36(3): 285-291.

Shen Y F, Li Q, Pei X J, et al. 2023. Ecological restoration of engineering slopes in China—A review. *Sustainability*, 15(6): 5354, doi: 10.3390/su15065354.

Simon A, Curini A, Darby S E. 2000. Bank and near-bank processes in an incised channel. *Geomorphology*, 35(3-4): 193-217.

Stokes A, Douglas G B, Fourcaud T, et al. 2014. Ecological mitigation of hillslope instability: ten key issues facing researchers and practitioners. *Plant and Soil*, 377: 1-23.

Sun C, Tang C S, Cheng Q, et al. 2022. Stability of soil slope under soil-atmosphere interaction. *Earth Science*, 47(10): 3701-3722. (in Chinese) Sun J, Zhang L K. 2024. Influence of different plant roots on shear strength of bank slope soil. *Water Resources and Power*, 42(2): 192-196. (in Chinese) Wiel M J V D, Darby S E. 2007. A new model to analyse the impact of woody riparian

vegetation on the geotechnical stability of riverbanks. *Earth Surface Processes and Landforms*, 32(14): 2185–2198.

Wu T H, McKinnell III W P, Swanston D N. 1979. Strength of tree roots and landslides on Prince of Wales Island, Alaska.

Canadian Geotechnical Journal, 16(1): 19–33. Yu G A, Li Z W, Huang H Q, et al. 2017. Human impacts on fluvial processes in a very arid environment: case of Tarim River in China. *Advances in Water Science*, 28(2): 183–192. (in Chinese) Zaini M S I, Ishak M F, Zolkepli M F. 2020. Monitoring soil slope of tropical residual soil by using tree water uptake method.

IOP Conference Series: Materials Science and Engineering, 736: 072018, doi: 10.1088/1757-899X/736/7/072018.

Zhang X L, Fu Y M, Pei Q H, et al. 2024a. Study on the root characteristics and effects on soil reinforcement of slope-protection vegetation in the Chinese Loess Plateau. *Forests*, 15(3): 464, doi: 10.3390/f15030464.

Zhang Y, Liu W, He S M. 2024b. Effect of vegetation growth on morphological traits of vegetation and biomechanical features of roots. *Plant and Soil*, 494(1): 395–411.

Zhang Y Y, Chen X, Gao M, et al. 2021. Simulation of transpiration for typical xeromorphic plants in inland arid region of northwestern China. *Acta Ecologica Sinica*, 41(19): 7751–7762. (in Chinese) Zhang Z, Zhang W, Zhai Z J, et al. 2007. Evaluation of various turbulence models in predicting airflow and turbulence in enclosed environments by CFD: Part 2—Comparison with experimental data from literature. *HVAC&R Research*, 13(6):

Zhu H, Zhang L M, Garg A. 2018. Investigating plant transpiration-induced soil suction affected by root morphology and root depth. *Computers and Geotechnics*, 103: 26–31.

Zhu H, Zhang L M. 2019. Root-soil-water hydrological interaction and its impact on slope stability. *Georisk: Assessment and Management of Risk for Engineered Systems and Geohazards*, 13(4): 349–359.

Zong Q L, Feng B, Cai H B, et al. 2018. Mechanism of riverbank protection by desert river vegetation roots in Tarim River Basin. *Chinese Journal of Rock Mechanics and Engineering*, 37(5): 1290–1300. (in Chinese)

Note: Figure translations are in progress. See original paper for figures.

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