Control of Bank Slope Instability by Vegetation During Rainfall

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Abstract. In civil engineering, while the impact of vegetation on bank slope stability is well-recognized, its role in managing slope instability during rainfall remains underexplored. In this study, a numerical model considering bank slope instability control by vegetation during rainfall is developed. The results show that the vegetation root system improves slope stability by enhancing soil cohesion and regulating seepage processes. Woody plants are more effective for slope protection in the early stage of rainfall, while herbaceous plants are more significant in later stage. Planting on the top of bank slope is more effective during the early stages of rainfall, whereas planting on the slope surface provides better slope stability during whole rainfall. Vegetated slope is the most effective at low to moderate intensity rainfall, but its stability effect becomes less obvious under extreme rainfall.

Keywords: Bank slope stability, Vegetative slope protection, Numerical model, Rainfall

1 Introduction

Vegetation plays a vital role in stabilizing bank slopes in civil engineering. The root system of plants strengthens the soil, reduces erosion and improves the soil structure, thus increasing the stability of bank slope [1]. Vegetation protection measures are becoming an effective means of addressing landslide risk on slopes [2]. Many studies have focused on testing the shear strength of root-containing soils [3]. Kokutse et al. [4] modeled the combined effects of slope geometry, soil type, and vegetation parameters on the slope stability. Wang et al. [5] explored and found that the spatial variation of the root system has a significant effect on the slope stability, and that trapezoidal slope is more stable than rectilinear one. However, former studies mainly focused on the mechanical reinforcement of root system, and the hydrological effect, especially the effect of vegetation slope protection under rainfalls remained to be understudied.

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This study focuses on the vegetation effects on bank slope stability in rainfalls. A vegetation slope model was developed to investigate the effects of vegetation species and planting location on bank slope stability under rainfall conditions. The study aims to reveal how these factors affect slope stability under rainfalls. The findings aim to inform civil engineering practices by optimizing vegetation strategies for slope protection.

2 Materials and Methods

2.1 Root-Soil Complex Theory

Different types of vegetation have different root development patterns, and the effect of slope stabilization varies greatly. According to the distribution and morphology of the root system, the root system of common vegetation can be divided into three types: Tap, Plate and Heart. The slope protection of vegetation root system is mainly reflected in the hydrological and mechanical effects, through the friction and adhesion between the root system and soil to form the root-soil complex, to change the hydraulic properties of the soil body as well as reinforcement of it, to improve the shear strength and stability of the bank slope.

2.2 Simulation Plans

The study focused on a plain reservoir bank slope, using Robinia pseudoacacia, Cynodon dactylon, and Salix matsudana for vegetation-based slope protection. For effective civil engineering applications, different vegetation setups were tested: Robinia pseudoacacia (tree) and Cynodon dactylon (grass) were planted at the slope's top, while Salix matsudana was installed using a pile insertion method at a 45-degree angle to stabilize the steep bank. The rainfall intensities of 10mm/d, 20mm/d, 40mm/d, 80mm/d, 100mm/d and 150mm/d were considered. The rainfall duration was set to 5 days.

This study examined the impact of different vegetated slope protection designs, including bare slope, herbaceous protection, arborvitae protection, integrated grass/tree protection, and dry willow protection at the slope top. Details were provided in Table 1.

Table 1. Planting plans of non-vegetated and vegetated slope protection.

Case	Slope Top Planting	Slope Planting
1	None	None
2	Robinia pseudoacacia	None
3	Cynodon dactylon	None
4	Robinia pseudoacacia + Cynodon dactylon	None
5	None	Salix matsudana
6	Robinia pseudoacacia + Cynodon dactylon	Salix matsudana

2.3 Modeling

Cynodon dactylon, a plate-type plant, is densely planted at the slop top, forming a root-soil complex with a surface layer depth of 0.5 meters. Robinia pseudoacacia, also planted at the top, features a tap-type root-soil complex extending 2 meters in length and 2 meters in depth, with a 3-meter spacing between plants. Salix matsudana, planted on the slope surface, has a plate-type root-soil complex measuring 2 meters in length and 0.7 meters in depth, with a 2.5-meter spacing.

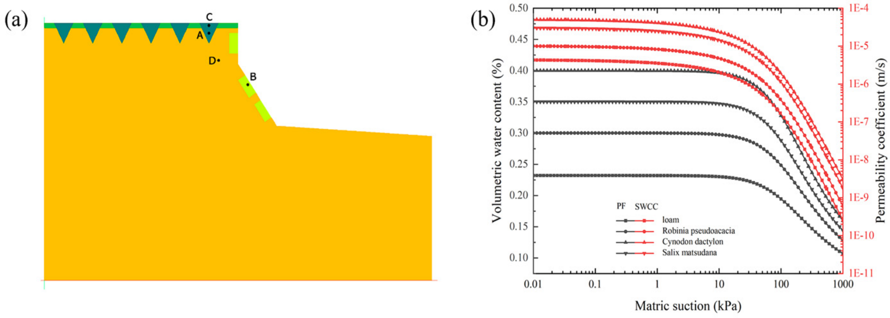

Fig. 1. (a) Root soil complex distribution and monitoring points A, B, C and D of planting plans 6; (b) SWCC and PF curve of soil and root-soil complexes [6].

In planting plans 6, illustrated in Fig. 1(a), the monitoring points A, B, and C are within the influence of root-soil complexes, while point D is located outside the root-soil complex. Soil parameters for the model are listed in Table 2, and the SWCC and PF curves for soil and root-soil complexes are shown in Fig. 1(b).

Table 2. Root-soil complex soil parameters [7].

	Saturated Hydraulic conductivity /m/s	Cohesion /kPa	Friction angle °	Saturated volumetric water content	Unite weight /kN/m^3
Loess-like loam	4.3×10^{-6}	16	26.4	23.2	18.0
Cynodon dactylon	5×10^{-5}	30	26.9	40.0	18.0
Robinia pseudoacacia	1×10^{-5}	50	26.9	30.0	18.0
Salix matsudana	3×10^{-5}	40	26.9	35.0	18.0

3 Results and Discussion

Under a continuous rainfall of 100 mm/d, Fig. 2(a) shows water content changes at point D on the bank slope. Different slope protection schemes affected seepage, with vegetation notably regulating slope permeability. Analysis reveals that soil water content changes were consistent post-vegetation planting, with final saturation levels similar across conditions. However, vegetation slowed the increase in water content and delayed saturation, likely due to root-induced changes in soil porosity, water distribution, and permeability.

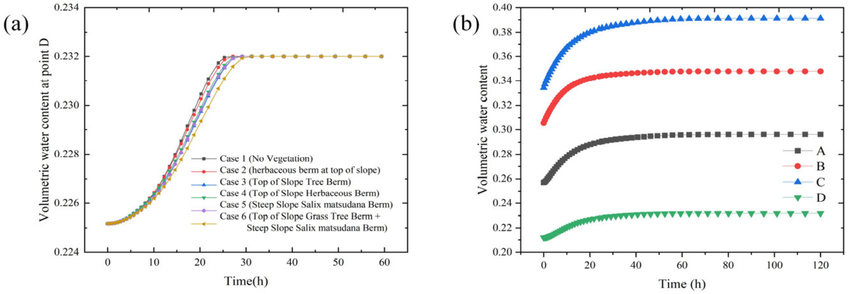

Fig. 2. (a) Volumetric water content at monitoring point D (b) Volumetric water content at monitoring points A, B, C, and D for Case 6 when the top of the slope was planted evenly

All three types of vegetation were planted under Working Condition 6, and the changes in volumetric water content at points A, B, C, and D are shown in Figure 2(b). Plant roots enhance soil porosity and permeability, significantly increasing the permeability coefficient of the root-soil complex. At both the beginning and end of rainfall, the water content ranked as C>B>A>D. This variation is due to differing vegetation impacts on soil permeability. Cynodon dactylon at monitoring point C, with its well-developed root system, notably increases saturated water content and affects the permeability coefficient, helping the soil maintain higher water content.

After rainfall began, root-soil complexes with high hydraulic conductivity changes water content quickly, reaching saturation faster than the surrounding bank slope soil. Salix matsudana at the slope surface and base facilitated drainage, rapidly expelling water due to its strong permeability. After 24 hours, drainage and infiltration equilibrated, and the water content distribution of the bank slope remained stable despite ongoing rainfall.

Fig.3(a) illustrates the factor of safety for different planting plans under 100 mm/d rainfall. The safety factor rapidly decreases during the rain, and its decrease rate becomes small when the bank soil is fully saturated. Without vegetation berms (case 1), the safety factor is the lowest, and vegetation enhance the bank slope stability.

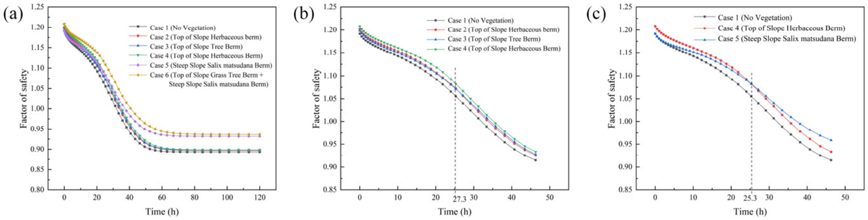

Fig. 3. Variation of bank slope safety factor under 100 mm/d rainfall.

For the slope top planting, the safety factor changes are illustrated in Fig. 3(b). Until the rain of 27.3 hours, the effectiveness of bank stabilized ranking is Case 4 > Case 2 > Case 3 > Case 1, the mixed planting of Robinia pseu-doacacia and Cynodon dactylon is the best. Planting Robinia pseudoacacia alone is more effective than Cynodon dactylon alone. After rain of 27.3 hours, the ranking is changed to case 4 > case 3 > case 2 > case 1, with the mixed planting still yielding the best results. Planting Cynodon dactylon only became more effective than Robinia pseudoacacia alone. Initially, Robinia pseudoacacia with deeper roots is better at managing water infiltration, while later, Cynodon dactylon's dense, shallow roots provides superior soil reinforcement.

Fig.3(c) shows the safety factor for cases 1, 4, and 5. The safety factor of case 5 with Salix matsudana is increased compared to that of case 1 without vegetation, indicating slope protection of planting. Salix matsudana is more effective at the slope top than that of case 4 during the late stages of rainfall. Early in the rainfall, Salix matsudana helps control infiltration, slowing the decline in safety factor. Later, its extensive horizontal root system enhances slope stability. Thus, selecting planting locations based on rainfall timing and plant characteristics can optimize slope protection.

The minimum values of bank slope safety factor for 24 h at different rainfall intensities, with vegetated slope protection at the slope top and slope face (case 6) as well as without vegetated slope, are shown in Table 3. It shows that bank slopes with vegetated berms have a higher safety factor compared to that without vegetation under all rainfall intensities. As rainfall intensity increases, the minimum safety factor decreases, and the vegetated slopes consistently show a large safety factor. The increase of safety factor for vegetated slopes decreases with large rainfall intensity, from 10.61% at low intensities (e.g., 10 mm/d) to 1.99% at high intensities (e.g., 150 mm/d). This indicates that vegetation enhances slope stability at low to moderate rainfall by increasing soil cohesion and slowing infiltration, its effectiveness reduces during extreme rainfall due to the limits of the vegetative root.

Table 3. Minimum safety factor for vegetated slopes under different rainfall intensities.

rainfall intensities	0mm/d	10mm/d	20mm/d	40mm/d	80mm/d	150mm/d
Without Vegetation	1.1822	1.1811	1.1793	1.1756	1.1650	1.1289
Vegetated slope	1.3076	1.2966	1.2814	1.2438	1.2160	1.1514
Safety factors increase	10.61%	9.78%	8.66%	5.80%	4.38%	1.99%

4 Conclusions

This study underscores the importance of vegetation in enhancing slope stability, a critical aspect of civil engineering for ensuring the safety and effectiveness of slope protection measures. The findings offer practical guidance for optimizing vegetation-based solutions in various rainfall scenarios.

1. Vegetation roots enhance slope stability by increasing soil cohesion and regulating seepage. Greater planting amounts and ranges improve slope stabilization more.

2. Woody plants stabilize slope better in early rainfall, while herbaceous plants are more effective in late rainfall.
3. Vegetation at the slope top is the most effective in the early rainfall, while vegetation on the slope surface offers better bank protection in the whole rainfall.
4. Vegetation is effective for slope stability in low and moderate rainfalls, but the effects are small under extreme rainfalls.

Acknowledgement

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References

1. Lann T, Bao H, Lan H, et al (2024) Hydro-mechanical effects of vegetation on slope stability: A review. Science of The Total Environment 926:171691. https://doi.org/10.1016/j.scitotenv.2024.171691
2. Stokes A, Sotir R, Chen W, Ghestem M (2010) Soil bio- and eco-engineering in China: Past experience and future priorities. Ecol Eng 36:247–257. https://doi.org/10.1016/j.ecoleng.2009.07.008
3. Forster M, Ugarte C, Lamandé M, Faucon M-P (2022) Root traits of crop species contributing to soil shear strength. Geoderma 409:115642. https://doi.org/10.1016/j.geoderma.2021.115642
4. Kokutse NK, Temgoua AGT, Kavazović Z (2016) Slope stability and vegetation: Conceptual and numerical investigation of mechanical effects. Ecol Eng 86:146–153. https://doi.org/10.1016/j.ecoleng.2015.11.005
5. Wang X, Ma C, Wang Y, et al (2020) Effect of root architecture on rainfall threshold for slope stability: Variabilities in saturated hydraulic conductivity and strength of root-soil composite. Landslides 17:1965–1977. https://doi.org/10.1007/s10346-020-01422-6
6. Hu W, Chen J, Li W, et al (2021) Stability analysis of eco-slope protection under conditions of water level sudden drop and rainfall. Water Resources and Hydropower Engineering 167–174. https://doi.org/10.13928/j.cnki.wrahe.2021.05.018
7. Jia L (2023) Study on stability of canal dike in Jiaozuo section of Middle Route Project of South-to-North Water Diversion (in Chinese). Master, North China University of Water Resources and Electric Power