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Numerical Simulation of the Structural Performance of Ecological Toughness of Canal Bank Slopes and Its Influence Law Study

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Abstract: *In this paper, the performance of the ecological toughness structure of canal bank slopes is investigated, and its influence law is analyzed through numerical simulation, aiming to provide scientific basis for the management and protection of canal bank slopes. Numerical simulation method is adopted in the study, and the main steps include numerical model establishment, parameter setting and adjustment and simulation of different working conditions. In the experimental stage, the performance of the ecological resilience structure of the canal bank slope and its influence law are investigated by numerical simulation method. In the stability experiment, the effect of shrub configuration is the most significant, in which the stability coefficient increases to 59. In the toughness experiment, the toughness index of clay increases to 60, and in the final environmental impact experiment, the ecological benefit coefficient of ecological berm increases to 0.93. From the above data conclusions, it can be seen that shrub configuration, clay, and ecological slope protection structure have the most advantages in improving the stability, resilience, and ecological benefits of canal bank slopes.*

Keywords: *Canal Bank Slopes, Ecological Resilience, Numerical Modeling, Vegetation Configuration, Soil Type*

1. Introduction

Canals, as an important part of water conservancy projects, not only bear the functions of transportation and irrigation, but also have important ecological value. However, with the increase of human activities and environmental changes, canal bank slopes are facing the problems of decreasing stability and degradation of ecological functions. Traditional methods of canal bank slope protection focus on strengthening the engineering structure, neglecting the enhancement of ecological resilience, resulting in the bank slopes being susceptible to scouring and damage. It is of great significance to study the performance of the ecological toughness structure of canal bank slopes and its influence law for the sustainable management and ecological protection of canals.

In this paper, the effects of different vegetation configurations, soil types and slope structures on the stability, resilience and ecological benefits of canal slopes are systematically investigated by numerical simulation methods. The study shows that appropriate vegetation configurations (e.g., shrubs), high-quality soil types (e.g., clay) and ecological slope structures have significant effects in improving the overall performance of canal bank slopes. The results of this study provide a scientific basis for the management and protection of canal bank slopes and suggest optimization measures and recommendations.

The paper is organized as follows: the first part introduces the background of the study and its importance. The second part describes the experimental method in detail, including the establishment of numerical model and parameter setting. The third part shows the experimental results and analysis, covering three aspects of stability, toughness and environmental impact. The fourth part summarizes the main research findings and proposes corresponding optimization suggestions.

2. Related Works

In recent years, many scholars have extensively studied the ecological restoration and resilient structure of canal bank slopes. For example, Eraky O M et al. studied the effect of rigid ditch bank vegetation on the flow velocity distribution and water surface profile of a trapezoidal open channel. They conducted 48 tests to explore the effects of different vegetation densities [1]. Riparian and floodplain vegetation can significantly affect energy losses. For this reason, D'Ippolito A et al. examined recent advances in the analysis of rigid and flexible vegetation after summarizing classical descriptive and photographic methods and presented some application cases to highlight the effect of vegetation on water depth and maintenance interventions [2]. Elzahry E F M et al. experimentally investigated the effect of rigid aquatic riparian weeds on the vertical velocity profiles and streambed morphology. In the experiment, weeds were staggered at 25, 50 and 75 mm spacing into unilateral and bilaterals and 168 scenarios were conducted with Froude's number ranging from 0.11 to 0.30 [3]. Sandbars are often formed at river confluences due to variations in flow or sand transport capacity, and once formed, these sandbars are ideal habitats for vegetation growth. For this reason, Artini G et al. analyzed the effect of vegetation above the confluence on the hydrodynamics of the river reach [4]. There is a strong nonlinear interaction between vegetation and water flow in natural rivers. Wang Z et al. experimentally investigated the effect of rigidly submerged vegetation on the flow structure, adopting the concepts of vegetation height and relative degree of submergence [5]. However, their study mainly focused on the selection of vegetation types and lacked a comprehensive analysis of the structural performance of bank slopes. Based on this, Abdella K's study aimed to assess, investigate and design appropriate river training works in the lower reaches of the Kulfo River. Within a defined 6-km reach, he conducted field investigations and secondary data collection to predict the flood extent using a one-dimensional hydrodynamic model [6]. The study by Sundriyal Y et al. aimed to investigate the impact of potential floods on the riverbank slopes of the North Arkhand state in the northwestern Himalaya. They used flood simulations to determine the potential impacts of flooding on riverbank slopes [7]. Friedrich H et al. showed how improved physical modeling can incorporate large wood transport, accumulation, and scouring processes to facilitate more reliable hazard and risk assessments and to improve river management in large wood-prone systems [8]. However, these findings are limited by experimental conditions and are difficult to generalize to practical canal projects. Therefore, the current studies still have some deficiencies in methodology and applicability.

In order to make up for these deficiencies, some researchers have tried to use numerical simulation methods to study the performance of ecological resilient structures on canal bank slopes in recent years. For example, the study of desert water conveyance canals in Xinjiang mainly focuses on the choice of construction technology, and it is not clear about the effect of bank slope reinforcement and its stability impact. Zhu J et al. used the finite element method to analyze the coefficient of safety, the overall displacement and the equivalent plastic zone of the wind-deposited soil bank slopes at three different stages before and after reinforcement [9]. Water level fluctuation is the cause of slope instability in many reservoirs. Sun L et al. developed a new slope analysis model based on the finite discrete element combination method for assessing the stability of reservoir slopes under the water-rock coupling effect [10]. Based on the above studies, this paper will adopt a numerical simulation method, aiming to analyze the performance of ecological toughness structure of canal bank slopes and its influence law more comprehensively.

3. Methods

3.1. Establishment of Numerical Model

In this paper, the study systematically analyzes the effects of different vegetation configurations, soil types and bank slope structures on the ecological resilience structural performance of canal bank slopes by establishing numerical models. The modeling includes several aspects such as topography, soil properties, vegetation characteristics and hydrodynamic conditions [11]. The following are the specific steps and parameter settings:

3.1.1. Terrain Modeling

First, a three-dimensional terrain model was established using Geographic Information System (GIS) software based on the actual canal topographic data. The model includes canal slope, bank slope height and slope shape. The specific parameters are shown in Table 1:

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Table 1: Canal topographic data

Parameter	Value Range	Unit
Slope	15-30	°
Slope Height	45327	m
Slope Shape	Linear, Concave, Convex	-

3.1.2. Soil Property Setting

Soil type is an important factor affecting the stability and toughness of bank slopes. In this paper, three typical soil types, sand, clay and loam, are selected and their physical property parameters are set as shown in Table 2:

Table 2: Soil property parameters

Parameter	Sand	Clay	Loam
Density (g/cm^3)	1.6	1.8	1.7
Friction Angle (°)	30	20	25
Saturated Hydraulic Conductivity (m/s)	0.0001	0.000001	0.00001

The selection of these parameters is based on the Mohr Coulomb criterion, which describes the yield conditions of soil, as shown in formula (1):

$$\tau = c' + \sigma\tan(\emptyset') \quad (1)$$

In formula (1), τ is the shear stress, c'represents the effective cohesive force, σ is the normal stress, and $\emptyset'$represents the effective internal friction angle.

3.1.3. Vegetation Characteristics

The reinforcement effect of vegetation configuration on bank slopes is mainly reflected in the strength and coverage of root systems. This article selects three configurations: no vegetation, herbaceous plants, and shrubs. The specific parameter settings are shown in Table 3:

Table 3: Vegetation configuration parameters

Parameter	No Vegetation	Herbaceous Plants	Shrubs
Coverage (%)	0	60	80
Root Strength (kPa)	0	5	10

The strength of the root system can be expressed by formula (2):

$$S_r = k_r \cdot R_d \quad (2)$$

In formula (2), $S_r$represents the shear strength of root reinforcement, $k_r$represents the root reinforcement coefficient, and $R_d$represents the root density.

3.1.4. Hydrodynamic Conditions

The simulation of hydrodynamic conditions includes extreme weather conditions such as floods and storms, with specific parameters shown in Table 4:

Table 4: Hydrodynamic parameters

Parameter	Value Range	Unit
Flow Velocity	0.5-2.5	m/s
Water Depth	45294	m
Flood Frequency	5-50	years

3.1.5. Numerical Simulation Tool

In this paper, the finite element analysis software Python is used for numerical simulation. Firstly, the three-dimensional model of the canal bank slope is established by Python, and the above topographic, soil, vegetation and hydrodynamic parameters are set. Then, simulations under different working conditions are carried out to analyze the effects of each configuration scheme on bank slope stability, toughness and ecological benefits.

Through the above steps and parameter settings, this paper establishes a more complete numerical model of the canal bank slope, which provides a solid foundation for the subsequent simulation analysis and experimental results.

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3.2. Parameter Setting and Adjustment

In this paper, after establishing the numerical model, the parameters of the model are set and adjusted in detail to ensure the accuracy and reliability of the simulation results. The parameter settings include soil properties, vegetation characteristics, and hydrodynamic conditions.

3.2.1. Soil Property Parameter Setting

Soil properties directly affect the stability and resilience of canal bank slopes. In order to accurately simulate the effects of different soil types on bank slopes, this paper selects three typical soils: sand, clay and loam. The density of sand is 1.6 g/cm ³, the internal friction angle is 30 degrees, and the saturated permeability coefficient is 1e-4 m/s. The density of clay is 1.8 g/cm ³, the internal friction angle is 20 degrees, and the saturated permeability coefficient is 1e-6 m/s. The density of loam soil is 1.7 g/cm ³, the internal friction angle is 25 degrees, and the saturated permeability coefficient is 1e-5 m/s. These parameters are determined through experimental measurements of actual soil samples and reference data to ensure their representativeness and accuracy [12].

3.2.2. Vegetation Characterization Parameter Settings

Vegetation configuration is a key factor affecting the stability and resilience of bank slopes. In this paper, three configurations of no vegetation, herbaceous plants and shrubs are selected. The coverage rate without vegetation is 0%, and the root strength is 0 kPa. The coverage rate of herbaceous plants is 60%, and the root strength is 5 kPa. The coverage rate of shrubs is 80%, and the root strength is 10 kPa. These parameters are determined based on on-site investigations and existing research results, reflecting the effectiveness of different vegetation configurations in reinforcing bank slopes.

3.2.3. Hydrodynamic Condition Setting

The simulation of hydrodynamic conditions includes extreme weather conditions such as floods and storms, which have significant scouring and erosion effects on bank slopes. The hydrodynamic parameters set in this paper are as follows: the water flow velocity is 0.5-2.5 m/s, the water depth is 1-3 m, and the flood frequency is 5-50 years. These parameters are determined by analyzing the actual hydrological data and simulating the extreme weather conditions in order to truly reflect the hydrodynamic environment of the canal.

3.2.4. Parameter Adjustment

After initial parameter settings, multiple simulations and adjustments were conducted to ensure the stability and reliability of the numerical model. The specific steps are as follows:

Preliminary simulation: Simulating based on the initially set parameters to observe the deformation and stability of the bank slope.

Parameter adjustment: Adjusting unreasonable parameters based on preliminary simulation results. For example, if a certain soil type is found to exhibit unrealistic high stability in simulations, it may be necessary to adjust its internal friction angle or density.

Verification simulation: Inputting the adjusted parameters into the model again for simulation to verify the adjustment effect. Through multiple iterations, the most reasonable parameter settings are finally determined.

3.3. Simulate Different Working Conditions

After the parameter settings and adjustments were completed, in order to comprehensively evaluate the performance of the ecological resilience structure of the Yunhe River slope under different conditions, this paper conducted detailed simulations of different working conditions. These working conditions include environmental conditions such as floods, storms, and daily water flow. By simulating these different working conditions, the impact on the stability, resilience, and ecological benefits of the bank slope is analyzed [13].

3.3.1. Flood Condition Simulation

Floods are one of the most significant natural disasters that affect the stability of canal bank slopes. To simulate flood conditions, the following parameters are set: the water flow velocity is 2.5 m/s, the water depth is 3 m, and the duration is 24 hours. During the simulation process, the researchers observe the displacement, stress distribution, and failure mode of the bank slope under different vegetation

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configurations and soil types. The results show that there are significant differences in the reinforcement effect of different vegetation configurations on the bank slope, especially the shrub configuration can significantly improve the flood resistance of the bank slope.

3.3.2. Storm Condition Simulation

Storms are also important factors affecting the bank slopes of canals, mainly manifested as a sharp rise in water level and accelerated water flow caused by heavy rainfall. To simulate storm conditions, the following parameters are set: the rainfall intensity is 100 mm/h, the duration is 6 hours, and the water flow velocity is 1.5 m/s. The simulation results show that soil type has a significant impact on the stability of bank slopes under storm conditions. Clay exhibits strong stability and toughness under storm conditions due to its high internal friction angle and low permeability coefficient [14].

3.3.3. Simulation of Daily Water Flow Conditions

Daily water flow conditions are a common occurrence in the normal operation of canals. To simulate daily water flow conditions, the following parameters are set: the water flow velocity is 0.5 m/s and the water depth is 1 m. In this working condition, the main focus is on analyzing the impact of different bank slope structures (such as gabion slope protection, ecological slope protection, and mixed slope protection) on the long-term stability and ecological benefits of the bank slope. The simulation results show that ecological slope protection can not only effectively protect the bank slope under daily water flow conditions, but also significantly improve ecological benefits. The fluid dynamics model of the slope protection structure is represented by formula (3):

$$\tau = \rho \cdot g \cdot h \cdot \sin(\theta) \quad (3)$$

In formula (3), τrepresents shear stress, $g$represents water density, $h$represents gravitational acceleration, represents water depth, and θrepresents slope angle.

3.3.4. Multi Condition Comprehensive Simulation

In order to further verify the combined effects of different working conditions on the performance of bank slopes, a comprehensive simulation with multiple working conditions was carried out. The specific steps are as follows:

Preliminary simulation: it independently simulates flood, storm, and daily water flow conditions to obtain their respective bank slope response data.

Working condition superposition: it superimposes and analyzes the simulation results of each individual working condition, observing the performance of the bank slope under multiple environmental pressures.

Comprehensive evaluation: it evaluates the comprehensive stability and resilience of the bank slope based on the superimposed simulation results, and proposes optimization suggestions.

4. Results and Discussion

4.1. Stability Assessment Experiment

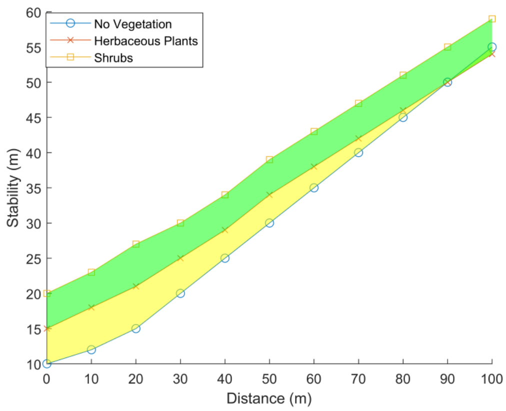

Figure 1: Stability experiment evaluation

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The stability assessment experiment evaluated the impact of different vegetation configurations on the stability of canal bank slopes. In the experiment, we set up three configuration schemes: no vegetation, herbaceous plants, and shrubs. Then, using numerical simulation methods, measure the stability coefficient of the bank slope under flood impact. After the experiment, this article sequentially recorded the stability changes under each scheme and plotted them in a graph, as shown in Figure 1:

Within the distance of 100 m in Figure 1, the shrub configuration has the highest stabilization coefficient of 59, the herbaceous configuration has the second highest stabilization coefficient of 54, and the unvegetated configuration is the worst. The results of this study indicate that appropriate vegetation configurations, especially shrubs, can significantly enhance the stability of canal bank slopes, and it is recommended that shrub configurations be prioritized in canal bank slope management.

4.2. Resilience Assessment Experiment

In the resilience assessment experiment, this article evaluated the impact of different soil types on the ecological resilience of the Yunhe River slope. The experiment set up three types of soil: sandy soil, clay soil, and loam soil. Through numerical simulation methods, the toughness index of the bank slope was measured after the storm. The simulated data includes multiple measurement points within a range of 0 to 100 meters from the starting point, sequentially recording the changes in toughness under various soil types, and analyzing the degree of influence of different soils on the slope restoration ability.

In Figure 2, the toughness index of sandy soil increased from 5 to 45, the toughness index of clay increased from 7 to 60, and the toughness index of loam soil increased from 6 to 55. Clay has the best performance, with a maximum toughness index of 60 within a distance of 100 meters, followed by loam with a toughness index of 55, and sandy soil with the lowest toughness index of 45. The results indicate that clay and loam are more suitable for improving the ecological resilience of canal bank slopes, and it is recommended to prioritize the use of clay or loam as fillers in canal bank slope management. The specific data is shown in Figure 2:

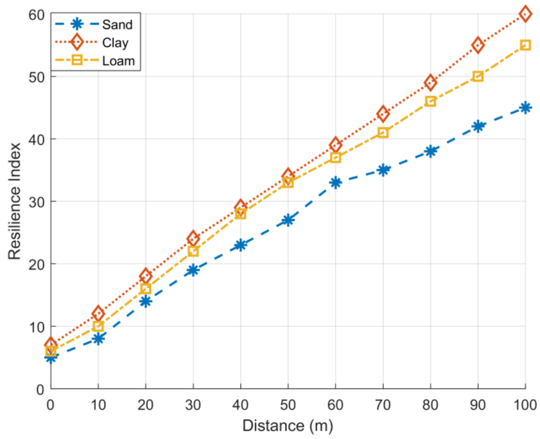

Figure 2: Resilience assessment

4.3. Environmental Impact Assessment Experiment

This experiment aims to analyze the effects of different bank slope structures on the surrounding environment. Three types of structures, namely gabion slope, ecological slope and hybrid slope, were set up in the experiment, and the eco-efficiency coefficients were measured by numerical simulation method under daily water flow conditions. The simulation data include multiple measurement points within 0 to 100 m from the starting point, and the ecological benefit changes under each structure are recorded in turn to analyze the impact of different bank slope structures on the environment, as shown in Figure 3:

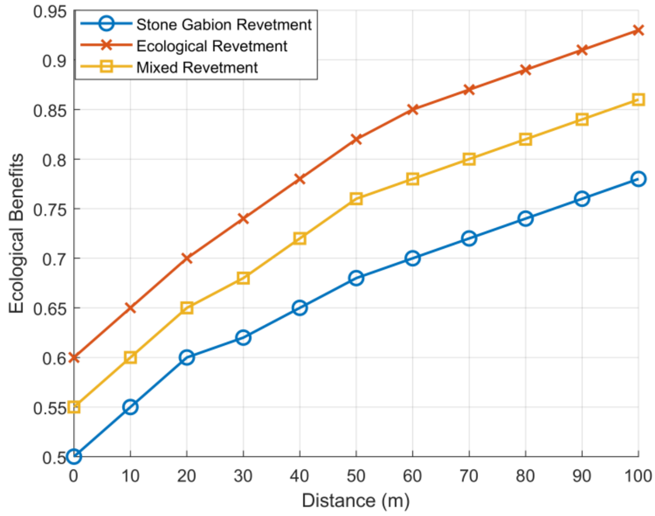

Figure 3: Environmental impact assessment

In Figure 3, the eco-efficiency coefficient of gabion berm increases from 0.5 to 0.78, that of ecological berm increases from 0.6 to 0.93, and that of mixed berm increases from 0.55 to 0.86. Ecological berms have the best performance in the 100-meter distance, with the highest eco-efficiency coefficient of 0.93, mixed berms the next highest, 0.86, and gabion berms the lowest, 0.78. The study shows that ecological berm structures can significantly enhance the ecological benefits of canal bank slopes. The study shows that the ecological slope structure can significantly improve the ecological benefit of canal bank slopes, and it is recommended to prioritize the use of ecological slope structure in the construction of canal bank slopes.

5. Conclusion

The performance and influence of ecological resilience structures on canal bank slopes are explored through numerical simulation in this study, which evaluates various vegetation configurations, soil types, and slope structures under conditions like flooding and storms. Results indicate that shrub setups notably enhance slope stability, clay soil optimally improves toughness, and ecological slope protection offers substantial environmental benefits. However, the paper acknowledges limitations such as the simulation parameters not fully capturing all real conditions, affecting the results' generalizability. Future research should refine these parameters, incorporate more real data for validation, and examine the impact of complex environmental factors. Additionally, implementing diverse vegetation arrangements and new ecological materials could further boost the resilience and environmental advantages of canal bank slopes.

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References

[1] Eraky O M, Eltoukhy M A R, Abdelmoaty M S, et al. Effect of rigid, bank vegetation on velocity distribution and water surface profile in open channel. Water Practice & Technology, 2022, 17 (7): 1445-1457.

[2] D' Ippolito A, Calomino F, Alfonsi G, et al. Flow resistance in open channel due to vegetation at reach scale: A review. Water, 2021, 13 (2): 116-124.

[3] Elzahry E F M, Eltoukhy M A R, Abdelmoaty M S, et al. Effect of rigid aquatic bank weeds on flow velocities and bed morphology. Water, 2023, 15 (18): 3173-3189.

[4] Artini G, Calvani G, Francalanci S, et al. Effects of vegetation at a bar confluence on river hydrodynamics: The case study of the Arno River at Greve junction. River Research and Applications,

ISSN 2663-1563 Vol. 6, Issue 4: 26-33, DOI: 10.25236/AJAGE.2024.060405

2021, 37 (4): 615-626.

[5] Wang Z, Zhang H, He X, et al. Effects of vegetation height and relative submergence for rigid submerged vegetation on flow structure in open channel. Earth Sciences Research Journal, 2022, 26 (1): 39-46.

[6] Abdella K, Mekuanent F. Application of hydrodynamic models for designing structural measures for river flood mitigation: the case of Kulfo River in southern Ethiopia. Modeling Earth Systems and Environment, 2021, 7 (4): 2779-2791.

[7] Sundriyal Y, Kumar V, Khan F, et al. Impact of potential flood on riverbanks in extreme hydro-climatic events, NW Himalaya. Bulletin of Engineering Geology and the Environment, 2023, 82 (6): 196-213.

[8] Friedrich H, Ravazzolo D, Ruiz-Villanueva V, et al. Physical modelling of large wood (LW) processes relevant for river management: Perspectives from New Zealand and Switzerland. Earth Surface Processes and Landforms, 2022, 47 (1): 32-57.

[9] Zhu J, Wang J, Feng C. Deformation characteristics and sensitivity analysis of aeolian soil bank slope in Xinjiang desert open channel. Environmental Earth Sciences, 2024, 83 (14): 1-16.

[10] Sun L, Tang X, Abdelaziz A, et al. Stability analysis of reservoir slopes under fluctuating water levels using the combined finite-discrete element method. Acta Geotechnica, 2023, 18 (10): 5403-5426.

[11] Jakiyayev B D, Moldamuratov Z N, Bayaliyeva G M, et al. Study of local erosion and development of effective structures of transverse bank protection structures. Periodicals of Engineering and Natural Sciences, 2021, 9 (3): 457-473.

[12] Han J K, Zhao J Y, Wei J, et al. Influence of shrub root combinations and spacing on slope stability: study case at the Yongding River flooding regime, Langfang, China. Environmental Science and Pollution Research, 2022, 29 (46): 69599-69617.

[13] Zhang J, Shang Y, Cui M, et al. Successful and sustainable governance of the lower Yellow River, China: A floodplain utilization approach for balancing ecological conservation and development. Environment, Development and Sustainability, 2022, 24 (3): 3014-3038.

[14] Alsubih M, Ahmed M, Alqadhi S, et al. Gabion water barrier structures as a sustainable approach to water and land conservation. Environmental Science and Pollution Research, 2023, 30 (60): 126057-126071.