

Article

Experimental Study and Numerical Simulation on Anti-Scouring Performance of 3D Ecological Protection Mat for Slope Protection

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Abstract

As an innovative ecological material widely adopted for surface protection of hydraulic soil–cement slope composites, 3D ecological slope protection mats remain insufficiently studied in terms of their anti-scour capacity under hydrodynamic erosion. This work combines physical model tests and numerical simulations to investigate its scour resistance, and adopts a radial basis function (RBF) neural network-based intelligent inversion method to calibrate numerical model parameters. Physical test results demonstrate that longer vegetation growing periods effectively strengthen slope anti-scouring performance. At 2 m/s flow velocity, extending the growth period from 2 months to 3 and 4 months increases bed shear stress of 3D ecological protection mat specimens by 41% and 19%, reduces soil loss by 49% and 33%, and decreases scour depth by 23% and 13%. Both scour depth and soil loss rise rapidly initially before leveling off, with larger ultimate values under higher flow velocities. The established numerical model achieves a 3.1% relative error between inverted and measured data, proving high inversion accuracy. Simulations under 1–5 m/s flow velocities reveal that flow velocity decreases significantly over the protected slope, and scour depth and scouring area expand gradually with increasing flow velocity.

Keywords: 3D ecological protection mat; anti-scouring performance; physical model tests; numerical simulation

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1. Introduction

Wading slopes widely exist in the natural environment and engineering construction. When subjected to water flow scouring, wading slopes face the risk of soil stripping and loss [1], which further reduces the overall stability of slopes and easily induces engineering disasters such as collapse and landslide [2,3]. Therefore, how to effectively protect riverbank slopes and ensure their stability has attracted extensive attention from researchers. Although traditional slope protection measures such as mortar-laid stone and concrete slope protection can resist erosion and protect slopes, they isolate soil and are not conducive to the vegetation growth and self-repair of ecosystems [4–6]. With the popularization of the concepts of sustainable development and ecological environmental protection, the governance of riverbank slopes is gradually evolving towards ecologicalization.

3D ecological protection mats for ecological slope protection is a new type of ecological slope protection technology that has been rapidly promoted in recent years [7,8]. Its unique three-dimensional mesh structure can provide additional reinforcement for vegetation roots, helping vegetation and soil jointly build an ecological protection system, thereby significantly improving the stability and erosion resistance of slope soil. This slope protection technology can effectively resist the erosion of slope soil by rainfall runoff and flood on the one hand, and help promote slope vegetation restoration and improve the slope ecological environment on the other hand. Therefore, it has been valued and applied in ecological slope protection construction. However, the research on 3D ecological protection mats for ecological slope protection is still in the initial stage, and most current research results focus on construction process optimization, project cost control and economic benefit evaluation. There are few research results on the anti-scour performance of 3D ecological protection mats for ecological slope protection, which requires further in-depth research and analysis.

In recent years, researchers have adopted physical model tests, numerical simulations and other approaches to investigate the scouring characteristics of ecological slope protection under water flow. Zhan et al. [9]. experimentally discussed the influence of ecological slope protection with different vegetation types on slope permeability under rainfall infiltration. Zhang et al. [10]. studied the anti-scouring performance of gabion ecological slope protection and further optimized the structural design of gabion nets. Tao et al. [11]. explored the effect of ecological slope protection on slope permeability under rainfall infiltration through laboratory tests. Sohan et al. [12] investigated the protective performance of ecological bag slope protection under flow scouring. Furthermore, numerical simulation serves as another effective tool for researching ecological slope protection and related engineering issues. Lin et al. [13]. utilized numerical simulation to analyze how rainfall scouring intensity affects the stability of ecological slopes. Ou [14] established a numerical model via the finite element method to investigate the variation law of slope stability affected by slope gradient under river flow scouring. Likitlersuang et al. [15] analyzed the protective performance of vetiver grass ecological slope protection against flow scouring via numerical simulation. Switala and Wu [16] adopted a numerical simulation to investigate the reinforcement effect of slope vegetation under rainfall-induced erosion.

To systematically study the anti-scouring performance of ecological slopes covered with 3D ecological protection mats, this paper combines physical model tests and numerical simulations. Taking advantage of the authenticity and reliability of physical tests, anti-scouring tests on slopes protected by 3D ecological protection mats are conducted and analyzed under various flow velocities and vegetation growth stages. Meanwhile, numerical simulation is adopted for its high efficiency and low cost. Apart from simulating the tested flow velocity conditions of 1~3 m/s, the numerical calculation is extended to 4 m/s and 5 m/s working conditions to analyze the corresponding flow velocity distribution, scouring depth and slope surface morphology. This study can provide systematic research methods and implementation references for analyzing the anti-scour characteristics of slopes reinforced with 3D ecological protection mat and their practical engineering applications.

2. Materials and Methods of Model Scouring Test

Physical model testing is a widely employed technical method in scientific research. Based on a flume scouring test system, this section establishes a detailed experimental scheme for the scouring test of slopes protected by 3D ecological protection mat for slope protection.

2.1. Test Materials

The test was conducted in an indoor laboratory, and the entire test setup constituted a closed circulation system (Figure 1). An elevated water tank was employed to regulate the upstream water head. The test flume, fabricated from acrylic glass, had dimensions of 6 m in length and 0.2 m in width, inside which a dimensionally matched vegetation trough was placed. The inlet flow rate was regulated by a valve, and an electromagnetic flowmeter installed downstream of the valve was used to measure the cross-sectional flow rate corresponding to different valve openings. A soil collection tank was arranged at the downstream end of the setup, which filtered the scoured water through a filter screen to collect the entrained soil particles.

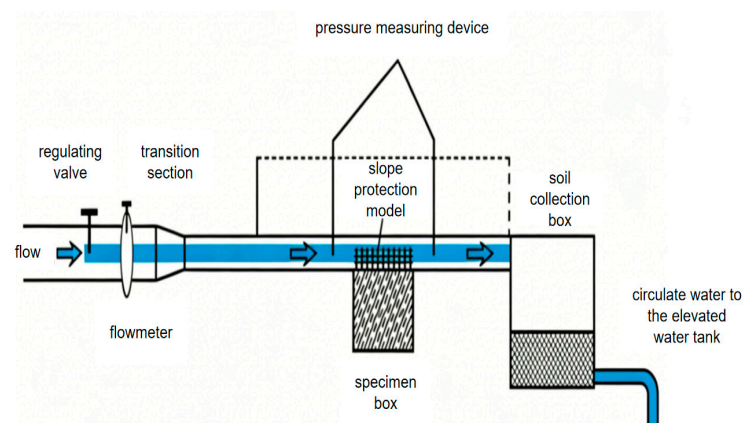


Figure 1. Schematic diagram of the overall structural layout.

The test in this study selected tall fescue, which exhibits excellent submergence tolerance and strong environmental adaptability, as the slope protection vegetation. This grass species features a rapid growth rate, well-developed root system and low post-planting maintenance cost. The planting was completed following the procedure of first leveling the slope surface, then laying the 3D ecological protection mat and broadcasting the grass seeds, and finally covering with a thin layer of topsoil [17]. Timely watering and maintenance were carried out after planting, and the 3D ecological protection mat slope for protection specimens were finally prepared (Figure 2).

2.2. Test Program

To analyze the effect of vegetation growth stage on the anti-scouring performance of 3D ecological protection mat slope for protection, three vegetation growth stages were designed: 2 months, 3 months and 4 months. To comparatively analyze the anti-scouring performance of 3D ecological protection mat slope for protection under different flow velocities, referring to similar experimental schemes of physical model tests [18], three flow velocity groups were set, and scouring tests were conducted at 1 m/s, 2 m/s and 3 m/s respectively. To investigate the variation law of soil loss during the scouring process of 3D ecological protection mat slope for protection, soil loss was collected at intervals of 0.5 h under each flow velocity condition.

The main monitoring indicators of the test were bed shear stress in the vegetation area, scouring depth of 3D ecological protection mat slope for protection and soil scouring amount. The water flow rate was adjusted by a manual flow control valve, the flow velocity was measured by an intelligent electromagnetic flowmeter, and the bed shear stress was measured by a differential pressure gauge. Three sections were arranged along the flow direction in the middle part of the vegetation trough, with 3 monitoring points set at each section. A total of 9 monitoring points across the 3 sections were used to measure the

scouring depth. Based on relevant scouring tests reported in previous studies [19], the scouring duration was set to 4 h, and scouring data were recorded every 0.5 h. To ensure the test accuracy, each test was repeated twice, and the average value of the data was taken as the final test result.



Figure 2. Specimen curing and scouring photographs: (a) specimen curing; (b) specimen scouring.

3. Results and Analysis of Model Scouring Test

In this section, scouring tests under various working conditions were carried out on slope protection specimens. Bed shear stress, scour depth and soil loss were selected as evaluation indicators to comprehensively analyze their anti-scour performance.

3.1. Analysis of Bed Shear Stress in Vegetation Area

In river channels, the failure of slope protection is mainly caused by the shear stress generated by water flow. As the flow scouring intensity continues to increase, the bed shear stress acting on the bed surface in the vegetated area also increases accordingly. According to the principle of mechanical equilibrium, if the slope protection can maintain overall stability without obvious damage when subjected to a higher bed shear stress, it possesses the anti-scouring performance corresponding to that flow velocity.

The scouring apparatus used in this study is equipped with a differential pressure gauge. By reading the differential pressure data upstream and downstream of the vegetation trough, the bed shear stress in the vegetation-covered area can be calculated, as shown in Figure 3.

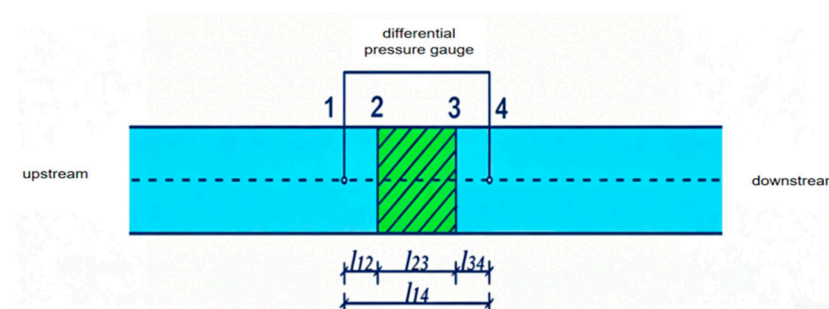


Figure 3. Schematic diagram of differential pressure measurement.

Four monitoring sections are set along the water flow direction, numbered 1 to 4 in sequence. The detailed layout of each monitoring cross-section is presented in Figure 3. By collecting the values of the differential pressure gauge between Sections 1 and 4 far away from the vegetation area, it can be used to calculate the bed shear stress in the vegetation-covered area.

The bed shear stress of the smooth wall can be calculated according to Equation (1):

$$\tau = \rho g R J = \rho g R \frac{\Delta h}{L} \quad (1)$$

where τ is the bed shear stress, with a unit of Pa, ρ denotes the water density, with a unit of kg/m³, g is the gravitational acceleration, whose value is 9.81 m/s²; R represents the hydraulic radius, with a unit of m, J is the hydraulic gradient, which is dimensionless, L stands for the length of the experimental measuring section, with a unit of m, and Δh is the head loss of the experimental section, with a unit of m.

Numerical calculations were first carried out for the smooth acrylic glass wall surface in the absence of vegetation. The same acrylic glass plate was placed at the position of the vegetation trough. After the water flow reached a stable state, the differential pressure gauge was used to measure the water head differences between the upper sides and between the lower sides of Section 1 and Section 4 respectively. The average wall shear stress between Sections 1 and 4 can then be derived using Equation (1).

Then, the specimens were placed into the specimen box, and the scouring tests for the 3D ecological protection mat slope for protection were conducted. The flow velocity was adjusted to the preset design value by regulating the flow control valve, and the water head difference was measured with a differential pressure gauge. The average shear stress τ_1 between Sections 1 and 4 after specimen placement can be derived in the same manner.

To obtain the bed shear stress in the vegetated area, the interference caused by the side walls of the acrylic glass flume on the measurement results must be eliminated. By subtracting the resistance effect of the acrylic glass walls of the flume from the total measured shear stress, the actual bed shear stress acting on the vegetated area can be accurately obtained.

3.1.1. Variation Law of Bed Shear Stress Under Different Flow Conditions

To analyze the variation law of bed shear stress under different flow conditions, scouring tests were conducted on the 3D ecological protection mat slope for protection specimens with a vegetation growth stage of 2 months at flow velocities of 1, 2 and 3 m/s respectively. The water head difference was measured, and the bed shear stresses in the vegetated area at each flow velocity were obtained, with specific values of 62 Pa, 108 Pa and 142 Pa respectively. It can be seen that the higher the flow velocity, the greater the bed shear stress in the vegetated area. Compared with the flow velocities of 1 m/s and 2 m/s, the bed shear stress of the 3D ecological protection mat slope for protection specimens at 3 m/s increased by 129% and 31% respectively.

3.1.2. Variation Law of Bed Shear Stress Under Different Vegetation Growth Stages

Due to the different vegetation growth stages, the flow retardation effect of vegetation under water flow scouring varies, thus resulting in different bed shear stresses in the vegetated area for specimens at different growth stages. A comparative study was conducted on the 3D ecological protection mat slope for protection specimens with vegetation growth stages of 2 months, 3 months and 4 months, and the bed shear stresses in the vegetated area under the three groups of flow velocity conditions are shown in Table 1.

Table 1. Bed shear stress in different growth periods.

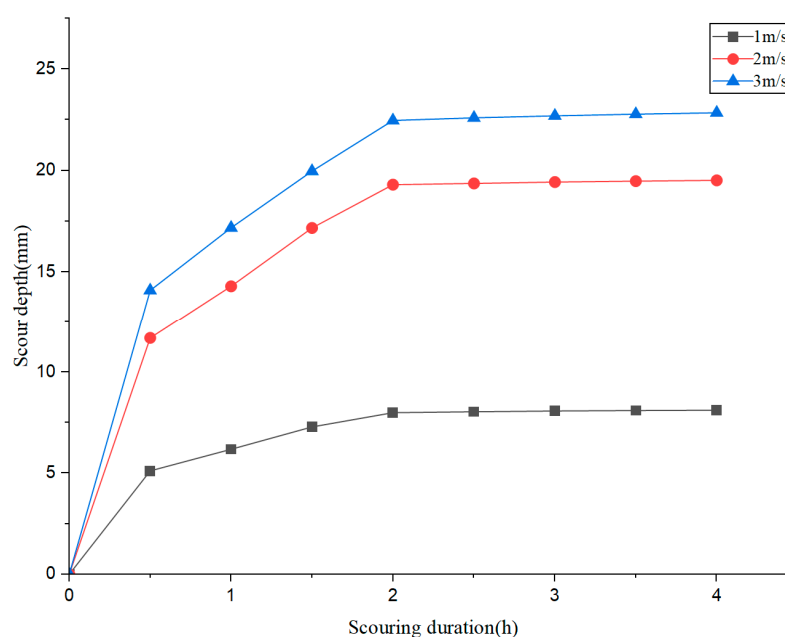
Flow Velocity	2-Month Growth Period	3-Month Growth Period	4-Month Growth Period
m/s	Bed shear stress(pa)	Bed shear stress(pa)	Bed shear stress(pa)
1	62	73.4	87.4
2	108	127.9	152.2
3	142	168	200

Table 1 shows that the bed shear stress in the vegetated area increases with the extension of vegetation growth stage. Specifically, taking the flow velocity of 2 m/s as an example, the bed shear stress in the vegetated area of the slope protection specimens at the 4-month growth stage increased by 41% compared with those at the 2-month growth stage, and increased by 19% compared with those at the 3-month growth stage.

3.2. Analysis of Scour Depth

3.2.1. Variation Law of Scouring Depth Under Different Flow Conditions

The variation curves of scouring depth with scouring duration for the 3D ecological protection mat slope for protection specimens with a 2-month vegetation growth stage at flow velocities of 1 m/s, 2 m/s and 3 m/s are plotted in Figure 4. It can be seen from the curves that the scouring depth increases continuously with the increase in scouring duration, and its growth rate gradually decreases.

**Figure 4.** Scour depth–scouring duration curves.

3.2.2. Variation Law of Scouring Depth Under Different Vegetation Growth Stages

A comparative analysis was conducted on the 3D ecological protection mat slope for protection specimens at different vegetation growth stages, and the scouring depths of these specimens after 4 h of scouring at different growth stages are shown in Table 2.

Table 2. Comparison of scour depth of 3D ecological protection mats for ecological slope protection in different growth periods.

Flow Velocity	2-Month Growth Period	3-Month Growth Period	4-Month Growth Period
m/s	Scour depth(mm)	Scour depth(mm)	Scour depth(mm)
1	8.12	6.34	4.56
2	19.53	16.3	13.06
3	22.88	20.29	17.7

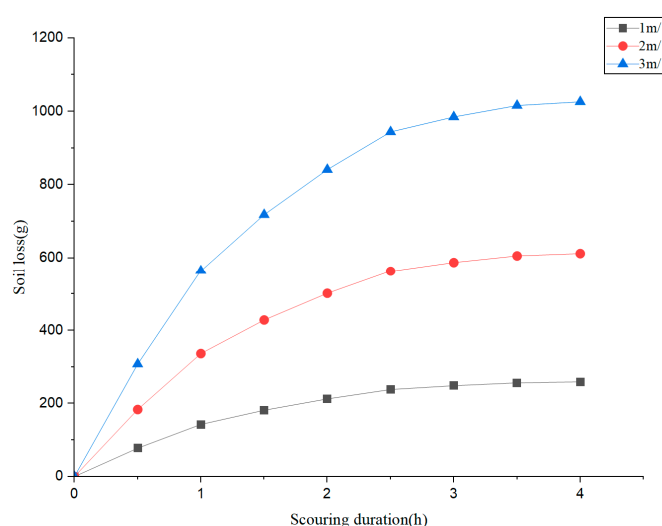
Test data indicate that at a flow velocity of 2 m/s, the scouring depth of the 3D ecological protection mat slope for protection specimens at the 4-month vegetation growth stage decreased by 23% compared with those at the 2-month growth stage, and decreased by 13% compared with those at the 3-month growth stage.

3.3. Analysis of Soil Loss

3.3.1. Variation Law of Soil Loss Under Different Flow Conditions

The variation curves of soil loss with scouring duration for the 3D ecological protection mat slope for protection specimens with a 2-month vegetation growth stage under flow velocity conditions of 1 m/s, 2 m/s and 3 m/s are plotted in Figure 5. From the scouring process reflected by the curves, the development of soil loss presents a characteristic of rapid initial growth followed by gradual deceleration.

In the initial scouring stage, the soil particles on the surface of the specimens are relatively easily scoured by water flow, resulting in a rapid increase in cumulative soil loss. In the middle scouring stage, most of the easily erodible soil particles on the specimen surface have been washed away by water flow, so the growth rate of cumulative soil loss slows down compared with the relatively high rate in the initial stage. In the late scouring stage, the soil above the 3D ecological protection mat has been washed away. Due to the integrated reinforcement effect formed by the 3D ecological protection mat, soil and vegetation roots, the remaining soil is not easily washed out by water flow, hence the cumulative soil loss increases slowly during this period. When the flow scouring force reaches equilibrium with the anti-scouring performance of the 3D ecological protection mat slope for protection specimens, the cumulative soil loss gradually reaches the scouring upper limit. The scouring upper limit increases correspondingly with the increase in flow velocity.

**Figure 5.** Soil loss scouring duration curves for 2-month growth period.

3.3.2. Variation Law of Soil Loss Under Different Growth Periods

A comparative study was conducted on 3D ecological protection mats for slope protection with growth periods of 2 months, 3 months and 4 months under high planting density. Table 3 shows the soil loss during the overall scouring process of 3D ecological protection mats for slope protection in different growth periods under the same conditions.

Table 3. Comparison of soil loss of 3D ecological protection mats for slope protection in different growth periods.

Flow Velocity	2-Month Growth Period	3-Month Growth Period	4-Month Growth Period
m/s	Soil loss (g)	Soil loss (g)	Soil loss (g)
1	259.2	216	180
2	612	520.8	396
3	1026	864	648

It can be seen from Table 3 that with the extension of vegetation growth period, the soil loss of 3D ecological protection mats for slope protection decreases significantly. Among them, the soil loss of specimens with a growth period of 4 months decreases by 49% and 33% compared with those of 2 months and 3 months respectively.

4. Analysis of Anti-Scouring Performance of 3D Ecological Protection Mat Slope for Protection Based on Numerical Simulation

This section first introduces the theoretical methods of numerical simulation. Then, the computational parameters are accurately obtained via parameter inversion, and numerical simulation analysis is conducted on the scouring process of slopes protected by 3D ecological protection mats.

4.1. Theoretical Method

This paper adopts the sediment transport model built in FLOW-3d to calculate the scouring process of slopes protected by 3D ecological protection mats, and the relevant fundamental theories are presented as follows.

The dimensionless critical Shields number θ_{cr} is calculated using the Soulsby–Whitehouse formula [20], which is expressed as

$$\theta_{cr} = \frac{0.3}{1 + 1.2d_*} + 0.55[1 - \exp(-0.02d_*)] \quad (2)$$

$$d_* = \left[\frac{g(\rho_i - \rho)\rho}{\mu^2} \right]^{1/3} d_i \quad (3)$$

where ρ_i is the density of the particle, with a unit of kg/m³; d_i is the particle diameter, with a unit of m; d_* is the dimensionless particle diameter, which is dimensionless; and μ is the dynamic viscosity of water, with a unit of kg/(m · s).

Since sediment becomes unstable on inclined beds, it is more easily entrained and transported by the flow. Therefore, the critical Shields number is adjusted and corrected, as given in the following equation:

$$\theta'_{cr} = \theta_{cr} \frac{\cos \psi \sin \beta + \sqrt{\cos^2 \beta \tan^2 \varphi - \sin^2 \psi \sin^2 \beta}}{\tan \varphi} \quad (4)$$

where β is the angle of slope of bed, ψ is the angle between the flow and the upslope direction, φ is the angle of repose for particle, and θ_{cr} is the modification of the critical Shields parameter, which is dimensionless.

The velocity at which bed sediment turns into suspended sediment during sediment incipient motion is calculated by the MaStbergen formula [21], as shown in Equation (5):

$$u_{lift} = \alpha n_s d_*^{0.3} (\theta_i - \theta_{cr}')^{1.5} \sqrt{\frac{g d_i (\rho_i - \rho)}{\rho}} \quad (5)$$

where u_{lift} is the sediment flux converted from bed sediment to suspended sediment, with a unit of m/s, α is the entrainment parameter, which is dimensionless, n_s is the normal direction of the bed surface, which is dimensionless, θ_i is the local Shields number, which is dimensionless, and the remaining variables are consistent with those defined earlier.

The local Shields number is calculated from the local bed shear stress, as expressed in Equation (6):

$$\theta_i = \frac{\tau}{g d_i (\rho_i - \rho)} \quad (6)$$

where τ is the bed shear stress, with a unit of Pa, and the remaining variables are consistent with those defined earlier.

The bedload transport rate is calculated using the Meyer–Peter and Müller bedload transport formula [22], as expressed in Equation (7).

$$\Phi = \beta_{MPM} (\theta_i - \theta_{cr}')^{1.5} \quad (7)$$

where Φ is the bed load transport rate, which is dimensionless, β_{MPM} is the bed load coefficient, which is dimensionless, and the remaining variables are consistent with those defined earlier.

4.2. Numerical Model

Based on the physical model tests, the test case with a 2-month vegetation growth stage was selected as an example. According to the structure of the physical test model described above, the corresponding numerical model was established using FLOW-3d software, and the two models have identical dimensions.

The boundary conditions were set as follows: the inlet of the flume was set as a velocity inlet boundary, the outlet was set as an outflow boundary, wall boundaries were applied to the bottom and side walls of the flume, and the air above the flume was set as a pressure boundary condition. The middle part of the model was the soil mass of the 3D ecological protection mat slope for protection with a length of 0.6 m and a thickness of 0.15 m. The front and rear ends of the soil mass were each connected to a flat region with a length of 2.7 m and a thickness of 0.15 m, which were used to simulate the organic glass plates of the test flume. Cylinders were used to simulate the vegetation plants [23], and their average diameter of 0.01 m and average height of 0.1 m were determined through actual observation of the plants on the specimens. The numerical calculation model is shown in Figure 6.

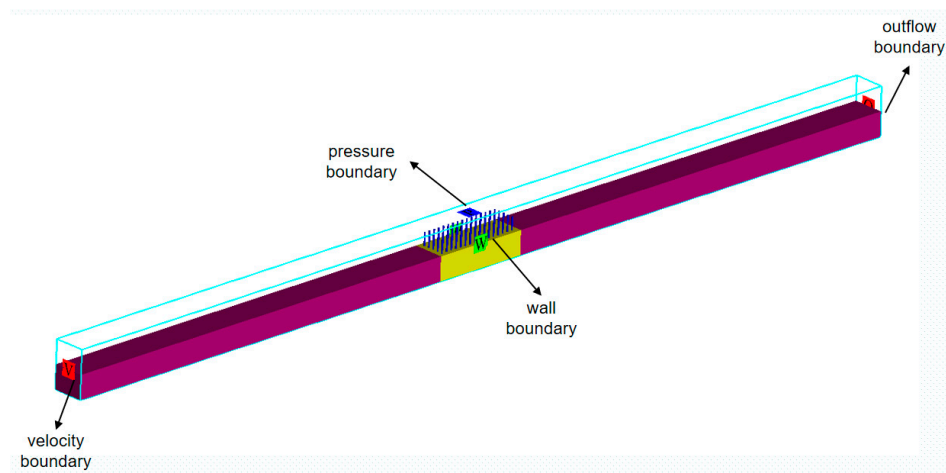


Figure 6. Overall numerical simulation model.

To ensure computational accuracy and balance computational cost, the model was mainly discretized using meshes with an edge length of 0.01 m. Local mesh refinement with an edge length of 0.005 m was applied to the soil mass and vegetation stalk regions. The mesh discretization of partial regions is shown in Figure 7.

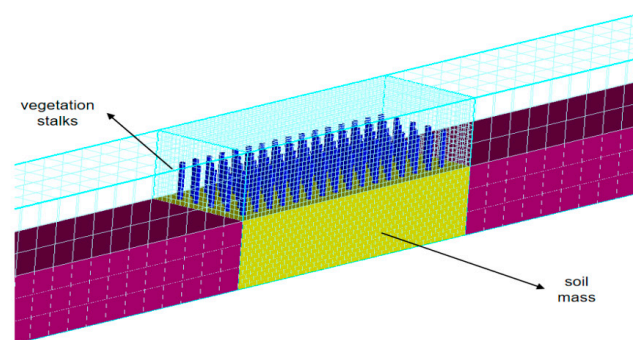


Figure 7. Mesh discretization diagram of local area of slope protection specimen.

4.3. Parameter Acquisition Process

The structure of the 3D ecological protection mat slope for protection is complex, making it difficult to determine its calculation parameters. To address the above issue, the combination of the mesh mat and soil is regarded as a homogeneous composite soil mass in the numerical model [24], and the calculation parameters are obtained by means of the inversion method. According to the theory in Section 4.1, the parameters of the composite soil mass involved in the scouring simulation calculation include particle diameter d_i , particle density ρ_i , bed load coefficient β_{MPM} , entrainment coefficient α , and angle of repose φ , while the remaining parameters can be derived through calculation. It can be seen from Equation (4) that the angle of repose φ is related to the correction of the critical Shields number under certain conditions. Since the test and research objects in this paper do not require correction of the critical Shields number, the influence of the angle of repose is not considered, namely: $\theta'_{cr} = \theta_{cr}$. Therefore, four parameters of the composite soil mass, namely d_i , ρ_i , β_{MPM} and α , are inverted in this paper. Based on the relevant literature [25–27], the preliminary value ranges of the parameters are given as follows: particle diameter 6–10 mm, particle density 1800–2000 kg/m³, bed load coefficient 4–12, and entrainment coefficient 0.014–0.022. Then the values of each parameter are determined by the inversion method.

The RBF neural network is a feedforward neural network based on radial basis functions, which has been widely adopted in the field of parameter inversion. Sufficient training samples are required to construct the parameter inversion model based on the RBF neural network. The orthogonal experimental design method is extensively used in multi-factor scientific experiments and engineering analyses [28]. Accordingly, 49 groups of parameter combinations are designed following the orthogonal experimental scheme. The scouring depth under a flow velocity of 2 m/s after 4 h of scouring is calculated via the numerical model. The calculated scouring depths are taken as input variables, and the corresponding parameter combinations are set as output variables. The RBF neural network is trained to establish a nonlinear mapping model between scouring depth and soil material parameters.

Subsequently, the experimentally measured scouring depth after 4 h is imported into the trained model, and the inverted composite soil mass parameters of the 3D ecological mat slope protection are obtained as follows: particle diameter of 7.8 mm, particle density of 1950 kg/m³, bed load coefficient of 6.5, and entrainment coefficient of 0.017. Using these inverted parameters, the equivalent critical Shields number of the soil mass is calculated to be 0.475 via Equation (2).

The inverted composite soil mass parameters are substituted into the established numerical model for forward calculation of scouring depth. The calculated average scouring depth after 4 h is 20.14 mm, while the corresponding experimental measurement value is 19.53 mm, yielding a relative error of 3.1%. It can be concluded that the inversion results exhibit satisfactory accuracy.

4.4. Numerical Calculation of Scouring Characteristics

In physical model tests research, it is often difficult to obtain detailed characteristics such as flow field and scouring morphology due to the influence of external factors such as measuring instruments and model dimensions. For high-velocity water flow, the requirements for test equipment and economic costs are relatively high, making it difficult to achieve long-term and full-coverage data acquisition. In view of this, using the accurate soil mass parameters obtained through inversion, this paper simulated and calculated the slope protection under the test flow velocity conditions of 1–3 m/s, and extended the calculation to the flow velocity conditions of 4 m/s and 5 m/s to analyze the corresponding flow velocity distribution, scouring depth and slope morphology.

4.4.1. Comparison of Flow Velocity Fields Under Different Incoming Flow Velocities

Figures 8–12 present the flow velocity distributions over the slope protected by 3D ecological protection mat at flow velocities of 1, 2, 3, 4, and 5 m/s. The coordinate system was established with the origin at the bottom of the right flume wall, where the positive X-axis was aligned with the flow direction and the Y-axis pointed towards the left flume wall. It can be observed that the flow velocity decreased significantly as the water flowed over the protected slope under all conditions. Specifically, the maximum velocity reduction reached 81% at a flow velocity of 1 m/s, while it was 50.2% at 5 m/s, indicating that the velocity reduction effect was more pronounced under low flow velocity conditions.

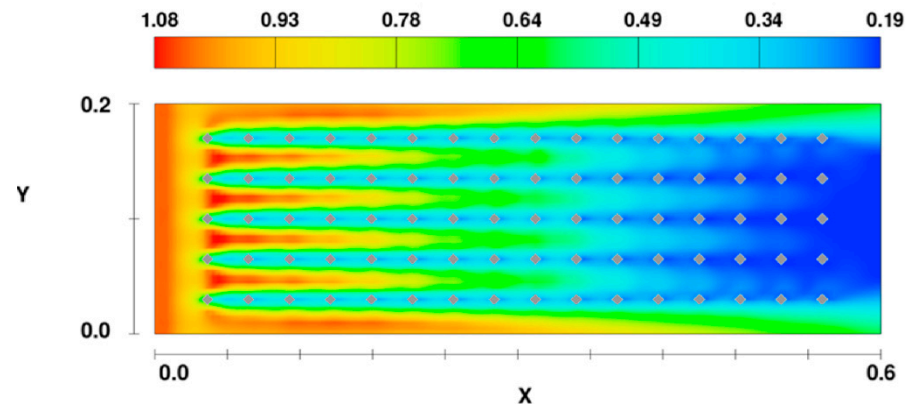


Figure 8. Flow-field distribution at the flow velocity of 1 m/s (unit: m/s).

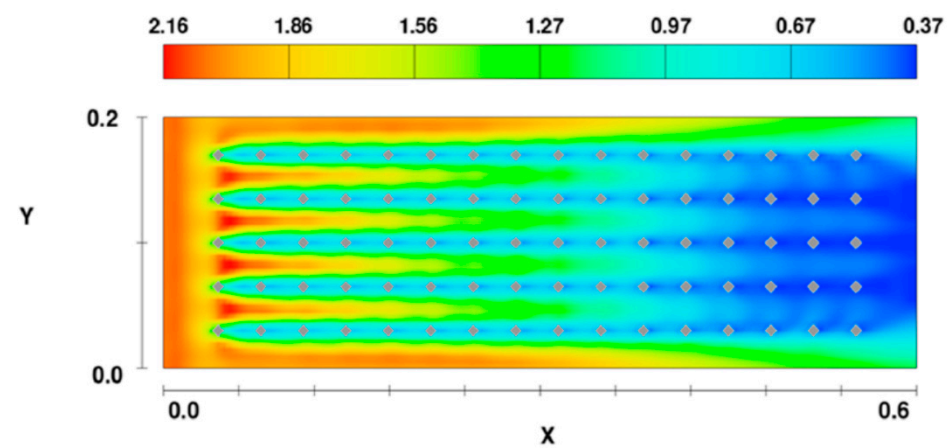


Figure 9. Flow-field distribution at the flow velocity of 2 m/s (unit: m/s).

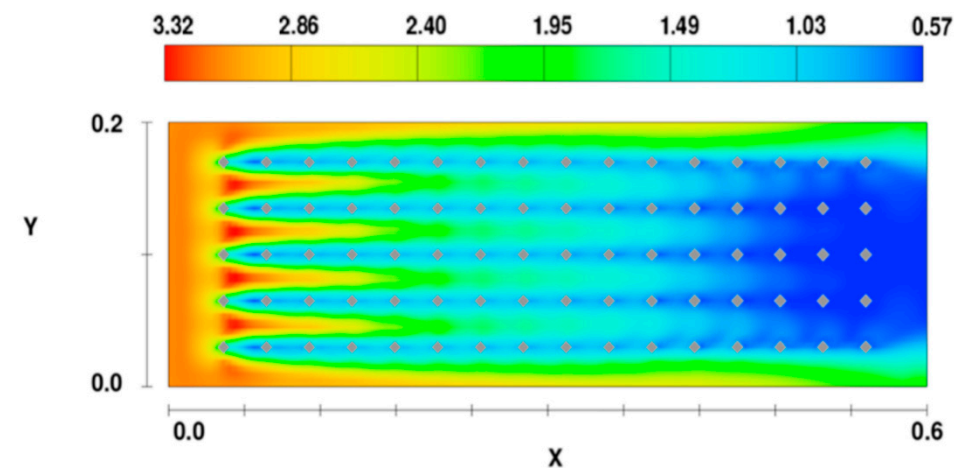


Figure 10. Flow-field distribution at the flow velocity of 3 m/s (unit: m/s).

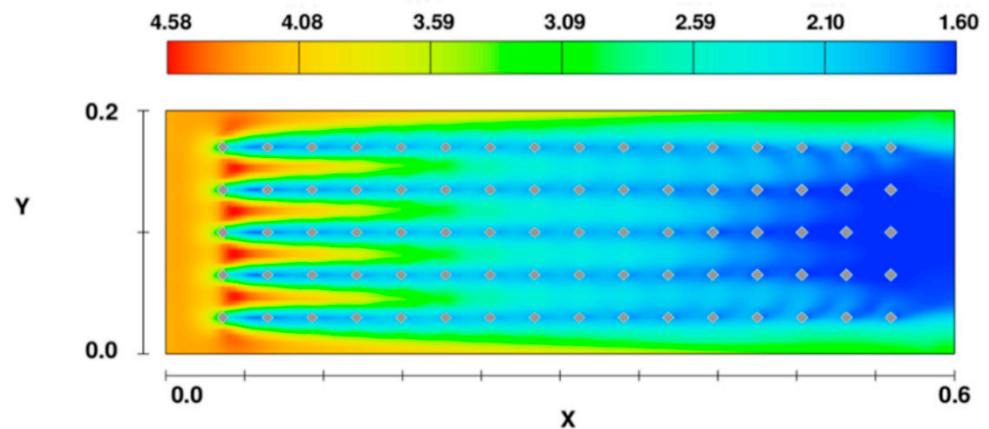


Figure 11. Flow-field distribution at the flow velocity of 4 m/s (unit: m/s).

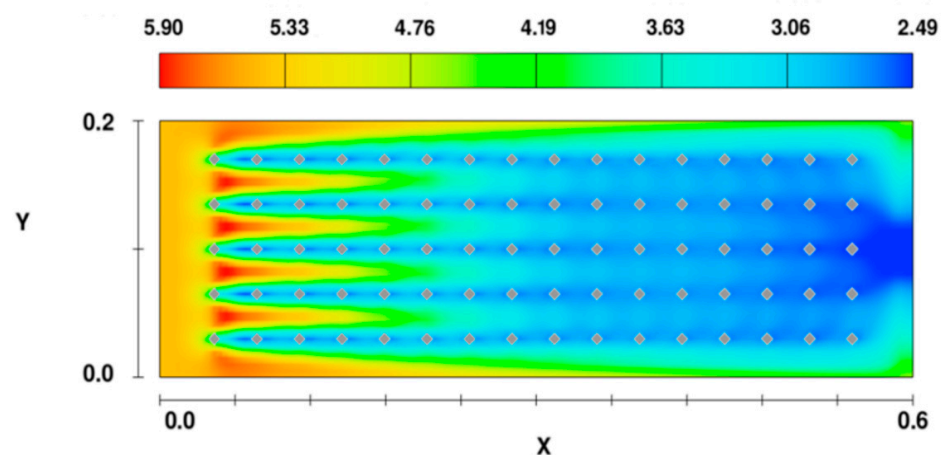


Figure 12. Flow-field distribution at the flow velocity of 5 m/s (unit: m/s).

4.4.2. Comparison of Scouring Depths Under Different Incoming Flow Velocities

Numerical simulation also enables the convenient, continuous and dense extraction of slope scouring depths at different moments, allowing for a more detailed analysis of the entire process of scouring development. To systematically analyze the evolution law of scouring depth of the 3D ecological protection mat slope for protection over time, the total simulation duration of the numerical simulation was set to 4 h, and the scouring depths of the slope protection surface at each corresponding moment were extracted step by step at a time interval of 0.25 h, as shown in Figure 13.

To comprehensively compare the experimental and numerical calculation results, the test case with a flow velocity of 2 m/s was taken as an example. The measured and calculated scouring depths at 8 moments from 0.5 h to 4 h were summarized in Table 4, and the average relative error at each moment was 2.54%. It can be seen that the numerical simulation results are in good agreement with the experimental data.

As can be seen from Figure 13, the calculated scouring depths under the five flow velocity conditions all follow the same pattern of rapid initial growth followed by gradual stabilization with increasing scouring time. The stable value of the calculated scouring depth increases with increasing flow velocity, reaching 28.1 mm at a flow velocity of 5 m/s, which is approximately 3.4 times the value of 8.3 mm at 1 m/s.

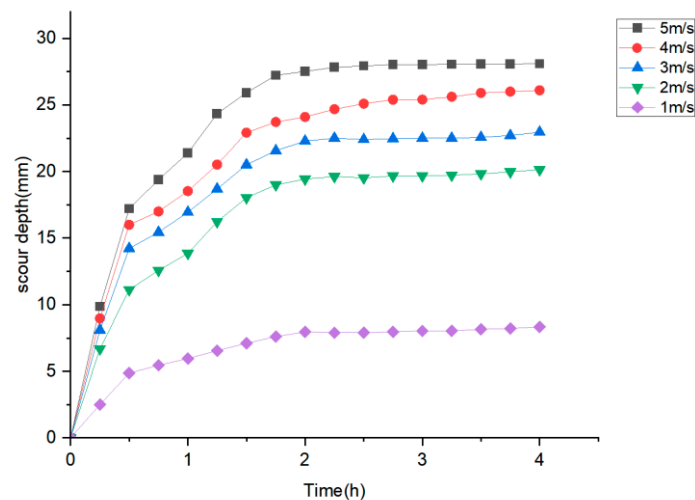


Figure 13. Curves of calculated scouring depth versus time under flow velocities of 1–5 m/s.

Table 4. Simulated and measured data of scouring depth.

Time (h)	0.5	1	1.5	2	2.5	3	3.5	4
calculated values (mm)	11.33	13.72	18.01	19.53	19.65	19.74	19.87	20.14
measured values (mm)	11.71	14.30	17.20	19.32	19.38	19.45	19.50	19.53

4.4.3. Comparison of Slope Morphologies Under Different Incoming Flow Velocities

Figures 14–18 show the dynamic variation characteristics of slope morphology of the 3D ecological protection mat slope for protection specimen during the scouring test under the incoming flow velocities of 1 m/s, 2 m/s, 3 m/s, 4 m/s and 5 m/s respectively.

It can be seen from the calculation results that during the scouring process obvious scouring traces appeared in the front section of the slope protection specimen in the vegetation troughs. This is because the local flow velocity in this area exceeded the critical incipient velocity of soil particles, causing the surface soil particles to be detached and transported downstream by the water flow. As the water flow continues to advance along the slope, affected by the retarding and energy dissipation effect of the 3D ecological protection mat slope for protection, the flow velocity gradually decreases and the scouring kinetic energy on the slope surface is significantly weakened. Therefore, the scouring phenomenon is relatively weak in the rear section of the slope protection specimen.

When the incoming flow velocity increases, the sediment carrying capacity and scouring influence range of the water flow increase synchronously. In addition to the intensification of scouring depth, the overall scouring range of the slope surface expands accordingly. Compared with the characteristics that only local scouring in the front section of the vegetation troughs is obvious under the working conditions of 1 m/s, 2 m/s and 3 m/s, the scouring under the working conditions of 4 m/s and 5 m/s gradually extends downstream.

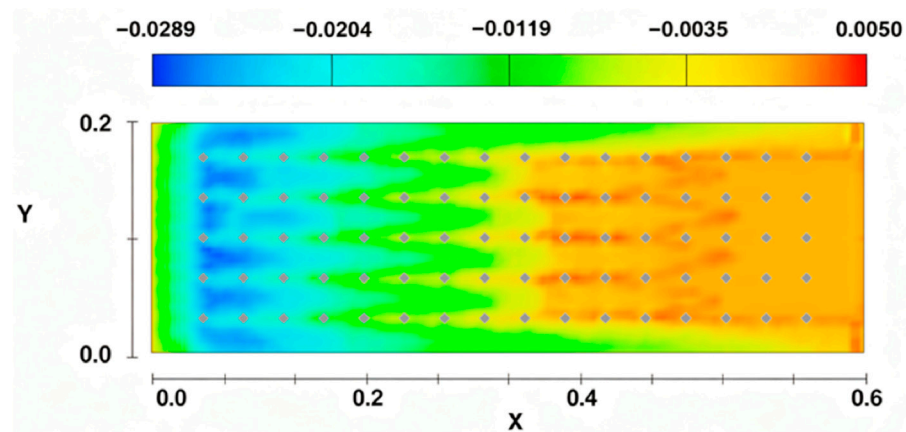


Figure 14. Scour morphology of slope protection sample under 1 m/s flow velocity (Unit: m).

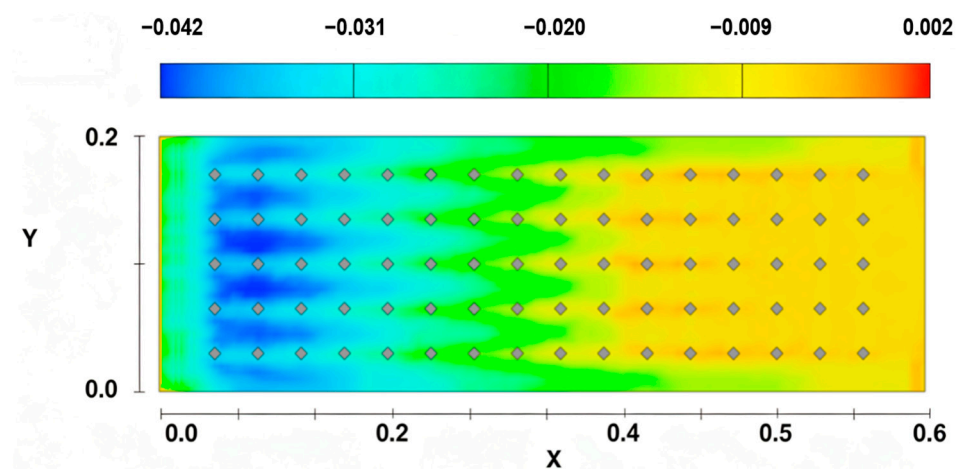


Figure 15. Scour morphology of slope protection sample under 2 m/s flow velocity (Unit: m).

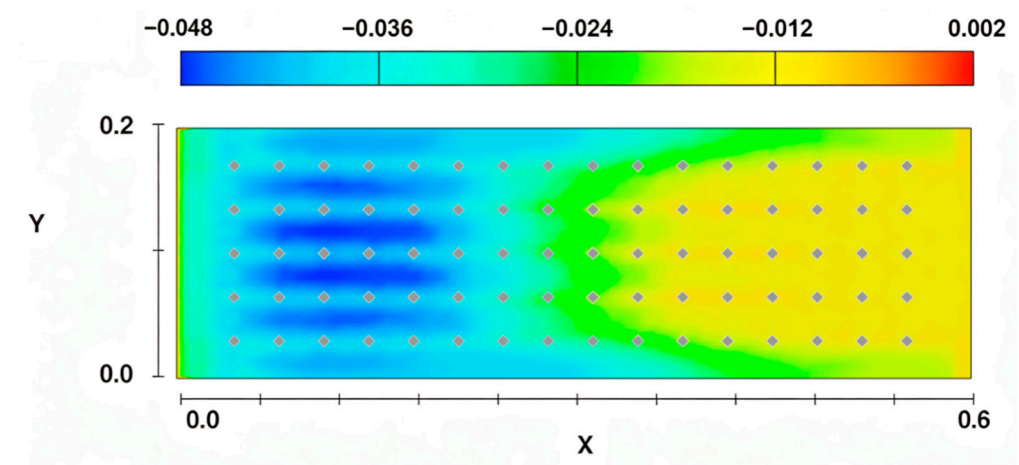


Figure 16. Scour morphology of slope protection sample under 3 m/s flow velocity (Unit: m).

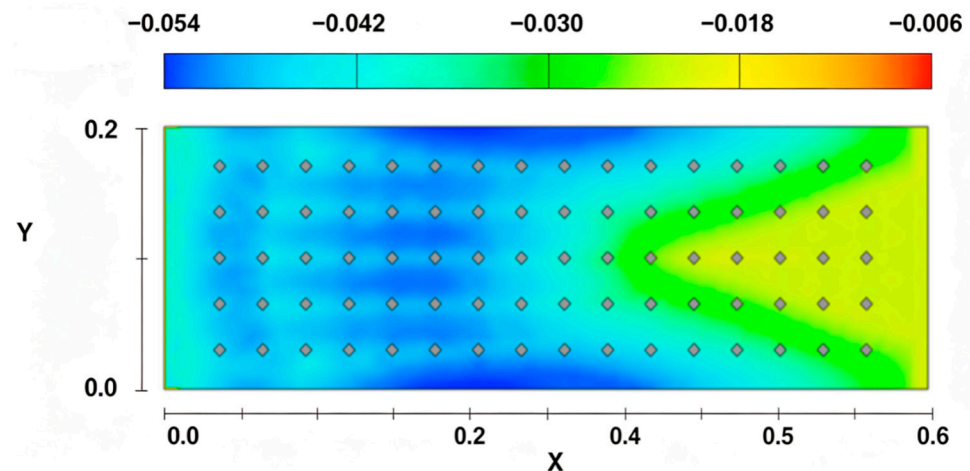


Figure 17. Scour morphology of slope protection sample under 4 m/s flow velocity (Unit: m).

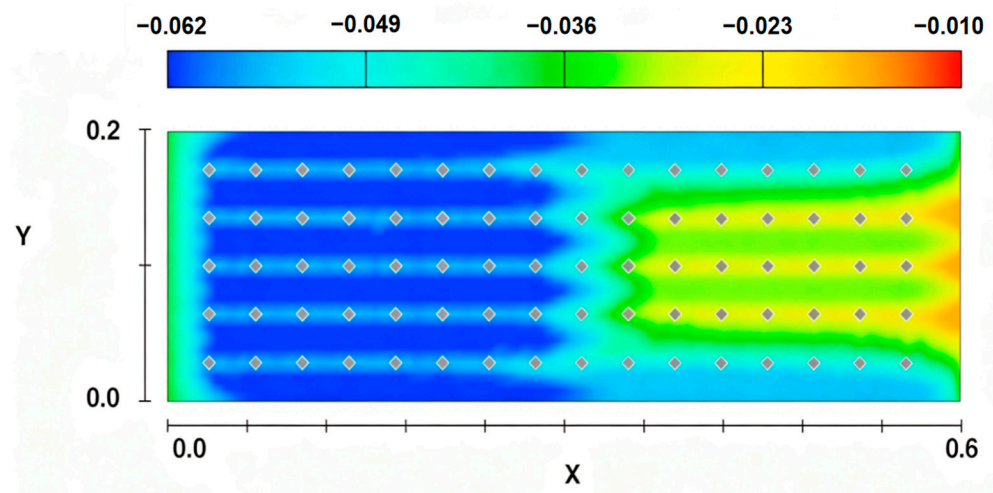


Figure 18. Scour morphology of slope protection sample under 5 m/s flow velocity (Unit: m).

5. Conclusions

Since research on the anti-scour performance of 3D ecological protection mat slope for protection is still in the initial stage, this paper carries out in-depth analysis by combining numerical simulation and physical model tests. The findings of this paper can provide systematic research methodologies and implementation references for analyzing the anti-scouring characteristics of 3D ecological protection mats and supporting their practical engineering applications. The specific conclusions are summarized as follows:

(1) Scouring tests with flow velocities of 1~3 m/s were conducted one by one on 3D ecological protection mat slope for protection specimens. Test data including flow velocity, scouring duration, bed shear stress, scouring depth and soil loss were recorded throughout the tests. The test results show that bed shear stress rises with the increase in flow velocity, vegetation growth period and vegetation density. At a flow velocity of 2 m/s, the average bed shear stress of specimens with a 4-month growth period is 41% and 19% higher than that of specimens with 2-month and 3-month growth periods, respectively. This indicates that the more mature the vegetation grows, the greater the flow resistance provided by the 3D ecological protection mat slope for protection. Both scouring depth and soil loss follow an evolution pattern of rapid growth at first then gradual stabilization over time, and their upper limit values increase with the rise in flow velocity. Proper extension of the vegetation growth period can effectively reduce scouring depth and soil loss: compared with 2-month and 3-month specimens, the 4-month specimens

exhibit a 49% and 33% reduction in soil loss, and a 23% and 13% reduction in scouring depth, respectively.

(2) Based on physical model tests, a numerical scouring calculation model for 3D ecological protection mat slope for protection was established via numerical simulation software. Mesh discretization and boundary constraints were implemented. Particle diameter, particle density, bed load coefficient and entrainment coefficient were selected as parameters to be inverted. The soil mass parameters were obtained by means of the RBF artificial neural network, and the inversion performance was verified. The results reveal that the relative error between calculated simulation values and experimental measured values is small, proving the reliable performance of the inversion method.

(3) Numerical modeling was used to calculate the flow velocity field and slope morphology, and an in-depth analysis was conducted on the flow velocity distribution and slope morphology during the scouring process of slopes protected with 3D ecological protection mat under flow velocities ranging from 1 to 5 m/s. The results show that the flow velocity is significantly reduced after passing through the protected slope at all tested flow velocities. As the incident flow velocity increases, the slope scouring depth shows a clear intensifying trend with increasing flow velocity. The stable scouring depth at a flow velocity of 5 m/s is approximately 3.4 times that at 1 m/s. The change in scouring range is also significant, with the slope scouring range gradually extending downstream as the flow velocity increases.

(4) While these research advances and achievements have been obtained, there remains much work worthy of further in-depth investigation in the future. Subsequent studies could explore the anti-scour performance of 3D ecological protection mat under different vegetation types.

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