

Article

Experimental Study on Anti-Scour Property and Erosion Resistance of 3D Mat Materials for Slope Protection in Waterway Engineering

Yanhua Yang, Haiyong Xu *, Xin Wang, Mingjin Zhang, Wanli Liu, Yude Zhu and Zhe Liu

Key Laboratory of Engineering Sediment, Tianjin Research Institute for Water Transport Engineering of Ministry of Transport, Tianjin 300456, China; yyh200@163.com (Y.Y.); yefuxinxin@aliyun.com (X.W.); zhang_mingjin@vip.sina.com (M.Z.); tjgliuwanli@163.com (W.L.); zhuyude2800@sina.com (Y.Z.); liuzhe@tiwte.ac.cn (Z.L.)

* Correspondence: xuhiyong@163.com; Tel.: +86-22-5981-2345

Abstract: 3D mats are environmentally friendly and ecological materials for protecting river and waterway banks. The anti-scour properties of the materials and the erosion resistance of the soil under them can be studied to provide decision support for the selection of slope protection materials and their applicable areas. In this paper, an indoor prototypical scouring experiment with a flume is carried out to study the anti-scour properties of three types of 3D mat materials (vegetation grass mats, Enkamat and reinforced Mike mat) and the erosion resistance of the underlying soil under typical combined conditions of flow rate and water stage. It is concluded that the 3D mats increase the resistance coefficient of the bed surface, and that with the same incoming flow, the average flow velocity is inversely related to the resistance coefficient. There are three scouring modes for 3D mats under the action of water flow: material failure caused by mechanical damage, performance failure caused by serious erosion of the soil mass and non-failure. Of the three mat materials, the reinforced Mike mats are more resistant to scouring than the other two unreinforced materials, and the erosion volume ratios of reinforced Mike mats, vegetation grass mats and Enkamat are 59.24%, 61.81% and 62.17%, respectively, under the same small flow rate and high water stage. The results show that the reinforced Mike mats have the best anti-scour property and soil conservation performance, followed by Enkamat and the vegetation grass mats. In addition, reinforced materials outperform non-reinforced ones in their anti-scour performance and their protection for the underlying soil on the bank slope.



Citation: Yang, Y.; Xu, H.; Wang, X.; Zhang, M.; Liu, W.; Zhu, Y.; Liu, Z. Experimental Study on Anti-Scour Property and Erosion Resistance of 3D Mat Materials for Slope Protection in Waterway Engineering. *Water* **2022**, *14*, 1392. <https://doi.org/10.3390/w14091392>

Academic Editor: Vito Ferro

Received: 15 March 2022

Accepted: 24 April 2022

Published: 26 April 2022

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

Keywords: slope protection material; resistance coefficient; anti-scour capacity; soil erosion; failure mode

1. Introduction

In the pursuit of long-term development, human society benefits from the clean water resources and beautiful water environments provided by healthy rivers and lakes, and these are the controlling factors in the ecological protection of water. In modern human activities and in sustainable economic and social development, the degradation of rivers and lakes with respect to water function has become the focus of global attention [1]. Rivers and lakes have become prominent areas in water environment pollution and water ecological damage in China [2,3], restricting the overall improvement in the development of water ecology and ecological civilization. Riparian zones and lakeshore zones exhibit material and energy exchange between the water body and the near-shore land [4]. Bank slope protection structures are used to prevent flood disasters and soil loss, representing the most important measure taken in river and lake governance [5,6].

Traditional rigid governance destroys the connectivity of rivers and lakes, and the horizontal exchange of water vapor and nutrients between water and banks, causing

ecosystem degradation, biodiversity loss and loss of natural resources [7,8]. Therefore, in terms of side slope protection technology for waterways in rivers and lakes, ecological protection technology should be strengthened and popularized [9]. Ecological structures for slope protection require comprehensive consideration of structural safety, soil stability and eco-friendly characteristics [10–12]. A variety of ecological structures have been developed for the governance of river and lake waterways at home and abroad, such as plant protection [13], artificial ecological block structures [14–16] and plant mat materials [17], and all have achieved good ecological effects [18]. In recent years, open and flexible 3D mat materials for slope protection have been widely used in river and lake waterways to protect bank slopes. These materials mainly feature simple construction, durability and low maintenance costs.

In previous studies, generalization-based flume experiments and in situ tests have mainly been adopted to explore the hydraulic scouring of 3D mat materials. According to generalization-based flume experiments, compared with natural turf, 3D mat materials result in a significant increase in the maximum anti-scour flow velocity and maximum shear stress when used for slope protection, reducing the soil loss rate considerably [19]. By introducing slope roughness and the trash rack model, a calculation method can be established for frictional head loss and local head loss caused by 3D geomats and vegetation [20]. Using outdoor grass-planting experiments under simulated conditions of rainstorm scouring, the calculation formula of mat strength is derived, and the design index for the mat opening size is identified [21,22]. According to the experimental flume device for an actual river channel with a large scouring flow velocity [23], the bed roughness of reinforced turf is higher than that of natural turf, and the 3D mats enhance the anti-scour property of turf [24,25]. The backwater slope is a vulnerable area where the materials are easily scoured. In terms of erosion resistance, the effects follow the sequence reinforced combination of 3D geomats and geogrids > 3D geogrids > 2D geogrids > natural turf [26]. Testing equipment for damage caused by strong flow in the prototypical test sites has been developed, and the dynamic mechanism of damage and failure has been analyzed for reinforced turf [27]. In the case of steep slopes, jute vegetation blankets, coir blankets and geogrids combined with turf structures for slope protection can significantly reduce the soil loss rate of bank slopes under the protection of geogrids and can also help conserve soil in vegetation growth [20]. In summary, existing studies have focused on simulation research on flow characteristics and anti-scour tests of mat materials for slope protection after the vegetation is established and the roots are well developed [28,29]. There is insufficient understanding of anti-scour properties in the early stage of vegetation growth, with weak roots in the soil. In addition, the hydrodynamic characteristics of 3D geomats such as the flow pattern and resistance are studied only under rainstorm and extreme overland flow conditions [30,31].

Based on an indoor prototypical scouring experiment with a flume, in this paper the anti-scour properties and the erosion resistance of vegetation grass mats, Enkamat and reinforced Mike mats are studied, with the aim of proposing different failure modes by analyzing the results of the anti-scour and erosion tests in combination. Finally, the adaptability and use conditions of 3D mats for slope protection are summarized with regard to their role as structural materials for bank revetments.

2. Maximum Scouring Experimental Design for 3D Mat Materials for Slope Protection

2.1. Design of the Experimental Device

The concrete-surfaced generalization-based experimental flume was 24 m long, with a 6 m test section starting from the water inlet which was 2 m wide internally and 0.5 m high, with a 1.25% bottom slope (Figure 1a). On either side of the flume, there was an upright wall and a bank slope with soil and mat materials. The bank slope of the flume was designed with a 1:3 slope (Figure 1b). In the experiments, the flow was controlled by an electromagnetic flowmeter, and the water stage was adjusted by the electric tailgate at the end of the flume. The water stage was measured by a fixed water gauge, and the

height of the slope soil eroded was measured by a steel scale. The average flow velocity in each experiment was measured by velocimeter, and the instantaneous flow velocity was measured using an acoustic Doppler velocimeter (ADV) along the depth direction in three vertical lines of the section 4 m downstream of the flume inlet. The ADV was produced by Nortek, Norway. The maximum sampling frequency was 200 Hz, and the measurement accuracy was 0.01 cm. The maximum flow rate measured reached 4 m/s. Then, the distribution of the turbulence intensity was calculated for the vertical lines, according to the instantaneous flow velocity. The positions for measuring the instantaneous flow velocity are shown in Figure 1a, where vertical lines L1, L2 and L3 are marked in red. The vertical line L1 is at the intersection of the side slope and the bottom slope of the experimental flume, and vertical line L2 and vertical line L3 are 25 cm and 50 cm, respectively, to the right of L1.

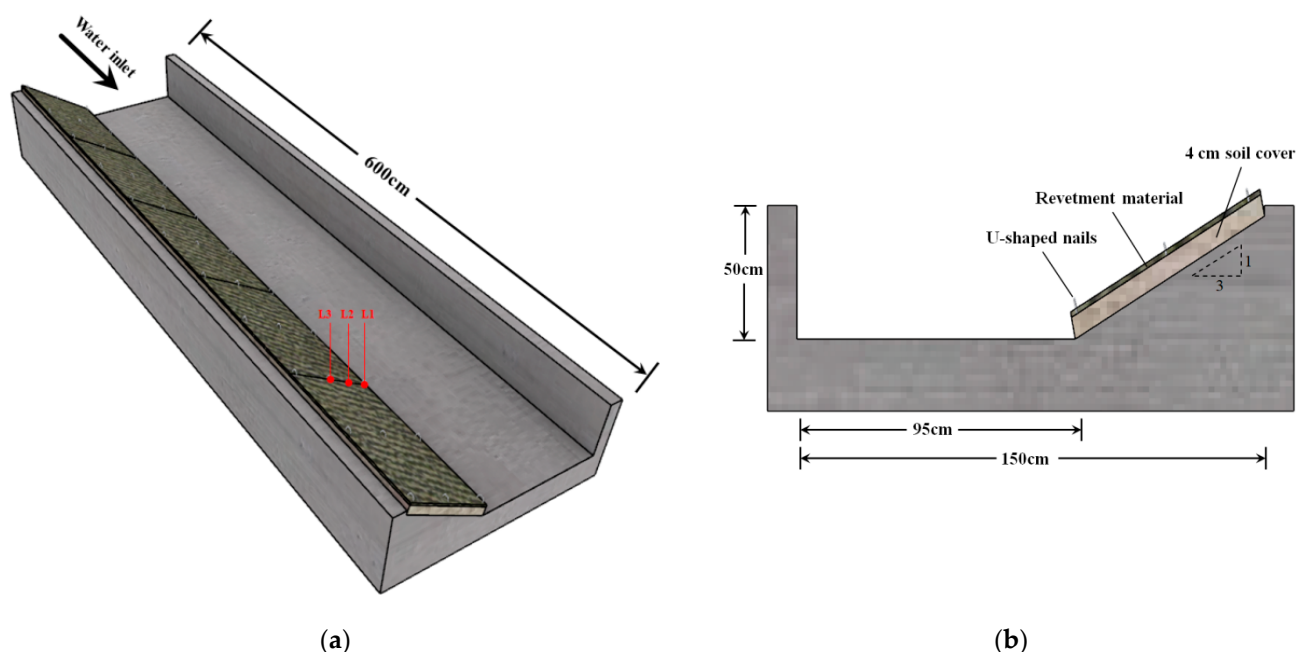


Figure 1. Schematic diagram of the experimental flume: (a) aerial view; (b) dimensions of cross section.

2.2. Characteristics of Experimental Soil

The experimental soil was taken from Shushan District, Hefei, Anhui Province, China ($31^{\circ}49'12''$ N, $116^{\circ}58'42''$ E), and the amount of planting soil was 4 tons, which was enough to completely cover the test section. The undisturbed planting soil directly from the site was laid on the bank slope with a total thickness of 4 cm, as shown in Figure 1b, after it was brought back to the laboratory. Nine groups of experimental soil samples were randomly selected for particle size analysis and statistics in indoor tests and were numbered #1~#9 in sequence, as shown in Figure 2. As the distribution range of particle sizes was $(0.5\sim100) \times 10^{-3}$ mm and the median particle size was 6.197×10^{-3} mm, the soil was silt loam, with physical and mechanical indexes as shown in Table 1.

2.3. Experimental Materials

Vegetation grass mats, Enkamat and reinforced Mike mats were selected as 3D mat materials with a thickness of 10 mm. Steel mesh was not used for the 3D core materials, that is, for vegetation grass mats and Enkamat, but the reinforced Mike mats were strengthened with hexagonal double-twisted Galfan-coated steel wire mesh (Table 2).

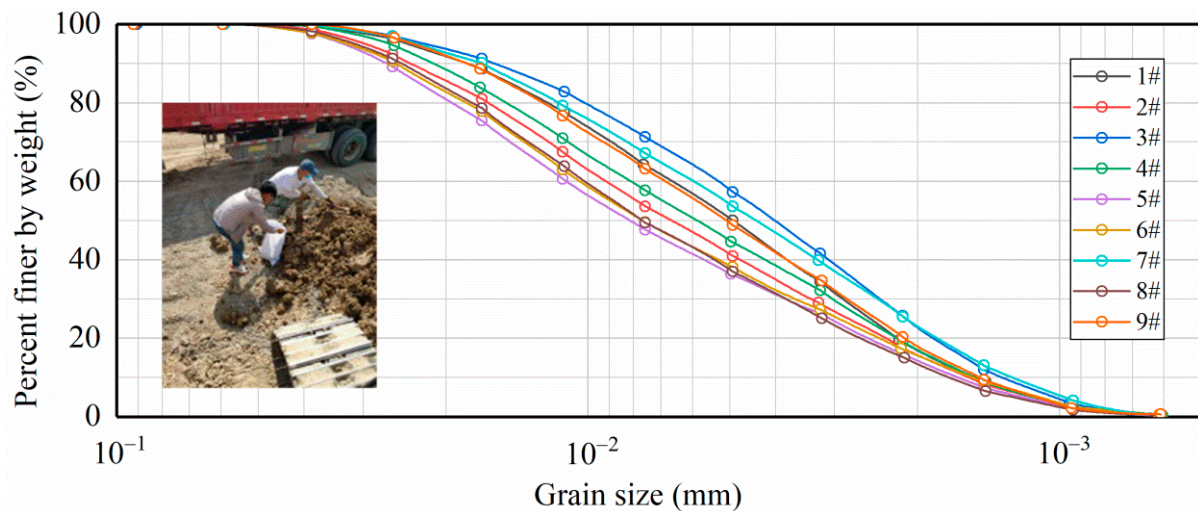


Figure 2. Cumulative distribution curves for particle size gradation of experimental soil.

Table 1. Physical and mechanical indexes of experimental soil.

Moisture Content (%)	Density (g/cm ³)	Plastic Limit (%)	Liquid Limit (%)	Dry Density (g/cm ³)	Soil Property
26.8	1.92	19.94	31.63	1.57	Silt loam

Table 2. Main technical parameters of experimental materials.

Material Type	Reinforced	Polymeric Materials	Reinforced Materials	Thickness (mm)	Unit Weight (g/m ²)
Vegetation grass mats	No	Straw, wheat straw, etc.	-	10	370
Enkamat	No	Amide	-	10	400
Reinforced Mike mats	Yes	Polypropylene	Hexagonal double-twisted Galvan-coated steel wire mesh	10	600

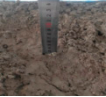
During the experimental preparation, 4 cm thick soil was laid on the bank with a 1:3 slope on one side of the experimental flume, then compacted and leveled. The 3D mats for slope protection were laid closely on the soil slope, with adjacent ones overlapping each other. In addition, 4 cm U-shaped steel nails were hammered into the overlapping areas on both sides of the material, the slope head, the slope foot and the center of the mats.

2.4. Experimental Scheme and Data Collection

The Enkamat manufacturer had previously carried out an anti-scour experiment for overland flow and found that the anti-scour flow velocity of the material was about 1~1.6 m/s in the case of soil laid under the mats for slope protection with no vegetation [32]. Therefore, the maximum velocity set in this experiment was greater than 1.6 m/s. The scenario proposed in this experiment was a gated river, and as the flow velocity in this case is shaped differently from that of natural rivers, the flow velocity shows significant nonlinear characteristics. Based on the design size of the experimental device, the boundary conditions were controlled through both the inlet and outlet of the flume. After multiple repeated tests, the combined conditions of water stage and flow rate for this experiment enabled the maximum flow velocity of 1.6 m/s to be reached (Table 3). The values of the large and small flow rates, as shown in Table 3, were 1000 m³/h and 300 m³/h, respectively, and the values of the high and low water stages were 0.46 m and 0.34 m, respectively. For the sake of simplicity in analysis and presentation, the terms “large flow rate” and “small flow rate” are employed to represent flow rate values of 1000 m³/h and 300 m³/h, and the terms “high water stage” and “low water stage” are employed to represent water stage values of 0.46 m and 0.34 m, respectively. The combination of small flow rate and low water stage represented the dry season, that of small flow rate and high water stage represented

the recession period, that of large flow rate and low water stage represented the rising water period and that of large flow rate and high water stage represented the flood period.

Table 3. List of experimental groups.

Experimental Group	Protection Materials	Flow Rate	Water Stage	Average Flow Velocity (m/s)	Average Water Depth (m)	Hydraulic Radius (m)	Slope Energy (‰)	Raw Material	Materials Laid
RUN 1	Bare soil	Small	High	0.052	0.458	0.447	0.021		
RUN 2		Small	Low	0.589	0.337	0.332	0.265		
RUN 3		Large	High	1.205	0.459	0.448	0.365		
RUN 4		Large	Low	1.907	0.337	0.331	0.205		
RUN 5	Vegetation grass mats	Small	High	0.045	0.458	0.447	0.005		
RUN 6		Small	Low	0.472	0.337	0.331	0.101		
RUN 7		Large	High	0.964	0.458	0.447	0.005		
RUN 8		Large	Low	1.724	0.337	0.331	0.091		
RUN 9	Enkamat	Small	High	0.045	0.458	0.447	0.004		
RUN 10		Small	Low	0.372	0.337	0.331	0.021		
RUN 11		Large	High	0.907	0.458	0.447	0.068		
RUN 12		Large	Low	1.687	0.337	0.332	0.237		
RUN 13	Reinforced Mike mats	Small	High	0.038	0.458	0.447	0.012		
RUN 14		Small	Low	0.459	0.337	0.331	0.031		
RUN 15		Large	High	0.874	0.458	0.447	0.110		
RUN 16		Large	Low	1.680	0.338	0.332	0.359		

The experiment used bare soil as the basic group, combined with three types of slope protection materials. Sixteen experiments were conducted in total. In repeated experiments with a circulating water supply, a fixed high-speed camera was used to record the complete damage process of the materials, the damage time and other parameters. Image recognition and the inversion method were adopted to analyze the impact of 3D mats on the height of the soil after erosion, as well as the erosion depth and volume of the soil.

3. Results

3.1. Average Flow Velocity, Resistance Coefficient and Turbulent Kinetic Energy Change

3.1.1. Distribution Law for Average Velocity

With the different combinations of flow rates and water stages, four types of flow velocity could be identified for each slope protection material. These were small flow rate and high water stage, small flow rate and low water stage, large flow rate and high water stage and large flow rate and low water stage (see Figure 3), in descending order of velocity. Under the same combination of flow rate and water stage, the flow velocities on the bare soil were all greater than those on the mats, and the general distribution law of the average velocity under the mat conditions followed the sequence vegetation grass mats > Enkamat > reinforced Mike mats.

3.1.2. Distribution Law for Resistance Coefficient

The Chezy resistance coefficient (C), Manning roughness coefficient (n) and Darcy–Weisbach resistance coefficient (f) can all be used to characterize the flow resistance in open channels and can all be converted into one another. Considering that the Darcy–Weisbach resistance coefficient f is more rigorous in terms of dimension and is highly related to the roughness of the side walls, we used the Darcy–Weisbach resistance coefficient f in these experiments to make a quantitative analysis of the bed resistance, using the following formula:

$$f = \frac{8gRJ}{U^2} \quad (1)$$

where g is the acceleration due to gravity, whose value is 9.81 m/s^2 ; R represents the hydraulic radius, with a unit of m ; J represents the water surface slope; and U represents the average flow velocity, with a unit of m/s .

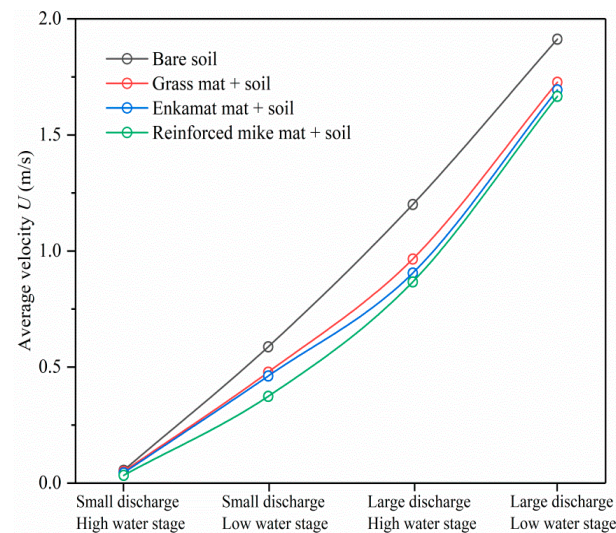


Figure 3. Distribution law for average velocity U under different flow conditions.

As shown in Figure 4, under the small flow rate and high water stage condition, the flow velocities were very low, and the average velocity U was 0.052 m/s , 0.045 m/s , 0.045 m/s and 0.038 m/s for the bare soil, vegetation grass mats, Enkamat and reinforced Mike mats, respectively, with large corresponding values of the resistance coefficient f . For the bare soil and the three materials, when the average velocity U was small, the resistance coefficient f varied considerably under different slope protection conditions, but as the average velocity U gradually increased, the values of the resistance coefficient f under the four slope protection conditions gradually became consistent. In other words, there was an increasingly small impact of the different slope protection materials on the distribution of the resistance coefficient f . From the overall distribution trend, the resistance coefficient f under different slope protection conditions decreased as the average velocity U increased, and thus f and U were negatively correlated. Under the same combination of flow rate and water stage, the resistance coefficient f in the bare soil was smaller than that in all the three mat materials for slope protection, and the distribution law of the resistance coefficient f in the mat materials for slope protection followed the sequence vegetation grass mats < Enkamat < reinforced Mike mats.

3.1.3. Distribution Law for Turbulent Kinetic Energy (TKE)

Turbulent kinetic energy (TKE) is an important indicator of the turbulent state of water flow and a key indicator of the energy loss of the water body due to turbulence. It has the following formula:

$$TKE = 0.5(\overline{u'^2} + \overline{v'^2} + \overline{w'^2}) \quad (2)$$

where u' , v' and w' denote the fluctuating velocities of water flow in the x , y and z directions, respectively, in m/s .

The average turbulent kinetic energy, the maximum turbulent energy (Figure 5) and the average flow velocity in the increasing direction along the transverse axis all gradually increased in the bare soil, vegetation grass mats, Enkamat and reinforced Mike mats. The distribution laws for the average turbulent kinetic energy and the maximum turbulent kinetic energy were basically consistent on all the vertical lines L1, L2 and L3 (see Figure 1 for their locations). Under the same slope protection conditions, the average and the maximum turbulent kinetic energy on the vertical lines L1, L2 and L3 showed a significant stepwise increase with an increase in flow velocity, i.e., the turbulence of the water body was intensified as the flow velocity increased. With the same average flow velocity, the

average and the maximum turbulent kinetic energy on the vertical lines L1, L2 and L3 followed the sequence reinforced Mike mats > Enkamat > vegetation grass mats > bare soil. This can be explained largely by the fact that the mats increase the bed resistance coefficient, resulting in more thermal energy being converted from the kinetic energy of the water.

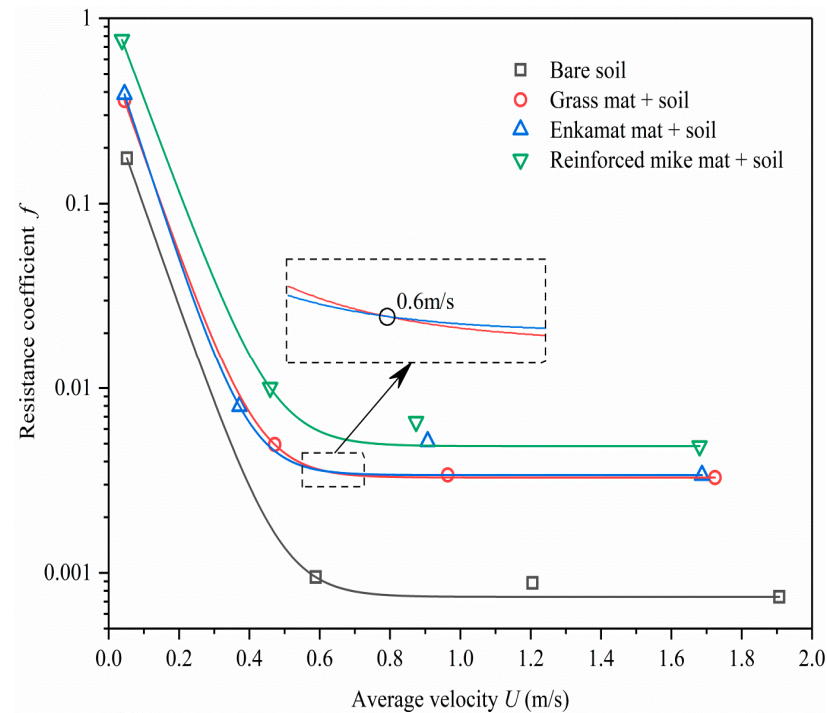


Figure 4. Trend lines for distribution of resistance coefficient f of various slope protection materials with different average velocities.

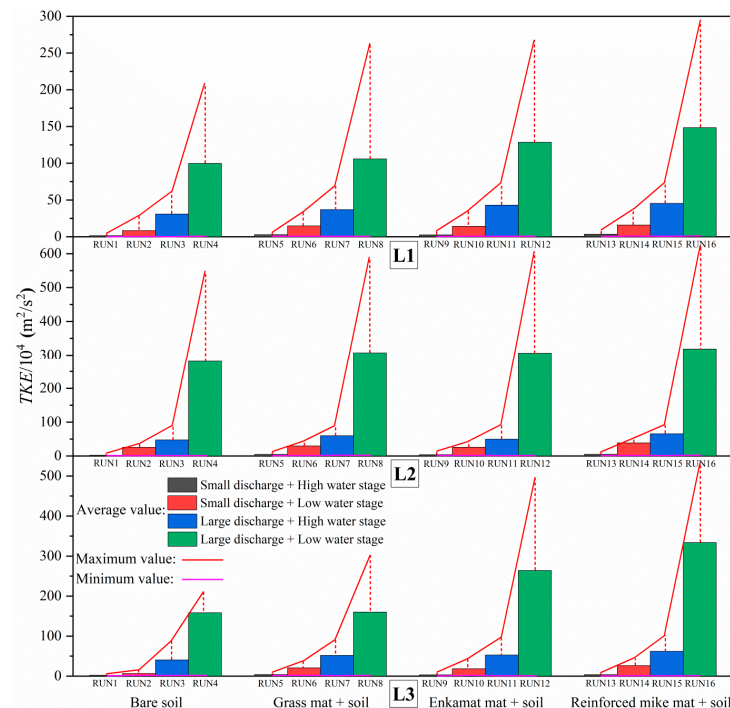


Figure 5. Distribution for turbulent kinetic energy on the vertical lines.

3.2. Erosion Resistance of 3D Mat Materials for Slope Protection

In the scouring tests for bare soil and the erosion tests for slope protection materials, there was considerable erosion of the soil mass at the inlet of the test section and the slope foot, with the prominent action of water flow (Figure 6a). The action of the water was mainly related to the great changes in bed topography and bed roughness, and the combination of the two resulted in strong local turbulence. In order to minimize the soil erosion at the inlet of the test section and the slope foot, it is suggested that the anchorage groove should be set at the junction of the inlet section, that the mat materials should be fixed at the inlet section and that the slope protection materials should be consolidated at the slope foot. In scouring tests of the bare soil, the soil mass was highly eroded as it was washed directly by the flow. The soil mass on the slope generally began to be eroded along the flow direction, while the erosion profile of the soil mass near the slope foot had a relatively regular shape (Figure 6b). In erosion tests of the mat materials for slope protection, the soil mass at the foot of the slope was scoured first (Figure 7a). The soil erosion mainly started from the initial contact points between the material and the soil and gradually spread to a larger area in a fan shape (Figure 7b).

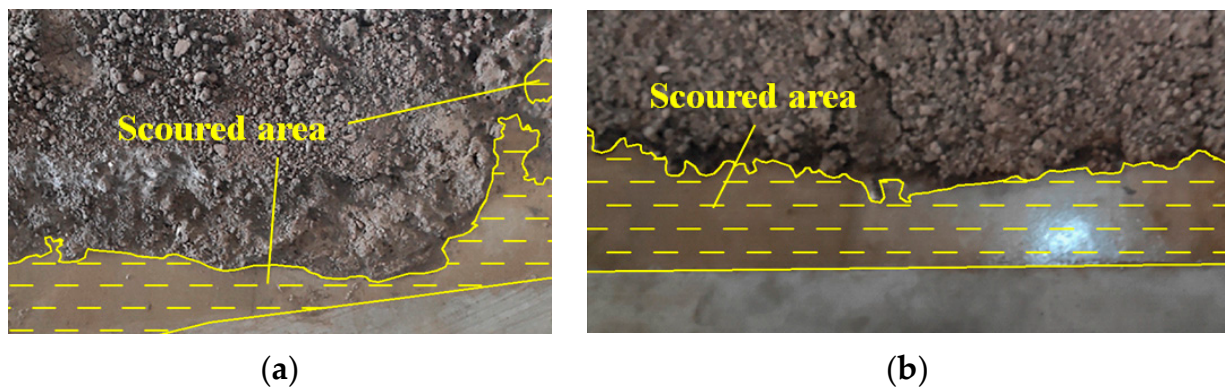


Figure 6. Soil erosion in the bare soil: (a) soil erosion at the inlet of the test section (RUN 3, after 18 h scouring); (b) soil erosion near the slope foot (RUN 4, after 29 h scouring).

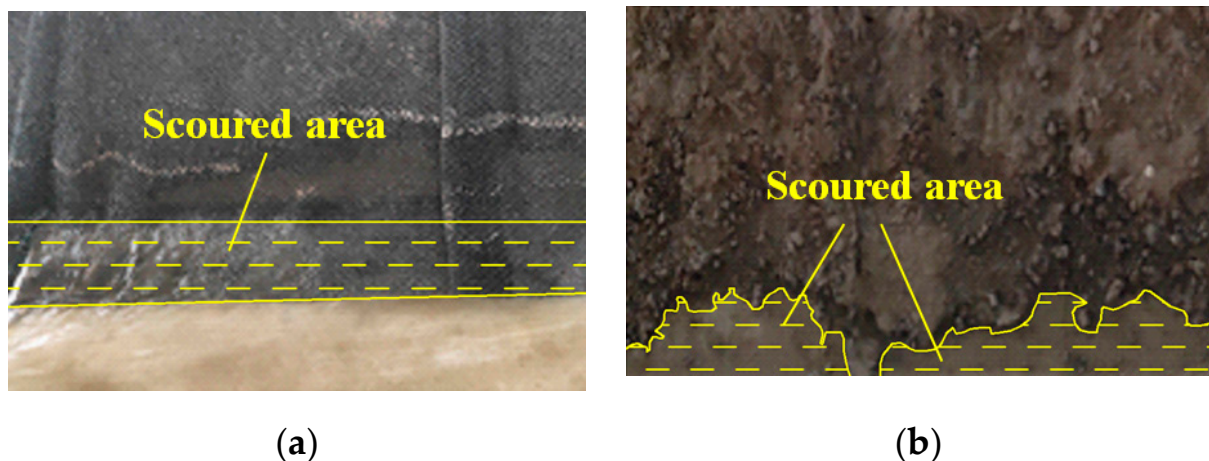


Figure 7. Soil erosion under different slope protection conditions: (a) initial stage of soil erosion at the slope foot (RUN 12, after 1 h scouring); (b) erosion shape of soil at the slope foot (RUN 9, after 40 h scouring).

4. Discussion

4.1. Anti-Scour Properties of Mat Materials for Slope Protection

Of the 12 experimental groups for the three types of slope protection mats, no damage to the protective mats occurred in 7 groups in the first 40 h, including RUN 5, RUN 6, RUN

9, RUN 10, RUN 13, RUN 14 and RUN 15, that is, the three materials under the small flow rate conditions and the reinforced Mike mats under the large flow rate and high water stage condition. In addition, a total of 5 experimental groups showed damage to the slope protection materials during scouring: the vegetation grass mats were damaged in two experimental groups, RUN 7 (with 0.964 m/s average velocity, damaged after 4.25 h of scouring) and RUN 8 (with 1.724 m/s average velocity, damaged after 2 h of scouring), and the damage process was dominated by the ejection of fixed steel nails and material floating (Figure 8). The Enkamat was also damaged in two experimental groups, RUN 11 (with 0.907 m/s average velocity, damaged after 4.25 h of scouring) and RUN 12 (with 1.687 m/s average velocity, damaged after 2 h of scouring), and the damage process was dominated by the ejection of fixed nails and material tearing and lifting (Figure 9). The reinforced Mike mats were damaged once in RUN 16 (with 1.670 m/s average velocity, damaged after 8.5 h of scouring), and their damage was essentially the same as that of Enkamat in process and type.



Figure 8. Damage types of vegetation grass mat material: (a) ejection of fixed steel nails (RUN 8, after 2 h scouring); (b) material floating (RUN 8, after 2.25 h scouring).

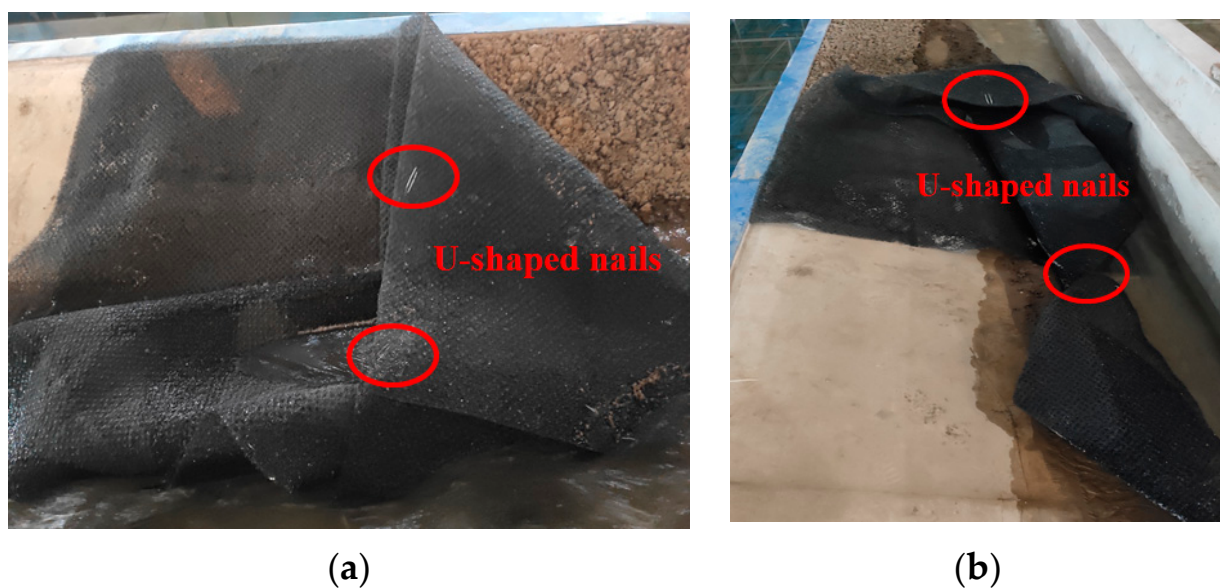


Figure 9. Damage types of Enkamat: (a) ejection of fixed nails and material lifting (RUN 12, after 3.5 h scouring); (b) material tearing after 4 h scouring.

Figure 10 shows the failure time for the three types of slope protection mat materials in the different experimental groups. Mechanical damage occurred in the three protective mats when the flow had been released for 40 h, thereby exposing the soil surface to the water. Situations such as the ejection of fixed steel nails, material floating and tearing can be regarded as “material failure”, representing the fact that mechanical damage to protective mat materials leads to the loss of their protection of bank slopes. Material failure of all three materials occurred mainly under large flow rate conditions, and the lower the water stage, the more likely it was that material failure would occur. In addition, material failure was directly related to the average velocity U in the scouring. A higher average flow velocity was more likely to cause material failure (Figure 10). Under the same combination of flow rate and water stage, the reinforced Mike mats were significantly more resistant to scouring than the other two unreinforced materials. Moreover, the failure time of Enkamat was 58.82% longer than that of the vegetation grass mats when scoured by water with similar, slightly lower average flow velocities. That is, Enkamat had a longer anti-scour time under the same flow conditions. Therefore, the order of the three materials in terms of anti-scour characteristics was as follows: reinforced Mike mats > Enkamat > vegetation grass mats. This is consistent with their distribution law for the resistance coefficient f but contrary to their distribution law for the average flow velocity, under different experimental schemes. This indicates that a larger material resistance coefficient results in the material hindering the water flow more strongly. In addition, if it can consume more of the energy of the water body under the same incoming flow conditions, the material is more resistant to scouring.

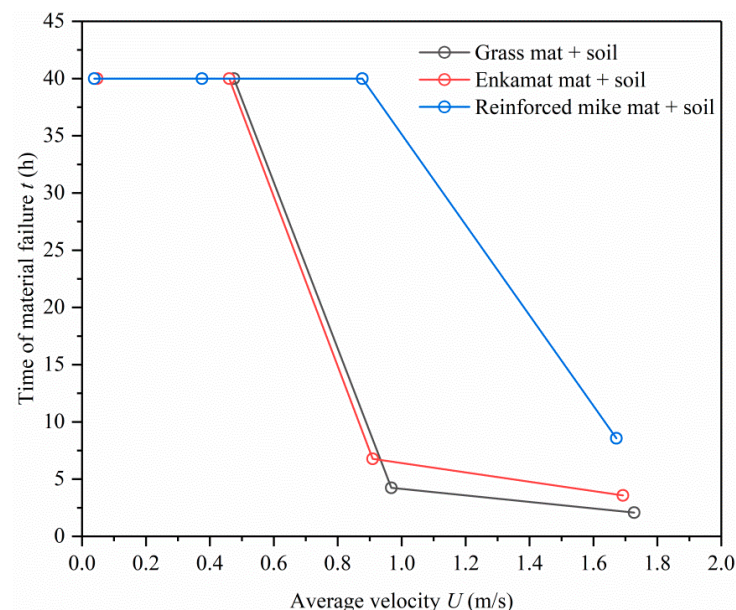


Figure 10. Anti-scour properties of slope protection mat materials.

4.2. Failure Characteristics Analysis of 3D Mat Materials for Slope Protection

In the bare soil, the amount of erosion of the soil mass was larger than that in the slope protection materials under the same incoming flow conditions (Figure 11). Among the four combinations of flow rate and water stage, the proportion of eroded soil in the three materials was above 50% under the small flow rate and high water stage condition or the large flow rate and high water stage condition, but it was below 50% under the small flow rate and low water stage condition or the large flow rate and low water stage condition. According to the experimental observations, when the remaining volume of the soil laid on the slope was less than 50%, i.e., when the volume ratio of the eroded soil exceeded 50%, it was deemed in this study to be “performance failure”. In the case of material damage in experimental processes of less than 40 h, if the volume of the eroded soil was more than 50%, it was regarded as material failure rather than performance failure. A statistical

method of determining the volume percentage of the eroded soil was used to relate the performance failure criterion for the material to the maximum allowable amount of erosion of the slope soil. That is, it was not determined based on the maximum scouring depth of the soil at a certain measuring point. This was to reduce the impact of instability of local testing points on the experimental measurement and results.

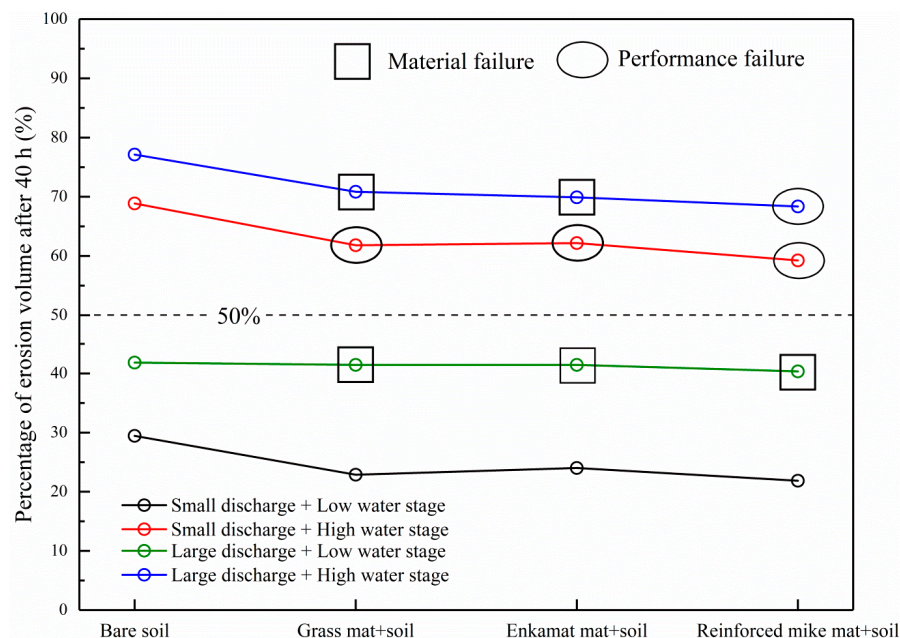


Figure 11. Volume percentage of the eroded soil after 40 h scouring for different materials.

Under the four experimental conditions, all the materials underwent performance failure under the following conditions: vegetation grass mats, Enkamat and reinforced Mike mats under the small flow rate and high water stage condition, and reinforced Mike mats under the large flow rate and high water stage condition. However, no performance failure occurred in any of the materials under the low water stage conditions. Performance failure of the three types of mat materials used in the experiment mainly occurred under high water stage conditions, and the larger the flow rate, the more likely it was that performance failure would occur in different materials. Under the small flow rate and high water stage condition, all the three mat materials used in this experiment underwent performance failure, but there were differences in erosion volume percentage for the different materials. Under the small flow rate and high water stage condition, the erosion volume ratio of vegetation grass mats and Enkamat was 61.81% and 62.17%, respectively, but that of reinforced Mike mats was 59.24%, which indicates that reinforced Mike mats outperform the other two for soil conservation. Under the large flow rate and high water stage condition, similar change characteristics were also found in the three types of mat materials for slope protection.

5. Conclusions

Based on an indoor flume prototypical scouring experiment, we investigated the anti-scour properties and soil conservation performance of the 3D mat materials vegetation grass mats, Enkamat and reinforced Mike mats, for slope protection, and discussed the failure modes of mat materials for slope protection. The conclusions were mainly as follows:

- (1) Compared with the bare soil, the 3D mats for slope protection caused more thermal energy to be converted from the kinetic energy of the water, as they increased the comprehensive resistance coefficient of the bed surface, in the order reinforced Mike mats > Enkamat > vegetation grass mats, under the same incoming flow condi-

tion. In addition, the average flow velocity in a channel was inversely related to the comprehensive resistance coefficient.

- (2) The failure types of 3D mat materials for slope protection can be divided into material failure and performance failure. The former refers to mechanical damage to the mats, such as material tearing, ejection of fixing steel nails, material floating, etc., while the latter means that the ratio of the volume of the eroded soil on the bank slope to the soil volume before scouring was greater than 50% after the maximum scouring time of 40 h. When the scouring time of the flow reached the maximum duration of 40 h and neither material failure nor performance failure had occurred, this was regarded as “no failure”.
- (3) Non-reinforced materials (vegetation grass mats, Enkamat) were dominated by material failure, while reinforced materials (reinforced Mike mats) were dominated by performance failure. Material failure mainly occurred under large flow rate conditions and was more likely to occur when the water stage was lower. Performance failure mainly occurred under high water stage conditions and was more likely to occur when the flow rate was larger. Among the three types of mat materials for slope protection, the order for anti-scour and soil conservation properties was reinforced Mike mats > Enkamat > vegetation grass mats. Moreover, the general law showed that reinforced materials apparently outperform non-reinforced materials in their anti-scour performance and their protection for soil.

Author Contributions: Y.Y. designed the experiment and wrote the paper; H.X. analyzed the experimental datasets; X.W. and Z.L. participated in the experiments; M.Z. contributed to the conception of the research; W.L. and Y.Z. revised the manuscript. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China (51979132, 51809130), Central Public Research Institutes Fundamental Research (TKS20220106) and National Key R&D Program of China (2018YFB1600400).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

- HaRa, J.; Mamun, M.; An, K.G. Ecological River Health Assessments Using Chemical Parameter Model and the Index of Biological Integrity Model. *Water* **2019**, *11*, 1729. [\[CrossRef\]](#)
- Bian, Y.Z.; Xue, B.; Zhang, F.J. The changes of Lake Hongze and its driving forces over the past three hundred years. *J. Lake Sci.* **2021**, *33*, 1844–1856.
- Cao, Y.X.; Xu, L.G.; Fan, H.X.; Mao, Z.Y.; Chen, J.X.; Wang, D.C.; Wu, Y.K. Impact of climate change and human activities on the changes of ecological flow indicators in the Lake Poyang Basin since 1960s. *J. Lake Sci.* **2021**, *34*, 232–246.
- Wang, G.H.; Liu, B.B.; Li, X.P.; Liu, J.T.; Ao, H.Y.; Li, Q.M. Seasonal variation of water quality of Xinyunliang River Dianchi Basin and the impact of the riparian ecological restoration. *J. Lake Sci.* **2012**, *24*, 334–340.
- Chen, B.F.; Huang, W.; Chen, K.N. Research progress on the ecological revetment in riparian. *Environ. Eng.* **2018**, *36*, 74–77.
- Xia, J.Q.; Liu, X.; Deng, S.S.; Zhou, M.R.; Li, Z.W.; Peng, Y.M. Temporal and spatial distribution of bank retreat in the Jingjiang reach of the Yangtze River after the Three Gorges Project operation and its influence on channel adjustment. *J. Lake Sci.* **2021**, *34*, 296–306.
- Rini, D.S.; Arisoelaningsih, E.; Harisuseno, D.; Soemarno, S. Application of Ecohydraulic Bank Protection Model to Improve River Bank Stability and Biotic Community in Surabaya River. *J. Degrad. Min. Lands Manag.* **2017**, *5*, 975. [\[CrossRef\]](#)
- Alam, G.M.; Alam, K.; Mushtaq, S.; Clarke, M.L. Vulnerability to Climatic Change in Riparian Char and River-Bank Households in Bangladesh: Implication for Policy, Livelihoods and Social Development. *Ecol. Indic.* **2017**, *72*, 23–32. [\[CrossRef\]](#)
- Zhang, J.Y.; Wang, X.J. Issues related to building of water ecological civilization. *China Water Resour.* **2014**, *7*, 1–4.
- Patsinghasanee, S.; Kimura, I.; Shimizu, Y.; Nabi, M. Experiments and Modelling of Cantilever Failures for Cohesive Riverbanks. *J. Hydraul. Res.* **2018**, *56*, 76–95. [\[CrossRef\]](#)

11. Bejarano, M.D.; Sordo-Ward, Á.; Alonso, C.; Jansson, R.; Nilsson, C. Hydropeaking Affects Germination and Establishment of Riverbank Vegetation. *Ecol. Appl.* **2020**, *30*, e02076. [[CrossRef](#)] [[PubMed](#)]
12. Udomchai, A.; Hoy, M.; Horpibulsuk, S.; Chinkulkijniwat, A.; Arulrajah, A. Failure of Riverbank Protection Structure and Remedial Approach: A Case Study in Suraburi Province, Thailand. *Eng. Fail. Anal.* **2018**, *91*, 243–254. [[CrossRef](#)]
13. Recking, A.; Piton, G.; Montabonnet, L.; Posi, S.; Evette, A. Design of Fascines for Riverbank Protection in Alpine Rivers: Insight from Flume Experiments. *Ecol. Eng.* **2019**, *138*, 323–333. [[CrossRef](#)]
14. Jafarnejad, M.; Franca, M.J.; Pfister, M.; Schleiss, A.J. Time-Based Failure Analysis of Compressed Riverbank Riprap. *J. Hydraul. Res.* **2017**, *55*, 224–235. [[CrossRef](#)]
15. Thompson, D.M.; Puklin, L.S.; Marshall, A.E. The Long-Term Impact of Channel Stabilization Using Gabion Structures on Zealand River, New Hampshire. *Ecol. Eng.* **2016**, *95*, 779–792. [[CrossRef](#)]
16. Beikircher, B.; Florineth, F.; Mayr, S. Restoration of Rocky Slopes Based on Planted Gabions and Use of Drought-Preconditioned Woody Species. *Ecol. Eng.* **2010**, *36*, 421–426. [[CrossRef](#)]
17. Zhang, J.L.; Wu, T.T.; Chen, Q.W.; GAO, Y. Application of Reinforced Three-Dimensional Mat in Beach Protection Engineering. *Port Waterw. Eng.* **2012**, *8*, 204–206.
18. Symmank, L.; Natho, S.; Scholz, M.; Schröder, U.; Raupach, K.; Schulz-Zunkel, C. The Impact of Bioengineering Techniques for Riverbank Protection on Ecosystem Services of Riparian Zones. *Ecol. Eng.* **2020**, *158*, 106040. [[CrossRef](#)]
19. Nelsen, R.J. Research Quantifies Performance of TRM Reinforced Vegetation. In *Erosion of Soils and Scour of Foundations*; Briaud, J.-L., Bhatia, S.K., Eds.; American Society of Civil Engineers: Reston, VA, USA, 2005; pp. 1–11.
20. Xiao, C.Z.; Sun, J.C.; Li, Y.R.; Liu, X.P. Mechanism Analysis of Ecological Slope Protection against Runoff Erosion by Grass Jetting on 3D Geomat. *Rock Soil Mech.* **2011**, *32*, 453–458.
21. Xiao, H.L.; Wang, Z.; Zhang, J.F. Study on the Design Indexes of Three Dimensional Geomat. *Rock Soil Mech.* **2004**, *25*, 1800–1804.
22. Xiao, H.L.; Zhang, J.F. A Study on Erosion-Resistance and Seeding Test of Three Dimensional Geomat. *Highway* **2005**, *4*, 163–166.
23. Zhong, C.X.; Zhang, W. Method and Equipment of Model Test for Scouring Resistance of Riverbank with Grass Cover. *J. Hohai Univ. (Nat. Sci.)* **2008**, *36*, 170–174.
24. Zhang, W.; Zhong, C.X.; Ying, H.H. Experimental Study on Hydraulic Roughness of Revetment with Grass Cover. *Adv. Water Sci.* **2007**, *18*, 483–489.
25. Zhong, C.X.; Zhang, W. Experimental Research on Hydraulic Characteristics of Eco-Bank Protection Covered with Grass. *Shuili Shuidian Jishi (Water Resour. Hydropower Eng.)* **2010**, *41*, 22–25.
26. Hu, Y.Z.; Pan, Y.; Chen, Y.P. Experimental studies on scouring resistance of reinforced turf on land-side slope. *Hydro-Sci. Eng.* **2016**, *1*, 51–57.
27. Álvarez-Mozos, J.; Abad, E.; Giménez, R.; Campo, M.A.; Goñi, M.; Arive, M.; Casali, J.; Díez, J.; Diego, I. Evaluation of Erosion Control Geotextiles on Steep Slopes. Part 1: Effects on Runoff and Soil Loss. *Catena* **2014**, *118*, 168–178. [[CrossRef](#)]
28. Lu, Y.; Wang, W.; Lu, Y.J.; Song, Y.T.; Yan, D.L. Theoretical and Experimental Study on Resistance Characteristics of Shrub Vegetation Distribution Area. *Adv. Water Sci.* **2020**, *31*, 556–564.
29. Huai, W.X.; Zhong, Y.; Yang, Z.H. Study on mechanism of energy spending and transition in open channel flow with suspended canopy. *J. Hydraul. Eng.* **2018**, *49*, 397–403.
30. Wang, G.Y.; Du, G.S.; Wang, Y. The Experimental Research on Hydrodynamic Characteristics of the Overland Flow on the Slope with Three Dimensional Geomat. *Chin. J. Hydrodyn.* **2015**, *30*, 406–411.
31. Wang, G.; Sun, G.; Li, J.; Li, J. The Experimental Study of Hydrodynamic Characteristics of the Overland Flow on a Slope with Three-Dimensional Geomat. *J. Hydrodyn.* **2018**, *30*, 153–159. [[CrossRef](#)]
32. Enkamat Permanent Erosion Prevention Mat. Available online: www.geosyntetika.cz/files/download/enkamat_gb_2008.pdf (accessed on 10 March 2022).