Recent understanding on the hydraulic erosion of vegetated HPTRM system

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Abstract. In recent years, High Performance Turf Enforcement Mat (HPTRM) has been widely noticed and used in revetment projects due to its advantages in both erosion resistance and landscape ecology. Studies have shown that the vegetated HPTRM system has a much better performance in erosion resistance than vegetation lining while it has similar landscape and ecological benefits with vegetation lining. In this paper, firstly a brief overview of existing researches on the hydraulic erosion of vegetated HPTRM System is given, and then a series of experimental and numerical studies on the erosion process of vegetated HPTRM system are introduced, including full scale fume experiments, Erosion Function Apparatus (EFA) tests, high-speed open-channel flow tests and numerical flume tests that conducted by the authors from 2009 to 2018. Based on the test results, new understanding on the erosion characteristics of vegetated HPTRM system is presented, e.g., the feature of erosion development and “upper limit” of erosion. Some useful equations are also given. The vegetated HPTRM system performs effectively in the resistance of hydraulic erosion of open channel flow up to 6 m/s. At last, problems that need to be solved and prospects on future studies are suggested.

1. Introduction

Due to the growing interest from the government and public to consider ecological factors in civil engineering, vegetation has been widely used in the lining project of levees, dams, road slopes, channels and spillways, for their benefits in landscape ecology and soil and water conservation. However, under the effects of high velocity and long duration flow, the vegetation linings are easy to fail which may lead to catastrophic consequences, i.e. the levee failures during Hurricane Katrina [1]. Therefore, temporary and permanent Rolled Erosion Control Products (RECP) have been designed for the purpose of protecting the slopes from soil erosion [2]. Turf Reinforcement Mat (TRM) is a kind of RECP which has been employed to enhance the vegetation linings and control the hydraulic erosion. High Performance Turf Reinforcement Mat (HPTRM) is enhanced TRM by using high strength materials. HPTRM is usually made of high strength nylon filaments matrix which enable the enhanced vegetation lining to resist hydraulic erosion of high flow velocity. An illustration of enhanced vegetation lining by HPTRM is shown in figure 1.
Although interest in and usage of TRM/HPTRM has intensified in recent years, the first study on the erosion feature of vegetated TRM appears to be conducted in 1980s. By means of a series of large-scale experimental tests under steady overflow conditions, Hewlett et al [3] provided permissible velocity and duration curves of vegetation lining and different types of vegetated TRM covers, and pointed out that three dimensional TRMs has much better erosion resistance than two dimensional ones.

Since 2005, Colorado State University (CSU) group has carried out a number of laboratory and field experiments to study the erosion resistance of vegetated TRM/HPTRM system. Lipscomb et al [4] developed a protocol for laboratory testing of vegetated TRM systems. Based on the protocol, Nelsen [5] studied the erosion resistant of vegetated TRM system under steady flow conditions via experimental tests in large-scale channels, and the results shows that in some cases the permissible shear stress of vegetated TRM system is six times of that of vegetation lining. Recent years, CSU group conducted a series of full scale overtopping tests with Overtopping Simulator [6-8]. Soil, grass, TRM and HPTRM were tested under different covering conditions and the results showed that the failure of vegetation was correlated to the cumulative unit-width volume of wave overtopping.

Jackson State University and Hohai University (JSU & HHU) group has carried out a series of experimental and numerical researches to understand the erosion feature of vegetated HPTRM systems since 2009 [9-17]. Full scale overtopping tests, sample erodibility tests, high-speed open-channel flow tests and numerical flume tests were carried out to investigate the erosion and failure process of enhanced vegetation lining by HPTRM. In this paper, the researches of JSU & HHU group from 2009 to 2018 are introduced briefly, and recent understanding on the erosion feature of enhanced vegetation lining by HPTRM is introduced.

2. Full scale fume experiments
The full scale experimental study was carried out in the Large Wave Flume in Oregon State University. Figure 2 shows the experimental set-up and installation of vegetated HPTRM system. The Large Wave Flume is 104 m (length) × 3.66 m (width) × 4.57 m (height). The levee model was built with a trapezoid section and a 0.76 m deep groove where pre-cultivated vegetated HPTRM system was installed. Four capacitive wave gauges (WG1 to WG4) were installed in the upstream side of the levee model. At five measurement points (P1 to P5) on levee crest and landside slope of the levee, the flow depth was measured with Acoustic Range Finders (ARF), and the flow velocity was measured by Acoustic Doppler Velocimeters (ADV). Four high-powered water pumps were used to generate return discharge for the purpose of counterbalancing the average discharge due to wave overtopping and surge overflow. More details of the experimental set-up are provided in Pan et al [13].

A total of 9 experimental tests of wave overtopping were carried out under different wave conditions and freeboard. After each test the elevations of the soil surface at the measurement points (P1-P5) were recorded. For each measurement point from P1 to P5 as shown in figure 2(a), the elevations of 9 points around the measurement point were recorded, and the average value of them
was calculated as the surface elevation of the measurement point. The measured historic erosion depths are plotted in figure 3. Figure 3 indicates that after the test of trial 4, soil losses of all measurement points did not increase obviously, as mentioned by Pan et al [14] as “upper limit” of erosion of vegetated HPTRM system. This observation can be explained by the exposure of HPTRM mat and the coinstantaneous increasing of anti-erosion strength. The “upper limit” is the result of the balance between erosion force and anti-erosion strength, as pointed out by Pan et al [11]. It is also found that the erosion depths at all the measurement points are better correlated to average flow velocities compared to shear stresses.

![Wave maker](image1)

(a)

![Flume test set-up](image2)

(b)

![Installation of HPTRM system](image3)

(c)

**Figure 2.** Experimental set-up and installation of vegetated HPTRM system. (a) The LWF and the flume test set-up, (b) Test section and (c) Installation of HPTRM system.

**Figure 3.** Historic erosion depths at the five measurement points.

3. *Erosion function apparatus tests*

When the full scale flume experiments were finished, samples were taken from the surface of landslide slope and tested with Erosion Function Apparatus (EFA) procedure [18] to study the erodibility. The samples were 152.4 mm high cylinders diameters of 76.2 mm. Because it was hard to test the samples with HPTRM mat on it, the HPTRM mat was removed when the samples are taken, in which way the two sides of a sample are with grass and clay respectively. Both sides of the samples were tested with EFA procedure to investigate the erosion features of clay and clay with grass. During the tests, 1 mm
of sample was maintained out of the sample tub, as shown in figure 4. For some samples in poor condition, the clay side was broken during sample taking and thus only the other side was tested. More details of the test set-up are present in Yuan et al [17] and Pan et al [14].

![Figure 4. Erosion Function Apparatus: (a) structure illustration; (b) photograph.](image)

Figure 5 shows the erosion resistance of clay, grass-covered clay and vegetated HPTRM, using the data from EFA and full scale fume experiments. As shown, erosion started to happen after a certain critical velocity was reached for each sample. The critical velocity of clay samples was around 0.5 m/s, while the critical velocities for both grass-covered clay and vegetated HPTRM were around 1.5 m/s. As seen, both grass cover and HPTRM increased the critical velocity of clay by 1 m/s approximately. The scattered distribution was able to be explained by different surface conditions of the samples. After the flow velocity exceeded the critical velocity, the erosion rate increased rapidly with the increasing of flow velocity. However, increases of erosion rates of the vegetated HPTRM system samples were relatively much slower.

![Figure 5. Erosion rate versus flow velocity. The clay and grass data are from EFA tests and the HPTRM data are from full scale fume experiments.](image)

4. High-speed open-channel flow tests
As pointed out by Hughes [19], it is difficult to study the hydraulic erosion of vegetated HPTRM via numerical simulation or scaled physical model due to limited understanding on the erosion mechanism of the underlying soil. Hence the design guidance of TRM/HPTRM is usually based on full scale experimental studies, including full scale fume experiments, field experiments and Overtopping Simulator tests. The EFA test provides a low-cost way to investigate the erosion process of vegetated HPTRM samples. However, it is argued that the pressure flow in a horizontal tube of EFA testing method is different from the overflow and overtopping flow on slopes, and thus the results of the EFA
tests may not be suitable to explain the overflow and overtopping erosion processes of vegetated HPTRM slopes. Therefore, a special flume was designed to investigate the erosion process of vegetated HPTRM under the conditions of open-channel flow up to 5 m/s. With a high horizontal flume and an inclined flume, the special flume could generate high-speed (the flow velocity is up to 5.5 m/s) open-channel flow, as seen in figure 6. A total of 48 samples, including 3 types of HPTRM and natural vegetation, were grown and tested under high-speed open-channel flow in the specially-designed flume. The samples were tested under regular test procedure and continuous test procedure. The regular test procedure was a 30 min - 30 min - 60 min - 60 min flushing test under steady open-channel flow, and during the test intervals the soil erosion was measured. The continuous test procedure was an uninterrupted 5 hour flushing test. The soil erosion of the continuous test was measured after it is finished. Based on the analysis of measured erosion processes of the 48 samples, some new insights on the erosion process of vegetated HPTRM system were proposed [15].

**Figure 6.** Sketch of the special flume for high-speed open-channel flow.

Because the erosion process is affected by many factors, the measured erosion process of one sample seems random. In order to understand the general feature of the erosion process, averaged erosion processes are calculated among samples under the same discharge condition. The averaged erosion processes are given in figure 7. As seen, the averaged erosion rates of the continuous test are significantly smaller than those of regular tests. A first-flush assumption is proposed to explain the significant different erosion rates in regular and continuous tests. It is assumed that the erosion is mainly induced by the first flush (i.e., the flush induced by the front of flow at the beginning of a test),

**Figure 7.** Discharge-condition averaged erosion processes. Disc. 1 = 1096 m³/h/m, Disc. 2 = 1260 m³/h/m, Disc. 3 = 1386 m³/h/m.
while continuous flow contributes little to the erosion. Based on this assumption, the first flush after each erosion measurement induces most of the erosion, which explains why the continuous tests have smaller soil erosion rates. For the regular tests, the erosion rates of the first hours are significantly larger than those of all hours, as shown in equation (1). The reduction of erosion rate is similar to the “upper limit” of the soil erosion observed in the full scale flume experiments of wave overtopping conditions [14] as illustrated in figure 3. However, compared to figure 3, the “upper limit” seems not entirely reached for the erosion gets slow but doesn’t stop, which is due to the shorter test period in the high-speed open-channel flow tests.

\[ E = 1.77v - 7.20 \text{ for the first hour} \]
\[ E = 1.60v - 6.74 \text{ for all three hour} \]

where \( E \) is the erosion rate (mm/hour) and \( v \) is the flow velocity (m/s). It should be mentioned that the application of equation (1) should be limited to the tested condition and range of parameters.

5. Numerical modelling

During the full scale flume experiments, the erosion rates of vegetated HPTRM lining on the landside slope and levee crest were recorded and analyzed. However, the erosion feature at the toe of landside slope could not reflect reality because this part of vegetated HPTRM lining was always submerged during the test intervals. In order to investigate the erosion feature of vegetated HPTRM lining at the toe of landside slope, a three dimensional wave overtopping and levee erosion model was set up on the basis of ECOMSED (Estuarine and Coastal Ocean Model with SEDiment transport) model according to the dimensions of the full scale flume experiments. The ECOMSED model considers the processes of convective diffusion, macroscale turbulence and sediment transport [20,21]. This wave overtopping and levee erosion model was verified by comparison between the simulated and experimental data, including turbulent shear stress and turbulent kinetic energy at P1 to P5 [16]. The governing equations of the hydrodynamics and erosion flux and verification of the model are described in Yuan et al [16]. A total of 41 combined wave and surge overtopping cases were simulated with different combinations of wave parameters and freeboards. Overtopping hydraulic parameters, turbulent shear stresses, turbulent kinetic energies, and erosion rates during all the test cases were calculated. The simulated erosion parameter \( E/(R_c) \) versus relative freeboard \( R_c/H_{m0} \) is plotted in figure 8, where \( R_c \) is the freeboard (m), \( H_{m0} \) is the energy-based significant wave height (m) and \( E \) is the erosion rate (mm/hour). As seen, the erosion parameter is well related to the relative freeboard. According to the best-fit curve, equation (2) is provided to estimate the erosion rate of vegetated HPTRM system at the toe of landside slope.

![Figure 8. Erosion rate versus relative freeboard at the toe of landside slope.](image-url)
\[
E / \left(-R_c\right) = 27.763 \left(-R_c / H_{eq}\right)^{-0.327}
\]

where \(E\) is the erosion rate (mm/hour). It should be mentioned that the application of equation (2) should be limited to the simulated condition and range of parameters.

6. Conclusions

HPTRM increases the erosion resistance of vegetative lining significantly while keeping the ecology effects, so it has been widely noticed and used in revetment projects in recent years. Since 2009, the JSU & HHU group has conducted a series of experimental and numerical researches on the erosion process of vegetated HPTRM system and some new understanding is gained.

Full scale fume experiments of wave overtopping over a levee were conducted with pre-cultivated vegetated HPTRM system installed in the landside slope of the levee model. The observations during the full scale fume experiments show no obvious failure of the surface of vegetated HPTRM lining. With the development of the erosion depth, the erosion rate decreased and at last an “upper limit” of erosion was reached. This “upper limit” is the result of the balance between erosion force and anti-erosion strength due to the gradual exposure of HPTRM mat.

After the full scale fume experiments were finished, samples were taken from the surface of landside slope and tested with the EFA procedure to study the erodibility. The results showed that both the grass cover and HPTRM mat increased the critical velocity of clay by 1 m/s approximately. However, for the vegetated HPTRM system samples, the increase in erosion rates was much slower after the critical velocity is reached.

High-speed open-channel flow tests were conducted to simulate more realistic conditions. The averaged erosion rates of the continuous test were significantly smaller than those of regular tests of which the duration was shorter. A first-flush assumption was proposed to explain this significant different erosion rates in regular and continuous tests. Also, the erosion rate decreased with the increase of the erosion depth under discontinuous open-channel flow, which was similar to the “upper limit” observed in the full scale fume experiments. The explanation of “upper limit” also applies here.

In order to study the erosion of vegetated HPTRM lining at the toe of landside slope, a three dimensional wave overtopping and levee erosion model was set up and verified on the basis of the full scale fume experiments. According to the analysis of simulated results, empirical equation is given to estimate the erosion rate of vegetated HPTRM lining at the toe of the landside slope of a levee.

In all existing researches, vegetated HPTRM system performs effectively in resisting hydraulic erosion of open channel flow up to 6 m/s. Hence it is reliable to be used in most of river slopes and landside slopes of levees. However, when the flow direction is not parallel to the surface of vegetated HPTRM system, the erosion rate is much larger according to some trial tests. And hence it needs future study on the usage of HPTRM in the slope of curved river or in the levee when breaking waves happens. In addition, under unidirectional flow the lying grasses are pushed tightly to the soil surface and thus the soil is protected by the layer of lying grasses, but the effects of reciprocating flow due to waves induced by wind or ships are not known yet. Hence the performance of vegetated HPTRM system under wave effects is needed. In methodology respect, laboratory and numerical tests can not reflect the long-term effects of multiple natural factors, and thus field research and case study are needed for more comprehensive evaluation of vegetated HPTRM system.

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