Advanced Technology for Cyclones Storm Damage Risk Reduction Systems and Flood Protection Levees

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Abstract

In August 2005, Hurricane Katrina became one of the most expensive natural disasters in U.S.A. history. The storm surge overtopping resulted in scouring of levee land sides, and in some cases led to overturned flood walls and breaches. Lack of protection of levee land sides from erosion was cited as a major cause of catastrophic destruction and spurned new requirements for resiliency of levee infrastructure across the United States. In response to the impacts of Hurricanes Katrina and Rita in 2005, the U.S. Army Corps of Engineers (USACE) embarked on one of the largest and most comprehensive public works projects in American history to provide a 100-year level of risk reduction, meaning that infrastructure would be established to defend against a storm surge that has a 1% change of occurring in any given year. Testing showed that using an armouring system consisting of high performance turf reinforcement mat (HPTRM) with Engineered Earth Anchors performed substantially better than all other systems in protecting against erosion. This armouring system has been recognised by the Environmental Protection Agency (EPA) as well as the Federal Highway Administration (FHWA) as a Best Management Practice (BMP) to improve water quality in the management of urban flows in channels. Today, this system is still performing extremely well in preventing erosion and maintaining its integrity, despite significant rainfall and storm events since 2012. An additional 2.5 million square metres of HPTRM product is planned to be installed in the near future. This anchored armouring system has provided the USACE with a reliable solution for protecting lives and properties in areas vulnerable to cyclones and severe floods. Recently, a further rigorous testing program verified that this system exceeds USACE design standards.

1. INTRODUCTION

1.1. Background

Armoured levees are intended to provide protection of earthen construction from erosion caused by overtopping. Adding resilience to earthen flood protection structures such as dams and levees is critical to future risk mitigation as building higher and stronger structures to prevent overtopping waves, storm surge, and flood waters is more costly. Riprap, articulated concrete blocks, concrete slope paving, and other traditional hard armour solutions are often used which are not cost effective or environmentally friendly. Finding alternative solutions which can reduce the costs and provide the same or better performance is always a goal for clients, including the United States Army Corps of Engineers (USACE). Engineers at USACE were looking for an armouring system for the earthen levees in the 214km of the Hurricane & Storm Damage Risk Reduction System for southeast Louisiana, with a high attention to mitigate the costs. Research over the years has established HPTRM reinforced vegetation performance in steady state flow in a flume. However, there was little knowledge of HPTRM performance in wave and storm surge overtopping. The USACE armouring focus turned to High Performance Turf Reinforcement Mats (HPTRMs) after a levee armoured with vegetation reinforced by this synthetic mat in Lafitte, Louisiana survived the storm surge and wave overtopping produced during Hurricane Ike in 2008. This success encouraged the USACE to begin a 10-year intensive research program to determine the hydraulic performance threshold, cost effectiveness, and long-term durability of vegetation reinforced by a HPTRM for adding resilience to the re-built levee system destroyed by Hurricane Katrina. Research at the Hydraulics Laboratory of Colorado State University has established the HPTRM reinforced vegetation performance in both outdoor flume testing and in the world’s largest full-scale Wave Overtopping Simulator at a maximum average discharge volume of 370 l/s per m.

This paper presents these research works and review four separate wave overtopping data sets and test results showing that HPTRMs can be a suitable alternative to traditional hard erosion control solutions. The paper also explains the required performance parameter and the importance of key material properties when designing with HPTRMs.

1.2. High Performance Turf Reinforcement Mats (HPTRMs)

Turf Reinforcement Mats (TRMs) are permanent non-degradable 3D Roll Erosion Control Products (RECPs) which consist of non-degradable UV stabilised synthetic fibres and filaments processed into permanent, high-strength, three dimensional matrices. TRMs are designed to impart immediate erosion protection, enhance vegetation establishment and provide long-term functionality by permanently reinforcing vegetation during and after maturation. TRMs are designed for permanent and critical hydraulic applications such as storm water and drainage channels and slopes where design discharges exert velocities and shear stresses that exceed the limits of mature natural vegetation (EPA, 1999). TRMs with high tensile strengths of more than 44 kN/m and high hydraulic performance are called High Performance Turf Reinforcement Mats (HPTRMs) and are designed to be used for higher shear stresses and velocities and steeper slopes (Kilgore and Cotton, 2005). A HPTRM is a matrix composed of polypropylene monofilament yarns designed to allow vegetation roots penetrate and interlock in the body of the mat. By growing vegetation through the high-strength fibers of the high performance turf reinforcement mat, stems and roots intertwine with the polypropylene matrix to bolster the hydraulic resistance of natural vegetation (figure 1). HPTRMs also reduce evaporation and insulates the soil, reduce soil moisture loss, moderate soil temperature, prevent crusting and sealing of the soil surface and may increase infiltration (ECSWQM, 2014).

Figure 1 High Performance Turf Reinforcement Mat-HPTRM (left), Turf reinforcement mechanism (middle), HPTRM reinforced vegetated drainage channel (right)

Test hydraulic performance comparison results show that the HPTRM solution is superior to 900mm riprap when bank slopes become steeper than 3H: 1V, superior to 600mm riprap when bank slopes become steeper than 4H: 1V and superior to 300mm riprap for all slopes even with no vegetation (Thompson and Loizeaux, 2018). Considering supply and installation costs and risks, a HPTRM solution can always be considered as a cheaper alternative with fewer risks. A TRM/HPTRM solution can be up to 80% cheaper compared to traditional hard armour systems such as rock riprap and concrete (Kilgor and Cotton, 2005).

When adding resilience to earthen flood defense structures, traditional hard (sometimes referred to as grey) armour solutions can increase the carbon loading significantly when compared to soft (green) solutions. Using HPTRMs reduces construction risks and provides a low carbon solution, which is in-line with the Australian Work Health and Safety Strategy 2012–2022.

1.3. HPTRM Engineered Earth Armoring Solution (EEAS)

The HPTRM Engineered Earth Armoring Solution (EEAS) is an Anchored Reinforced Vegetation Armouring System (ARVAS). EEAS is the most advanced flexible armouring technology available for severe erosion and surficial slope stability challenges. This system is consisting of a High Performance Turf Reinforcement Mat (HPTRM) and Engineered Earth Anchors (EEAs). Anchors act as tie-down mechanisms, securing the HPTRM firmly to the ground for additional safety factors and providing surficial stability. The anchoring system increases the safety factor against hydraulic forces and leads to a lightweight protection layer securely anchored to the subgrade for a long-term design life.

EEAS can be used in erosion control applications where additional factors of safety are required, including protecting earthen levees from storm surge and wave overtopping, and stream, river and canal banks from scour and erosion. In addition, this system is ideally suited to protect storm water channels in arid and semi-arid environments where vegetation densities of less than 30% coverage are anticipated. For slope stability applications, the system can be further engineered to provide surficial slope stabilisation to resist shallow plane failures. Figure 2 shows the Anchored Reinforced Vegetation Armouring System and its application in flood protection levees.

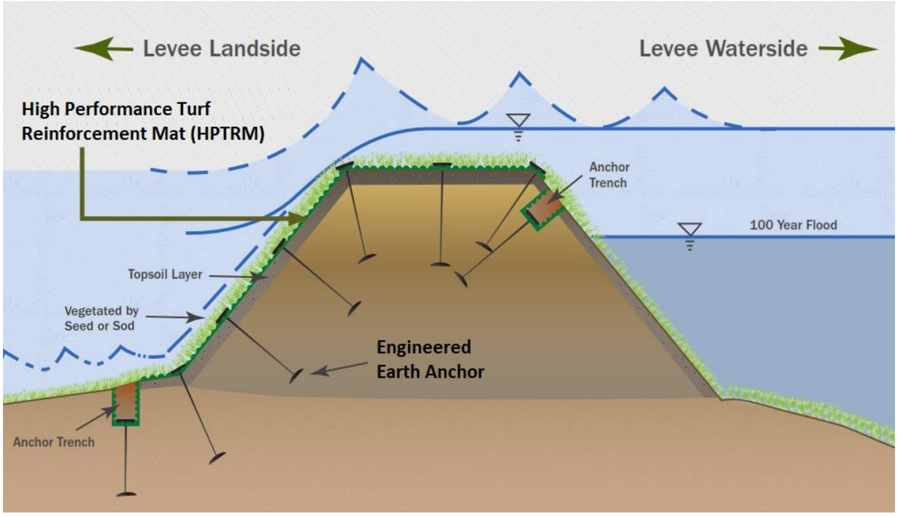

Figure 2 Application of HPTRM Engineered Earth Armouring Solution (EEAS) in flood protection levees

As presented in the following sections, the EEAS is proven to outperform and be more cost effective than conventional methods, including Rock riprap, Rock slope protection, Gabions and Rock Mattresses, Concrete blocks or paving, and Fabric formed revetments.

2. RESEARCH PROCEDURE

USACE began nearly a decade of intensive research to assess the hydraulic performance threshold, cost effectiveness, and long-term durability of different armouring alternatives for the levee system that failed during the Cyclone/Hurricane Katrina event in Southeast Louisiana (USA) in 2005. The USACE-New Orleans District initiated the $14.5 billion Hurricane and Storm Damage Risk Reduction System (HSDRRS) program in 2006, strengthening levees, floodwalls, gated structures and pump stations for a 200km perimeter. One of the most critical measures of the HSDRRS was protection of refurbished earthen levees against the erosion-causing hydraulic forces of storm surge overtopping. A group of 150 experts from around the world was formed by USACE to assess the damage caused by the cyclone and to make recommendations on how to improve the flood protection system against future storms. One of the main findings was the need for providing resilience to the earthen levees in the form of armouring as the final protection. According to USACE, resilience is the ability to anticipate, prepare for and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions. USACE also mentioned that the added armouring resilience will result in the levees continuing to exist even if overtopped by a 500-year storm with 0.2 percent chance of occurring in any year (Sphat, 2012a; Schleifstein 2014).

After the 2005 cyclone, the Penn flood protection levee was armoured with vegetation reinforced by Armormax® EEAS consisting of a woven 3D pyramid structured HPTRM and secured with earth anchors up to 0.6 m long. Root reinforcement, with the use of a suitable EEAS was required to hold the vegetation in place, as laboratory hydraulic flume tests had indicated the unreinforced vegetation to resist erosion at approximately 120 Pa (max) of shear stress and 1.8 m/s (max) of velocity. This new armoured levee, which had previously failed during cyclone Katrina in 2005, survived the storm flow produced by Category 3 Cyclone Ike with winds of 178-208 km/h in 2008 and which caused coastal flooding throughout Texas and Louisiana. Figure 3-left and 3-middle show the Penn Levee with the Armormax® armouring being installed on the upstream (dry side) and being overtopped by storm flows recorded up to 3 m above the normal tide. Figures 3-right shows the undamaged levee after the flood. The successful performance of this armoured Penn Levee was the basis for a 10-year USACE research program to fully understand the design process and requirements of HPTRM reinforced vegetation systems.

Figure 3 Armormax® EEAS on Penn Levee (left), Stormwater overtopping Armormax® armoured Penn levee (middle), Successful performance of Armormax® EEAS after the storm (right) (Thompson and Loizeaux, 2018)

The USACE completed extensive research and full-scale testing on an array of armouring materials and applications in 2011 to assess erosion resistance in order to armour the system. The testing included research on wave overtopping on a specially constructed simulator at Colorado State University, as well as additional scaled transition testing at Texas A&M University, flood-side wave erosion at the Corps' Engineer Research and Development Center, and grass studies by Louisiana State University. This testing determined that a suitable HPTRM with a defined grass quality could withstand drastic wave overtopping. The next step to armouring the system was finding the minimum physical requirements of HPTRM products, which led to a pilot research project. This research had two phases: the field experience and the wave overtopping test. Phase 1 of the pilot research was the field testing of High Performance Turf Reinforcement Mat (HPTRM) materials, with stringent requirements for withstanding installation and maintenance loads. Vegetation establishment through HPTRMs, as well as ease of installation was observed over a two-year pilot program on HSDRRS levees. Phase two, the final qualification of HPTRMs for armouring of HSDRRS levees, was performed at Colorado State University (CSU) where vegetated HPTRMs were tested using a full-scale Wave Overtopping Simulator, replicating cyclone storm surge waves over many hours (USACE-Sources Sought Notice: W912P8-12-SS-0007). These two phases are described in the following sections.

2.1. USACE Field Test

The field test was conducted on two 1,524m long levees. The two HSDRRS levee sections involved in the pilot project were Lake Pontchartrain & Vicinity (LPV 5.2B) in St. Charles Parish, and West Bank & Vicinity (WBV 14f.2) in the Westwego/Harvey area.

The relative performance of different systems/products was evaluated based on the ability of each HPTRM system (HPTRM material, anchoring system including spacing layout) and grass combination to withstand normal operations and maintenance (e.g. mowing), and the ability of the grass to grow through the HPTRM fabric and anchor to the underlying soil (Sphat, 2012a). Also, the wheel load resistance performance was evaluated for each of the selected HPTRM systems installed, under the same environmental and levee field conditions. Anchor system/method for securing or anchoring the HPTRM to existing levee slopes was evaluated for ease of installation and subsequent removal.

HPTRMs had to conform to the following material specifications in Table 1 to be approved to be used in the pilot research:

Table 1 HPTRM specification

Property	Test Method	Average Roll Value
Mass per unit area	ASTM D6566	≥ 288 g/m2
Thickness	ASTM D6525	≥ 7.6 mm
Light Penetration (% passing)	ASTM D6567	≤ 45%
Tensile Strength	ASTM D6818	≥ 45 kN/m
Elongation	ASTM D6818	≤ 65%
Resiliency	ASTM D6524	≥ 70%
UV Resistance @2500 hrs	ASTM D4355	≥ 80%

The products' relative performance was evaluated based on the ability of each HPTRM material and grass combination to withstand normal operations and maintenance, and the ability of the grass to grow through the HPTRM fabric and anchor to the underlying soil (Sphat, 2012a).

All of the HPTRMs were installed on the levee crown and landside slope in discrete distinguishable areas normal to the levee centerline. Each HPTRM was installed in a 300m section, half covered with grass sod (turf) and the other half with grass from fertilized grass seed and mulch. Grass was established to a quality defined as minimum ground cover of 90%, total root length exceeding 37.72cm, total root volume exceeding 3.63cm3, and weight exceeding 13.9g. To determine the adequate grass quality in the field, the grass stems were measured/counted in a 100mm diameter area by measuring the density of the grass using this stem count methodology at intervals of 90 to 120 days. Successful installation was defined as +95% turf establishment, no areas or browned / dead grass greater than 0.2m2, and a shoot count of a minimum of 50 in a 100mm diameter area. After the grass had reached the quality as stated above, the field performance tests commenced. Figure 4-left shows the installation of HPTRMs on the levees. More details on the field test can be found in Sphat (2012b).

The wheel load used for field testing was the mowing tractor that exerts the greatest wheel bearing pressure in kPa (psi) from the Levee District where the testing was undertaken. To be considered acceptable, the HPTRM had to pass the wheel load test for both Levee Districts (East Bank of St. Charles Parish and West Bank of Jefferson Parish). Figure 4-right highlights the size of the maintenance equipment repeatedly used to traffic the most critical sections of the levees.

Figure 4 Left: Installation of the HPTRMs on the levee (Sphat, 2012b), Right: Maintenance equipment used in the field trial (Thompson and Loizeaux, 2018)

The maximum and average mower wheel load impressions on the unreinforced section and each HPTRM reinforced section was determined by measuring at 15m intervals (and in extreme problem areas in between) using a 1.5m long straight edge centered on the wheel track. The total deflection was measured as the depth of the impression plus the pushup of the immediately adjacent surface to the wheel track. The (HPTRM) armoured levee test result was compared to both the performance of an un-armoured levee and the minimum standard of performance in order for each HPTRM system to be considered acceptable for this phase of the testing program. The total deflection of each HPTRM reinforced section to be approved had to be less than 50% of the unreinforced section or a total of 38mm, whichever was the lessor, after a minimum of a 25.4mm rainfall and a minimum of 35% moisture content of soil and a minimum wait time of four hours (USACE-Sources Sought Notice: W912P8-12-SS-0007).

The conclusion of the first phase of the pilot research was that even under the heaviest non-hydraulic loading, vegetation reinforced with an anchored HPTRM was deemed a success and a viable levee armouring solution with respect to frequent maintenance operations. The successful conclusion of the field test and review of the installation costs demonstrated the significant savings of an HPTRM reinforced vegetation system as compared to hard armour alternatives and answered the levee Districts' concerns of being able to cost effectively maintain the levee system.

2.2. USACE Full Scale Wave Overtopping Test

The second phase was to conduct storm surge and wave overtopping laboratory tests based on a 500-year cyclone/hurricane on alternative armouring materials at Colorado State University (CSU). The CSU Wave Overtopping Simulator is the largest in the world, with total wave reservoir capacity of 31 m3. The simulator can release overtopping wave volumes approaching 17m3/m, and it can simulate wave overtopping events having average overtopping discharges as high as 370 l/s per m. During wave overtopping simulations, water enters the simulator vessel at a constant rate, and the release of prescribed wave volumes is controlled by a computer program that operates the release valve (USACE-Sources Sought Notice: W912P8-12-SS-0007).

CSU's device simulated overtopping waves that replicate both the flow volume and flow velocity of the equivalent overtopping wave. Each water release produced unsteady and turbulent flow conditions across the test levee crest and landside slope. The testing required observation and measurement of the effects of a simulated wave overtopping on various armouring systems.

The levee landside slope in each test channel was comprised of two trays as shown schematically in Figure 5. The upper tray was straight and the lower tray was constructed with an angle at the inflection point. When the tray set was installed in the flume, the trays represented a levee with an 8.5m long section having a 1V:3H slope that transitions to a 3.7m long berm section having a 1V:25H slope.

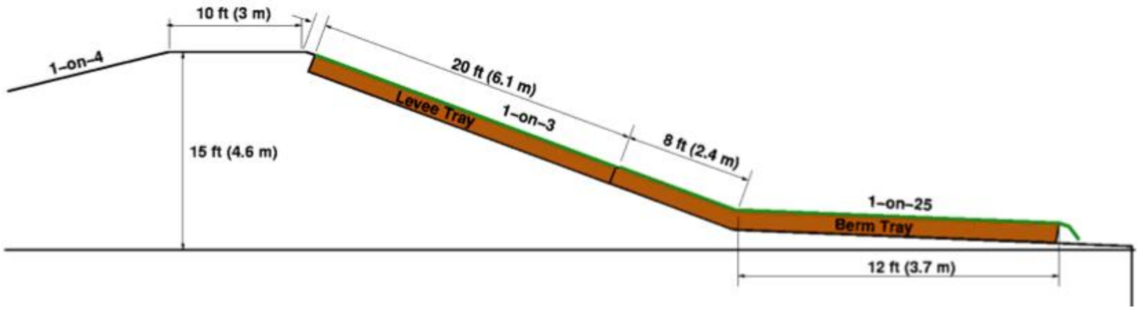

Figure 5 CSU test channel profile (Thornton et al., 2014)

The general procedure for preparing a set of trays for testing consisted of first placing a 5-cm-thick layer of pea gravel in the bottom of the trays for drainage, and then covering the gravel with a suitable geotextile filter cloth. Soil was added in two lifts of approximately 13 cm thickness, and each lift was compacted according to specifications. Finally, the selected grass sod was installed over the compacted soil. If a high performance turf reinforcement mat (HPTRM) was being tested, the HPTRM was installed prior to the turf placement (Figure 6).

Figure 6 Preparing and testing the CSU testing trays (Thornton et al., 2014)

The overtopping tests were conducted in such a way to represent a full-scale replica of a levee protected side slope (including a 3m wide horizontal crest). Completion of the test trays required fabricating 0.6-1.8m w x 6m L x 300mm deep steel trays, installing HSDRRS clay in the trays according to HSDRRS specifications, placing the HPTRM according to each manufacturer/supplier's specifications and populated with 38mm. thick grass sod on top of the clay, and cultivating the grass during the growing season, until reaching the acceptable grass quality as described in the field test phase before testing commences. Once in place, the trays and supporting infrastructure replicated a levee having a slope of 1V:3H and a downslope length of approximately 8.5m. At the toe of the slope the levee was transitioned into a protected side berm, which had a slope of 1V:25H over a distance of a minimum of 3.7m (USACE-Sources Sought Notice: W912P8-12-SS-0007).

Overtopping flow was controlled using a fixed overtopping wave simulator device. This device was capable of storing sufficient quantities of water such that the full potential energy of the largest and smallest specified overtopping wave volume could be tested along with all intermediate volumes required. The release of water and the creation of the "slug" of unsteady, turbulent flow was achieved using a gravity discharge mechanism. Valve and discharge infrastructure was such that the typical tongue of an overtopping wave was simulated across the width of the levee section and the device was ready to fill and discharge flow as quickly as the desired wave conditions demanded (USACE-Sources Sought Notice: W912P8-12-SS-0007).

A single test was defined as one wave overtopping simulation down the flume for a 3 equivalent test hours. Passing this wave overtopping test was defined as surviving the 3 equivalent test hours without visible damage. This passing criteria was actually defined as follows: no loss of grass in a single location greater than 13 cm2, no total summation of visible loss of grass of greater than 38.7cm2, and/or less than 60mm of soil/grass erosion over a 0.37m2 area. A more detailed description of the equipment and testing procedure can be found in Thornton, et al. (2012, 2014).

From 2010 to 2014, four sets of wave overtopping tests were completed which include healthy and dormant grass on clay in 2010 and 2012 and 2014, and healthy grass with 50% or 30% coverage on sandy soil in 2012. Some of the tests examined the increased resiliency provided by turf reinforcement mats. From the tray sets with stiff clay tested in 2010, one tray set had only bare clay, four tray sets had grass, one tray set had lime stabilised clay, one tray set had Artificial Concrete Blocks (ACBs), two tray sets had medium-strength open weave turf reinforcement mats (TRM) installed under Bermuda sod, and two of the tray sets had high performance turf reinforcement mats (HPTRM) under the Bermuda sod.

All TRM and HPTRM test trays had been developed and tested in the same manner including the same soil, compaction, moisture content, grass sod condition, watering, fertilizer, climate (temperature, sunshine), dormancy process and period, in order to ensure consistency so that the only significant variable is the type of HPTRM.

2.3. Results of the USACE Full Scale Wave Overtopping Test

In Figure 7, the results from the USACE sponsored tests in 2010 on New Orleans' clay are plotted in the graph as a function of cumulative wave overtopping volume versus duration time of test. The slopes of the curves indicate rates of average overtopping discharge during each hour of testing. Steeper slopes correspond to tests in which the overtopping rates were higher. The curves that end with no damage indicate that testing ended at that point, and damage had not occurred.

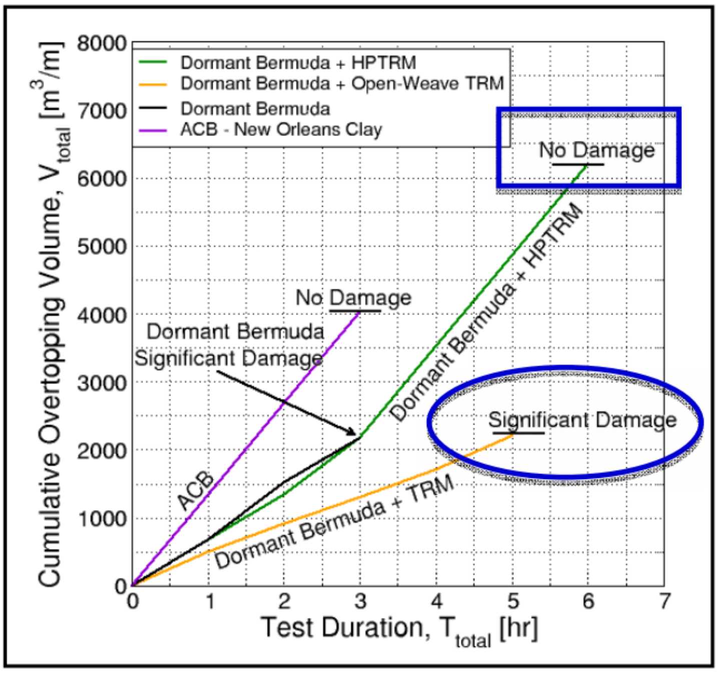

Figure 7 CSU Wave Overtopping Simulator test results on non-reinforced vegetation, a HPTRM reinforced vegetation, an open weave TRM reinforced vegetation, and an Artificial Concrete Block (ACB) with clay subgrade (Thornton et al., 2014)

The first key learning is that HPTRM reinforced vegetation performed as well as if not better than the ACBs. From the graph in Figure 7, the ACB and the grass reinforced with an HPTRM tests were both terminated at 3 hours and 6 hours respectively with no damage. The results show that the HPTRM solution exceeded cumulative wave overtopping volume by 50-60% before the test was terminated with no damage. The data should give designers, at a minimum, the confidence to consider HPTRM reinforced vegetation as a viable alternate to ACBs and other traditional hard armour solutions.

Secondly, the grass reinforced with the open-weave TRM suffered significant damage, while no damaged was observed for the grass reinforced with HPTRM. It appears that the open-weave TRM provided only minimum additional resiliency. The tray containing dormant Bermuda grass strengthened with the HPTRM was able to resist cumulative loading that was 2.8 times greater than the damaged dormant grass tray. In fact, the upper limit of cumulative loading that might be withstood by the dormant grass with the HPTRM is unknown because testing was ended before damage occurred.

Similar results were achieved from same wave overtopping loading testing on sandy soil as the subgrade, conducted by USACE in 2012. Results verified that using HPTRM to reinforce the turf could increase the performance and overtopping resistance. The tests on sandy soil exhibited a surprisingly high level of erosion resistance (figure 8).

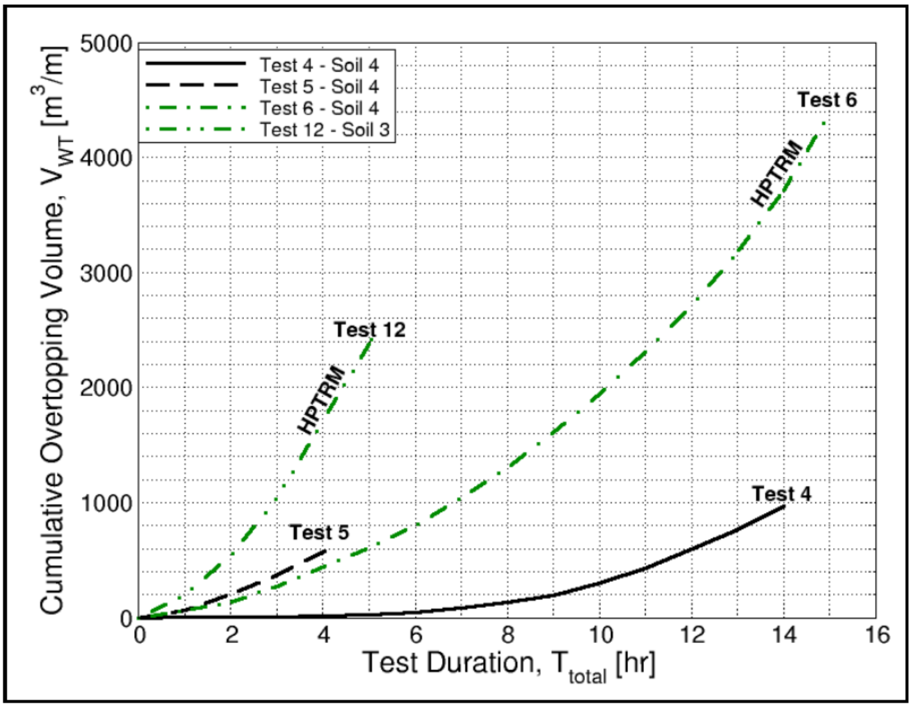

Figure 8 CSU Wave Overtopping Simulator test results on nonreinforced vegetation (test 4 & 5) and HPTRM reinforced vegetation (test 6 & 12) with sandy soil (Thornton et al., 2014)

2.4. Full Scale Wave Overtopping Test on Armormax® EEAS

ARVAS are described in section 1.3 of this paper. Armormax® ARVAS consists of a woven 3D pyramid structured HPTRM and secured with earth anchors up to 1.8 m long. This system helped Penn flood protection levee to survive during the Category 3 cyclone in 2008, and was the basis of the USACE pilot research as discussed in Section 2 of this paper. The anchors in the Engineered Earth Armoring Solution (EEAS) create a permanent anchorage for the mat and the entire system. This leads to an extra factor of safety against hydraulic forces provided by the anchors. Wave overtopping test results (figure 9) showed that the Armormax® system could provide the highest resistance against erosion and hydraulic forces, due to the anchoring system and the HPTRM, especially for the areas with low vegetation concentration.

Figure 9 Wave Overtopping Simulator test Armormax® EEAS (Thornton et al., 2012)

3. HPTRM PERFORMANCE PARAMETERS

An important fact to consider is that not all HPTRMs perform the same, even if they have similar physical properties. Hydraulic behavior (including allowable shear and velocity), vegetation growth capability, durability, and field performance test results shall also be considered to study HPTRMs and compare their performance. A minimum value is required for the important performance properties to guarantee the short term and long-term performance of a HPTRM reinforced system.

The USACE field test identified an important material property required for long-term performance. Recognising the importance of durability, the USACE set the minimum criteria for HPTRM tensile strength to a minimum of 45kN/m as defined by the US FHWA (FHWA 2003). The field study confirmed that purposely defining the material index property of tensile strength for the intended application is crucial for determining long-term performance. This is a significant departure from the common practice of only comparing various HPTRMs by hydraulic performance values determined in a laboratory flume test.

HPTRMs are usually compared on the basis “or equivalent” by their respective published hydraulic flume values ranging up to 766 Pa. There are other parameters of importance in the final selection of product. In addition to mower trafficking testing the tensile strength of the product in the field, Louisiana State University cored and sampled the vegetation to determine the density and root length interlocked in the HPTRM for use inclusion in the hydraulic testing protocol to follow, in Phase 2 of the research.

An obvious important performance parameter is the percent of light penetration (commonly referred to as percent open area) as measured by ASTM D-6567. This test method determines the amount of incandescent light that penetrates through a rolled erosion control product, indicating the openness of the weave of the mat structure. See Figure 10 for a visual comparison of the mats used in the New Orleans’ test and subsequent USACE tests. In addition to 10 varying vegetation density tests as can be read in Thornton et al (2012), two HPTRMs were used meeting the aforementioned basic definition of having greater than 45kN/m of tensile strength. The two HPTRMs in this test were similar in construction, with the primary difference being percent light penetration.

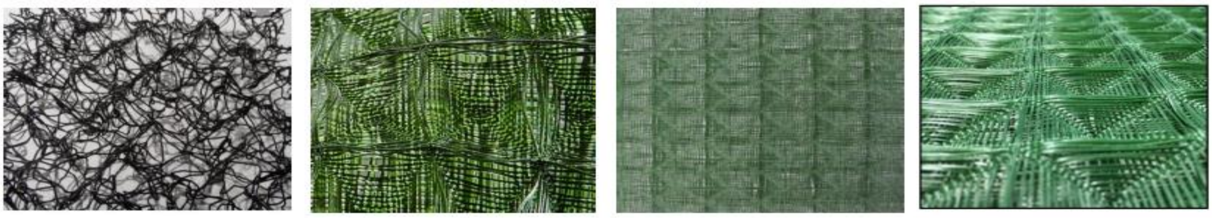

Figure 10 Different TRM and HPTRM products evaluated in the CSU wave overtopping test with different light penetrations of 90% (left), 35% (second from left), 25% (second from right), and 10% (right) (Thornton et al., 2018)

In Figure 11, the cumulative wave overtopping for four tests are plotted on one graph as a function of percent light penetration of the HPTRM. The data series in orange represents the USACE New Orleans’ District first test on clay in 2010 as described previously in this paper. It is comprised of three data points: turf only, turf reinforced with a 90% open TRM and turf reinforced with a 10% open HPTRM as viewed right to left. The data series in blue is the USACE's tests with sand. Results show that HPTRMs or TRMs with smaller percent light penetration (to a minimum necessary value) improved vegetation performance in hydraulic testing. In addition, less vegetation establishment is required in clay to equal the performance of much higher vegetation densities in sand.

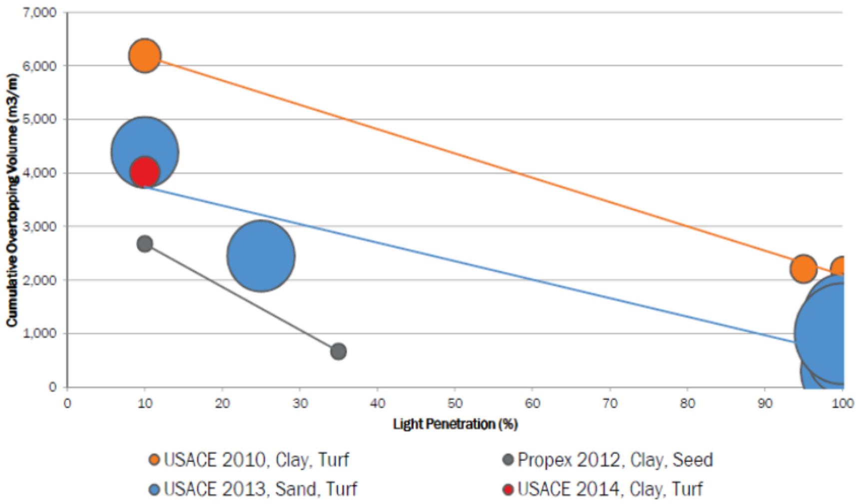

Figure 11 CSU wave overtopping test results- Performance of TRMs/HPTRMs in terms of cumulative overtopping volume for different product light penetrations (Thornton et al., 2018)

4. SUMMARY AND CONCLUSION

United States Army Corps of Engineers (USACE) conducted extensive testing and pilot research programs to find alternative solutions which can reduce the costs and provide the same or better performance than traditional hard armouring systems such as rock riprap and concrete for Hurricane & Storm Damage Risk Reduction Systems. Based on the successful performance of the Penn levee armoring system using Armormax® Engineered Earth Armoring Solution (EEAS), which was a combination of a High Performance Turf Reinforcement Mat (HPTRM) and Earth Anchors, field trials and full scale wave overtopping tests on different Turf Reinforcement Mats (TRMs) and High Performance Turf Reinforcement Mats (HPTRMs) were conducted by USACE and Colorado State University (CSU). Some conclusions from these tests and trials can be summarised as follows:

- HPTRM reinforced vegetation systems perform as well as if not better than the ACBs and significant rock armour protection layers for hydraulic applications such as storm water channels and flood protection levees in both clay and sandy soils.
- A HPTRM solution is a more cost effective and environmentally friendly solution than traditional hard armour solutions.
- Engineered Earth Armouring Solution (EEAS) which consist of a High Performance Turf Reinforcement Mat (HPTRM) and Engineered Earth Anchors (EEAs) can increase the safety factor of the armouring system against hydraulic forces and also provide slope surface stability.
- The type of the soil can affect the performance of the HPTRM system. Although the HPTRM provided significant improvement in the performance of the armouring system for both clay and sandy soils, less vegetation establishment was required in clay to equal the performance of much higher vegetation densities in sand.
- Tensile strength is the key component for durability and long-term performance of HPTRMs, especially for storm water and flood protection applications. FHWA minimum requirement for tensile strength of HPTRMs is 45 kN/m.
- UV resistance is another key parameter for the durability of TRMs and HPTRMs, especially in areas with lower chance of full vegetation, and for critical applications such as storm water management and flood protection. Accelerated UV tests (e.g. ASTM D4355) on HPTRMs for a period of 3,000hrs and 6,000hrs (up to 10,000hrs where required) is suggested to simulate the real long term site condition.

- A high resiliency (≥ 70%) is required for HPTRMs along with a high tensile strength to maintain their performance under non-hydraulic forces such as mowing.
- HPTRMs or TRMs with smaller percent light penetration, improves the vegetation performance in hydraulic testing whether established from seed or turf. A minimum light penetration is required to guarantee the vegetation growth though the mat.
- Light penetration of 10% as minimum and 50% as maximum is suggested for TRMs and HPTRMs to provide the required short term and long-term performance.

5. REFERENCES

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