Increasing the Resilience and Improving the Environmental Performance of Earthen Flood Defense Structures with High Performance Turf Reinforcement Mat Reinforced Vegetation

R. Thompson[1] and D.Loizeaux[1]

[1] Propex Operating Company, LLC, 4019 Industry Drive, Chattanooga, Tennessee 37416, United States

Abstract

Adding resilience to earthen flood defense 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 becomes more prohibitive. To add resilience riprap, articulated concrete blocks, concrete slope paving, and other traditional hard armor solutions are often used typically at a great cost to the owner and the environment. The United States Army Corps of Engineers (USACE) sought to mitigate these costs when selecting an armoring system for the earthen levees in the 214 km (133 miles) of the Hurricane & Storm Damage Risk Reduction System for southeast Louisiana. The USACE armoring focus turned to High Performance Turf Reinforcement Mats (HPTRMs) after a levee armored 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. As a result of this research, this paper will focus on using hydraulic data to reposition HPTRMs as a suitable alternative to traditional hard erosion control solutions and explain the importance of key material properties when comparing different HPTRMs. This paper will show that HPTRMs with a more closed structure and a smaller percent vegetation establishment perform better than the more open HPTRMs with a higher percentage of vegetation establishment. More research is required to determine specific design guidelines for correlating percent HPTRM openness to vegetation densities in different soil types as it relates to hydraulic performance. Even with low vegetation densities, HPTRM reinforced vegetation provides improved environmental outcomes and lower carbon emissions when compared to traditional hard armor solutions. Countries around the world may benefit greatly from investing in HPTRM reinforced vegetation to provide resilience on earthen flood defenses as an alternate to traditional hard armor systems that are more expensive, less aesthetically pleasing, and more detrimental to the environment.

1.0 Introduction

Traditional hard armor solutions, such as riprap, articulated concrete blocks (ACBs), or concrete slope paving are often used to add resilience to levees, dams, or other earthen flood defense structures, typically at a great cost to the owner and the environment. To mitigate these costs, the United States Army Corps of Engineers (USACE) began nearly a decade of intensive research to assess the hydraulic performance threshold, cost effectiveness, and long-term durability of vegetation reinforced with a High Performance Turf Reinforcement Mat (HPTRM) to add resilience to the re-built earthen flood defense levee system breached during Hurricane Katrina in New Orleans, Louisiana. An HPTRM is a matrix composed of polypropylene monofilament yarns designed to allow vegetation roots penetrate and interlock in the body of the mat. Research over the years has established HPTRM reinforced vegetation performance in steady state flow in a flume. However, there is little knowledge of HPTRM performance in wave and storm surge overtopping and as a result, the USACE commissioned testing in the world's largest, full scale Wave Overtopping Simulator to determine performance at a maximum average discharge volume of 370 l/s per m (4 ft^3/s per ft). This paper will review four separate wave overtopping data sets to demonstrate that HPTRM reinforced vegetation is a viable alternative to hard erosion control solutions and will focus on explaining the varying performance of the different HPTRMs. In addition, the benefits of incorporating vegetation into the resilience design instead of traditional hard solutions on earthen flood defense structures positively affects the environment and natural habitats. Countries around the world may greatly benefit from investing in HPTRM reinforced vegetation as an environmentally friendly, cost effective, and aesthetically pleasing erosion control solution to mitigate future flood risk. The intention of this paper is to use the existing research to establish general guidance on the use of HPTRM reinforced vegetation technology to increase the resilience and improve the environmental performance of earthen flood defense structures that are designed for permissible overtopping rates.

1.1 Adding Resilience to Earthen Flood Defense Structures

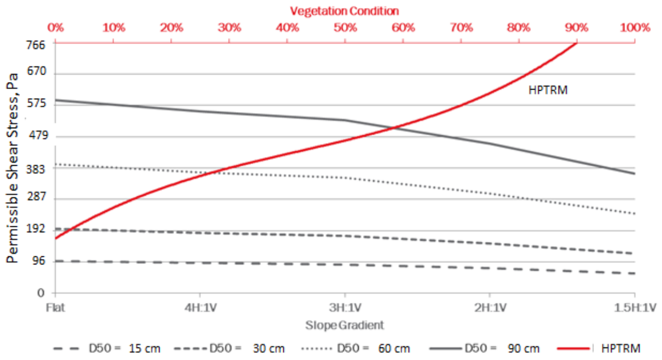
Earthen flood defense structures, including levees and dams, are earth filled embankments typically covered in grass for the purpose of managing and controlling flood water. To protect these structures against the erosive force of water, engineers commonly use hard erosion control methods such as rock riprap, ACBs, concrete slope paving, and open-stone asphalt. The use of these traditional hard materials can be at a great cost to the owner and the environment. One of the most commonly used hard materials is rock riprap. The monetary cost of rock riprap is dependent on many factors including, location, rock quality, thickness, accessibility, and area to be covered. The United Kingdom's (UK) Environment Agency (EA) in its Report SC080039/R3, Cost Estimation for Channel Management-Summary of Evidence, gives a broad range of pricing for installed costs of traditional hard armoring methods. The estimated costs for several products are listed in Table 1 and shows stone riprap to have a price range of £60 -150 per m^2 ($70-180 per yd^2). Hard solutions are almost always the most expensive form of stream and storm channel bank protection (SEPA 2008). HPTRM reinforced vegetated solutions are more cost effective and generally install for £15 -25 per m^2 ($18-30 per yd^2) while providing more erosion resistance than riprap in a channel. Figure 1 graphically depicts the performance of HPTRM reinforced vegetation versus different thicknesses of rock riprap and channel bank slopes. The graphs are based on US Federal Highway Administration (FHWA) HEC-15 modeling and show that when bank slopes become steeper than 3H:1V, the HPTRM solution is superior to riprap. Owners are becoming aware of these different solutions and are asking their designers to consider a wide range of different measures to address the flood and coastal erosion risk to communities and properties with an emphasis on environmental protection.

Table 1. General Guide to the cost of typical hard armor erosion control solutions in the United Kingdom (Jones *et al.* 2015, p.15-16).

Technique	Approximate cost guide	Source and comments
Stone rip rap	£26 per m	AINA (2008) based on information from British Waterways (2007 data)
Rock rolls	£46 per m	AINA (2008) based on information from British Waterways (2007 data)
Stone gabions	£250 per m	AINA (2008) based on information from British Waterways (2007 data)
General hard reinforcement costs	£1,075 per m	SNIFFER (2005) Generalised costs for concrete, laid stone, gabion baskets and riprap protection.
Gabion baskets	£50–65 per m^3	SNIFFER (2007)
Gabions	£1,216 per m	Environment Agency (2008) based on an average revetment volume of 16 m^3 per m and a unit cost of £76 per m^3.
Rock gabions	£50–70 per m^2	SEPA (2008)
Timber piling	£160 per m	AINA (2008) based on information from British Waterways (2007 data)
Non-live timber revetment	£100–350 per m^2	SEPA (2008)
Riprap	£60–150 per m^2	SEPA (2008)

The UK's construction industry strategy for 2025 has identified that reducing carbon reduces construction costs and the EA's intent is to evaluate the carbon footprint of projects to provide the lowest carbon solution possible on all infrastructure projects (Environment Agency 2016). When adding resilience to earthen flood defense structures, traditional hard (sometimes referred to as grey) armor solutions can

Figure 1. Estimated Hydraulic Performance per FHWA HEC-15 comparing a HPTRM to different thicknesses of riprap and channel bank steepness.



increase the carbon loading significantly as compared to soft (green) solutions. “Although the primary function of a wall or embankment may be flood defence, such structures also frequently have a secondary function – quite often with the aim of enhancing the environment or improving the amenity or both. Indeed, for any works commissioned or consented by the Environment Agency, there is a duty under the Environment Act 1995 to conserve and enhance the natural beauty of rivers and coasts” (Rickard 2010, p.9-2). More than ever, designers must be more creative and look beyond traditional hard erosion control solutions to solve problems in a more environmentally responsible and cost effective way.

2.0 United States Army Corps of Engineers' Levee Armoring Research

To mitigate the financial and environmental costs of hard armor, the USACE began nearly a decade of intensive research to assess the hydraulic performance threshold, cost effectiveness, and long-term durability of different armoring alternatives for the levee system breached by Hurricane Katrina in Southeast Louisiana in 2005. After the hurricane, the USACE formed a task force of 150 experts from around the world to evaluate the devastation caused by Hurricane Katrina and to make recommendations on how to improve the hurricane protection system against future hurricanes. Among many findings, one was the requirement of adding resilience in the form of armoring to the earthen levees as the final protection. “Resilience is the ability to anticipate, prepare for and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions” (USACE 2016, p.1). The USACE says the added armoring resilience “…will result in the levees continuing to exist even if overtopped by a hurricane with a 0.2 percent chance of occurring in any year, a so-called 500-year storm” (Schleifstein 2014). Having approximately 137 km (85 miles) of levee to armor, the USACE took special notice of the Penn hurricane protection levee in Lafitte, Louisiana that was armored with vegetation reinforced by a HPTRM and secured with earth anchors up to .6 m (2 ft) long. This armored levee, which previously failed during Hurricane Katrina, survived the storm surge produced by Hurricane Ike in 2008. Root reinforcement to hold the vegetation in place was required because laboratory hydraulic flume tests have set the maximum thresholds for unreinforced vegetation to resist erosion at approximately 120 Pa (2.5 lbs/ft^2) of shear stress and 1.8 m/s (6 ft/s) of velocity. Ike was 1.61 kph (1 mph) shy of being Category 3 status on the Saffir–Simpson scale when it made landfall causing coastal flooding throughout coastal Texas and Louisiana. A Category 3 hurricane has sustained winds of 178-208 km/h (111-129 mph). The pictures in Figures 2-4 show the Penn Levee with the HPTRM armoring being installed on the “protected (dry) side” and being overtopped by storm surges recorded up to 3 m (10 ft) above normal tide. The final picture shows the undamaged levee after the flood waters receded.

The successful performance of the HPTRM armored Penn Levee was the background for the USACE developing a two phase research program to fully understand designing with HPTRM reinforced vegetation. The first phase of research was to conduct field tests on two 1,524 meters (5,000ft) levee alignments. “The products' relative performance will be evaluated 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” (USACE 2012a). The second phase was to conduct storm surge and wave overtopping laboratory tests based on the 500-year hurricane on alternative armoring materials at Colorado State University (CSU). The research sponsored by the USACE is the capstone of over 20 years of laboratory testing around the world.

This paper will focus on explaining the varying performance of the different HPTRMs in the USACE

Figure 2. Installation of the anchored HPTRM on the Penn Levee, Lafitte, Louisiana. (2008)

Figure 3**.** Penn Levee wave overtopping and storm surge during Hurricane Ike. (2008)

Figure 4**.** The undamaged levee after the stormwater receded. The project's success started a 10 year USACE research program to understand HPTRM technology.

wave overtopping test in a variety of testing scenarios to include various vegetation establishment methods in different soil types. More testing is required to develop a specific design procedure and may not be feasible due to the significant expense of the CSU wave overtopping test and the many different soil and vegetation combinations. The intention of this paper is to use the trends in existing research to establish:

- HPTRM reinforced vegetation is a viable alternative to hard solutions on levees and dams;
- all HPTRMs are not equal and specific material properties are predictors of long-term performance;
- there is compelling environmental justification for designing with HPTRMs.

2.1 United States Army Corps of Engineers' HPTRM Field Test

Given the authority by the United States Congress to add armoring to the levees, the USACE invested in a two phase research program to answer the many questions surrounding the sustainability and long-term performance of vegetation reinforced with an anchored HPTRM. The individual levee districts that own and are responsible for the maintenance of the levees were initially against the use of HPTRM reinforced vegetation for armoring and were in favor of the construction of gravity walls to lower the overtopping rate below .03m^3 /sec (1 ft^3/sec) which is well within vegetation's accepted erosion resistance of 1.8 m/s (6 ft/s). With no Congressional authorization to build taller walls, the USACE's research had to convince the skeptical levee owners that not only would the HPTRM armoring protect from breaching, it would endure their normal maintenance operations. The details of the field demonstration test can be found in Sphat (2012b) and the conclusion was that even under the heaviest non-hydraulic loading, vegetation reinforced with an anchored HPTRM was deemed a success and a viable levee armoring solution with respect to frequent maintenance operations. Figure 5 highlights the size of the maintenance equipment repeatedly used to traffic the most critical sections of the levees. 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 armor alternatives and answered the levee districts concerns of being able to cost effectively maintain the levee system.

Figure 5. Anchored HPTRM reinforced vegetation being field tested in St. Charles Parish, Louisiana. USACE findings are that HPTRM technology is durable, maintainable, and is suitable for levee armoring.

The test also identified an important material property required for long-term performance. Recognizing the importance of durability, the USACE set the minimum criteria for HPTRM tensile strength to a minimum of 45kN/m (3,000 lbs/ft) as is 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 different HPTRMs by hydraulic performance values determined in a laboratory flume test. HPTRMs are usually compared to determine an "or equal" by their respective published hydraulic flume values ranging up to 766 Pa (16 lbs/ft^2) of shear stress and 7.6 m/s (25 ft/s) of velocity. In addition to mowers 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 II of the research.

2.2 United States Army Corps of Engineers' HPTRM Wave Overtopping Test

With operation and maintenance concerns being satisfied, the USACE proceeded to the second phase of the research to measure for the first time, full scale wave overtopping hydraulic performance at CSU. The testing at CSU goes further to show that simply comparing the product data sheets of two somewhat similar HPTRMs to determine "or equal" is problematic without a complete understanding of specific material properties and how they relate to the design application. The CSU overtopping simulator is styled after the Dutch mobile simulator and is designed to replicate hurricane wave overtopping on full scale levee sections. The CSU Overtopping Simulator has approximately three times the capacity of the Dutch mobile overtopping simulator with a reservoir capacity of 31m^3 (1,100 ft^3), has an average wave overtopping discharge of 200 – 370 l/s per m (2.2- 4ft^3/s per ft) and steady overflow of approximately 1.5 m^3/s per m . See Thornton, et al. (2012) for detailed description of the equipment and testing procedure. Unlike its Dutch predecessor and other in the field tests, the CSU overtopping simulator has the capacity to test different armoring products to failure. Figure 6 shows a schematic of the testing facility and Figure 7 is a photo of a wave overtopping test being conducted on Propex GeoSolutions' ARMORMAX®. From 2010-2014, four different sets of wave overtopping tests were sponsored by the USACE or Propex GeoSolutions. In Figure 8, 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 first key learning is that HPTRM reinforced vegetation performed as well as if not better than the ACBs. From the graph in Figure 8, the ACB and the dormant bermuda grass reinforced with an HPTRM tests were both terminated at 3 hours and 6 hours respectively with no damage. Not only did the HPTRM reach the cumulative wave overtopping

Figure 6. Diagram of Colorado State University Wave Overtopping Simulator (Thornton *et al.*2012).

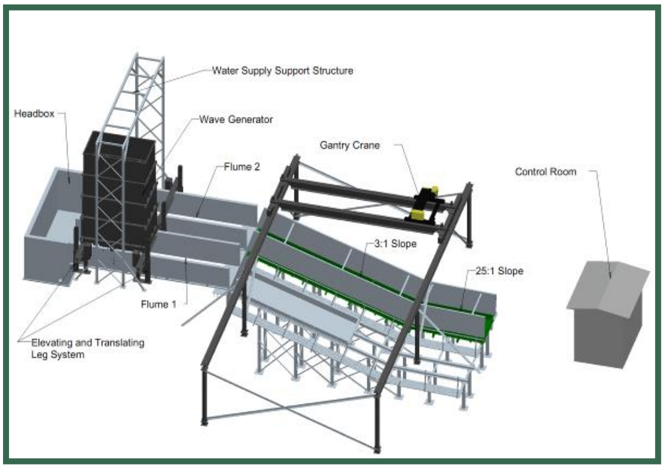
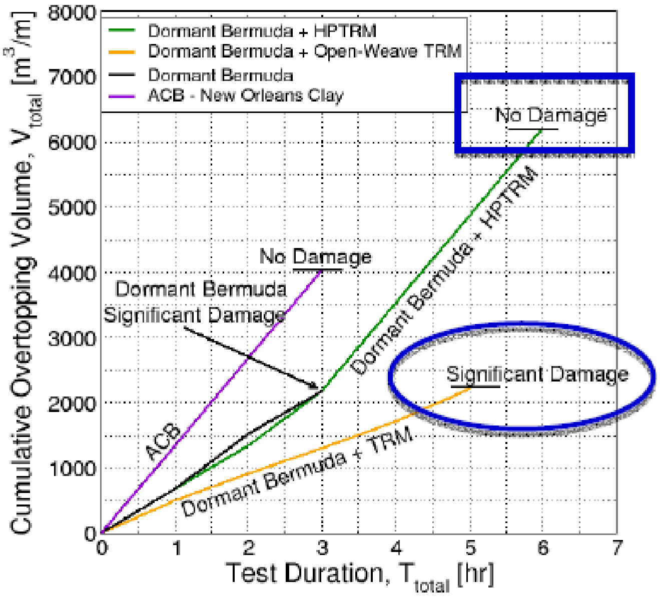


Figure 7. ARMORMAX tested on a full scale levee section for USACE (Thornton *et al.* 2012).

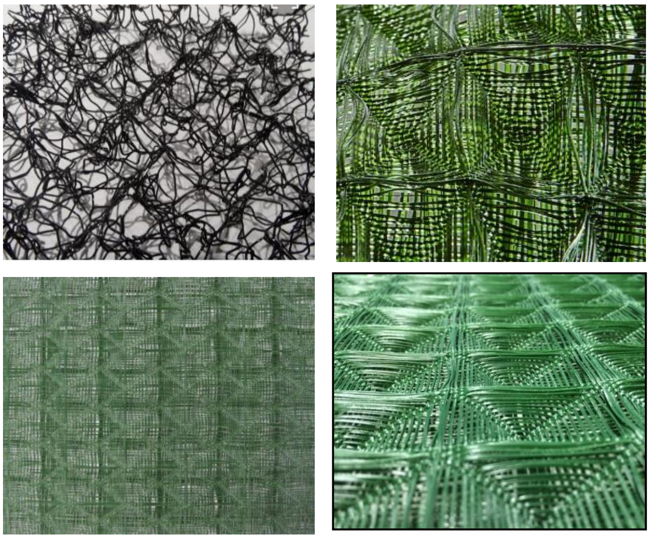
volume of the ACB, it exceeded it by 50-60% before the test was terminated with no damage. Unfortunately, the upper limit at which failure occurs was not determined for either and it is impossible to give a more accurate performance comparison. However, the data should give designers at a minimum the confidence to consider HPTRM reinforced vegetation as a viable alternate to ACBs and other traditional hard armor solutions.

Figure 8. Dormant bermuda grass testing in the CSU Wave Overtopping Simulator showing a distinct performance difference between an HPTRM versus an open weave turf reinforcement mat and ACB. (Thornton *et al.* 2012)



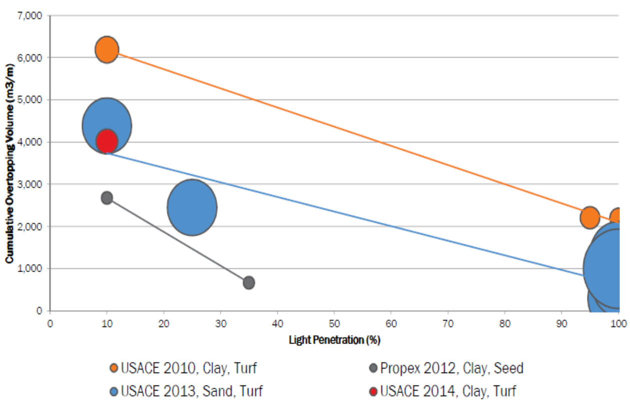
The second key learning is that all synthetic reinforcing mats are not the same and need to be evaluated independently to determine performance for a given application. The question to be answered in this paper is why is there a difference in performance between the turf reinforcement mat (TRM) and the HPTRM with vegetation quality being the same? The obvious difference to the researchers was percent light penetration (commonly referred to as percent open area) as measured by ASTM D-6567. This test method covers measuring the amount of incandescent light that penetrates through a rolled erosion control product, indicating the openness of the weave of the mat structure. However, it may not be a true measure of ground cover if the mat has fibers that are translucent (ASTM D-6567, 2017). The HPTRMs discussed in this paper did not have translucent fibers. In this research, the HPTRM has a densely woven matrix consisting of a 10% light penetration value, while the TRM was loosely formed and open with a percent light penetration greater than 90%. See Figure 9 for a visual comparison of the mats used in the New Orleans' test and subsequent USACE tests. Next in 2013, the Jacksonville District of the USACE did similar wave overtopping tests as described above, but used full scale levee sections made of sand instead of clay. In addition to 10 varying vegetation density tests as can be read about in Thornton *et al* (2012), two HPTRMs were used meeting the aforementioned basic definition of having greater than 45kN/m (3000 lbs/ft) of tensile strength. The two HPTRMs in this test were similar in construction with the main difference recognized to be percent light penetration. The first HPTRM, as was used in the 2010 USACE test, had a light penetration value of 10% and was evaluated against another HPTRM with a 25% value. While the cumulative wave overtopping values in the sand were not as high as those achieved in the clay test, the HPTRM reinforced bahia grass results were nevertheless an impressive improvement upon unreinforced bahia grass turf. In Figure 10, 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 bermuda turf 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 of the USACE's Jacksonville

Figure 9. The different products evaluated in the CSU wave overtopping test in order of descending percent light penetrations of 90%, 35%, 25%, and 10% respectively.



District tests on bahia grass turf in sand. This is a 12 point series that had 10 tests with varying densities of vegetation plotted on the right side of the graph with two other tests using turf reinforced with a 25% open HPTRM and a 10% open HPTRM with points plotted on the graph from right to left. The red point is an additional test sponsored by Propex GeoSolutions on New Orleans' clay and bermuda grass. The tests and data series discussed to this point have involved vegetation established as turf placed on the HPTRM then

Figure 10. CSU Wave Overtopping Test data as it relates to the percent light penetration (or openness) of the vegetation reinforcing HPTRM. The lower the light penetration value for the HPTRM, the higher the cumulative overtopping volume withstood. The size of the plot points are a representation of the health of the vegetation.



allowed to grow prior to testing. For vegetation established from seed, Propex GeoSolutions sponsored the gray data series that contains two points in a 35% open TRM and a 10% HPTRM. The size of the points plotted is indicative of the health of the vegetation which is measured as the root length x root volume /area. As explained in Thornton *et al* (2014), root volume per unit of surface area is an indicator of vegetation density and root length is indicative of how easily a root can penetrate the soil through the HPTRM. While more data points are needed, the graph suggests that the key learning's from this research:

- HPTRMs or TRMs with smaller percent light penetration improves vegetation performance in hydraulic testing whether established from seed or turf,
- HPTRMs with a smaller percent light penetration do not reduce vegetation establishment as compared to more open TRMs,
- Less vegetation establishment is required in clay to equal the performance of much higher vegetation densities in sand. However, the percent improvement is unknown without further research.

To further demonstrate the key points above, the 10% open HPTRM and 90% open TRM as shown in Figure 9 were tested through 1995-1997 in a straight flume at the Texas Transportation Institute (TTI) to determine performance in a storm water drainage channel. The test results for a shear stress range = 0 - 383 Pascals (0 - 8 lbs / ft^2) are listed in Table 2. The TTI research shows that a tightly woven product with only 10% light penetration retained about 70% more soil in place during flume testing as compared to a 90% open TRM. The 10% open HPTRM also had approximately 20% less vegetation further confirming that the weave of the material and percent light penetration are important to performance. This is extremely important for designers working in arid climates where vegetation densities give less than 30% coverage. While more data points are needed to create a design approach based on open area of the HPTRM, these results should assist designers in understanding that all HPTRMs or TRMs are not created equally and that certain index material properties are important to evaluate based on the specific parameters of the application. The designer should make comparisons between products based on relevant hydraulic laboratory test data as it relates to vegetation density, soil type, and percent light penetration of the HPTRM.

Table 2. TTI Laboratory results in 1995-1997 showing the relationship between percent light penetration, sediment loss, and vegetation density. Products with lower percent light penetration and less vegetation establishment retain more soil than more open products (TTI 2001 p.51).

Product	Percent Light Penetration	Average Sediment Loss	Final Vegetation Density
PYRAMAT 75	10%	.77	67.16%
PYRAMAT 75	10%	.78	72.14%
Enkamat 7020	90%	1.33	82.39%

Average Sediment Loss = Average downhill migration of soil movement expressed in centimeters

Final Vegetative Density = Percent vegetative cover achieved by final measurement

3.0 The Environmental Benefits of HPTRM Reinforced Vegetation

The United States Environmental Protection Agency (EPA) has established the use of vegetation as a best management practice (BMP). Vegetation acts to slow water velocities, increasing sedimentation and filtration of heavy metals, and encouraging infiltration of water back into the ground water table. An important part of flood risk management is to encourage infiltration, keeping water in place and minimizing the amount entering tributaries. Table 3 shows the percent removal of common pollutants in storm water runoff attributed to vegetation. Additionally, TRMs and HPTRMs are also designated as standard BMPs by the EPA to allow for the use of vegetated solutions where the hydraulic limits of unreinforced vegetation has been reached. Further environmental benefits are realized from the shipping and installation of HPTRMs. While rock riprap requires the use of heavy machinery for installation, HPTRMs can be installed by manual labor or light weight equipment showing an increase in productivity and a reduction in emissions. Carbon emissions are also reduced as it takes several hundred articulated lorries of riprap to transport an equal coverage area on one articulated lorry of HPTRM. There are already government agencies around the world requiring the evaluation of the environmental impact and carbon footprint of each solution as a part of the selection process. Understanding the appropriate use of this technology on flood management projects will play an important role in meeting these environmental goals.

Table 3. Effectiveness of Vegetated Swales at removing Pollutants from Stormwater Runoff (EPA 1999)

Pollutant	Median % Removal
Total Suspended Solids	81
Oxygen Demanding Substances	67
Nitrate	38
Total Phosphorus	9
Hydrocarbons	62
Cadmium	42
Copper	51
Lead	67
Zinc	71

4.0 Summary

Owners are asking their designers for more environmentally friendly options as they seek to manage flood risk. The use of HPTRM reinforced vegetation has been proven in full scale wave overtopping tests and is an environmentally and cost effective alternative to traditional hard armor solutions for adding resilience to earthen flood defense structures. The proper selection of an HPTRM, shown through research by the USACE and CSU, should be based on hydraulic laboratory testing, percent light penetration, and tensile strength of the HPTRM. All HPTRMs are not the same and a significant difference in performance was seen to be related to the percent light penetration of the HPTRM. HPTRMs with smaller percent light penetration improves performance in hydraulic testing, regardless of whether the vegetation is established from seed or turf and does so without inhibiting vegetation establishment. Smaller light penetration HPTRMs relative performance was seen in both clay and sand soils. Understanding this performance difference will be important for projects in arid climates where vegetation densities greater than 30% cannot be guaranteed. The US EPA has established the use of vegetation as one of the best way to remove pollutants from storm water runoff. More research is required to quantify the total percent reduction in carbon emissions by using HPTRM reinforced vegetation, but initially the total reduction in the number of lorries required to service a HPTRM project is significant enough to influence its selection over traditional hard armor methods. Additionally, the installed costs of the HPTRM system is at least half that of traditional hard solutions. Given these monetary and environmental cost savings, governments around the world will increasingly require the evaluation of HPTRM reinforced vegetation for flood control projects.

References

ASTM D6567-17, Standard Test Method for Measuring the Light Penetration of a Rolled Erosion Control Product (RECP), ASTM International, West Conshohocken, PA, 2017, www.astm.org

Environment Agency (2016) Carbon planning tool, Bristol, England: Environment Agency.

Jones, P., Keating, K. and Pettit, A. (2015). Cost estimation for channel management – summary of evidence, Bristol, England: Environment Agency.

Federal Highway Administration (FHWA) (2003). Standard Specifications For Construction of Roads and Bridges on Federal Highway Projects, WASHINGTON: United States Department of Transportation.

Rickard, C. (2010). Fluvial Design Guide, Floodwalls and flood embankments, Bristol, England: Environment Agency.

Schleifstein, M. (2014). Corps of Engineers to buy 703 football fields of sod to 'armor' New Orleans area levees, New Orleans: The Times-Picayune.

Scottish Environmental Protection Agency (SEPA) (2008) Engineering in the Water Environment, Good Practice Guide Bank Protection: Rivers and Lochs. Scottish Environmental Protection Agency, Scotland.

Sphat, S. (2012a). Task Force Hope Status Report Newsletter: Armoring Pilot Project now underway. United States Army Corps of Engineers, New Orleans.

Sphat, S. (USACE) (2012b). Task Force Hope Status Report Newsletter: Corps completes successful levee armoring test. United States Army Corps of Engineers, New Orleans.

Texas Transportation Institute (TTI) (2001). Final Performance Analysis - Through the 2001 Evaluation Cycle. Texas Department of Transportation, Austin, TX.

Thornton, C., Hughes, S., Scholl, B., and Youngblood, N. (2012) Full-Scale Wave Overtopping Tests of Propex Turf Reinforcement Mats for Levee Landward-Side Slope Stability. Colorado State University, Fort Collins, Colorado.

Thornton, C., Hughes, S., Scholl, B., and Youngblood, N. (2014) Estimating Grass Slope Resilience During Wave Overtopping: Results from Full-Scale Overtopping Simulator Testing. 34th Conference on Coastal Engineering, Seoul.

United States Army Corps of Engineers (USACE) (2016). 2016 USACE Resilience Initiative Roadmap. United States Army Corps of Engineers, Washington.

United States Environmental Protection Agency (EPA) (1999). Storm Water Technology Fact Sheet Vegetated Swales (832-F-99-006). United States Environmental Protection Agency, Washington.