Protections 2016
2nd International Seminar on
Dam Protection Against Overtopping
ISBN: 978-1-1889143-27-9 DOI:

Ft. Collins, Colorado, USA, 7-9 September 2016

Using an Innovative Revetment for Overtopping Protection of Levees and Dams

B.H. Cooley[1] and C. Thornton[2]
[1]Vice President of Civil Applications
Watershed Geosynthetics LLC
Alpharetta, GA 30022
USA
[2]Engineering Research Center – Hydraulic Laboratory
Colorado State University
Fort Collins, CO
USA
E-mail: bcooley@watershedgeo.com

ABSTRACT

This paper focuses on the tufted-geosynthetic revetment system (TGRS), and its performance for levee and dam overtopping. The TGRS is an innovative technology developed to be a permanent revetment system which resists significant hydraulic forces. It is a flexible, fiber-reinforced concrete revetment consisting of a high-friction geomembrane overlain by engineered turf which is infilled with a high strength concrete.

Extensive full-scale testing was performed on the TGRS at Colorado State University (CSU). Steady state evaluations included testing the performance under the following conditions: the intact system, impact and abrasion from heavy debris loads, intentionally damaged state, and hydraulic jump. Unsteady state testing was performed in the wave overtopping simulator in accordance with the testing methodology developed for the US Army Corps of Engineers. The installed system was evaluated under intact and intentionally damaged conditions. The TGRS performed exceptionally well in maintaining the underlying, highly-erodible subgrade soils during severe steady and unsteady hydraulic forces. Also, consideration of non-hydraulic stresses is important when assessing the performance of the TGRS. These include aerodynamic testing under hurricane force winds, weathering tests and functional longevity, and flammability testing.

This paper will introduce the TGRS and its different components. The procedures and results of the extensive full-scale testing performed at CSU will be presented. The testing and results for the non-hydraulic stress evaluations will be discussed. Also, a factor of safety methodology for designing with TGRS will be introduced.

Keywords: *overtopping, levee, dam, revetment, hydraulic, armoring.*

1. INTRODUCTION

The tufted-geosynthetic revetment system (TGRS) is a unique and innovative revetment system. The system is a fiber-reinforced, flexible concrete consisting of a high-friction, impermeable geomembrane layer overlain by an engineered-synthetic turf. The turf is then infilled with a high strength (5000 psi) cementitious mix. The turf fibers provide additional structural reinforcement for the infill and add an aesthetic natural look and feel. The system is secured to the subgrade with the “spikes” of the geomembrane and is secured on the upstream, downstream, and lateral edges with anchor trenches. A cross section of the TGRS is shown in Figure 1.

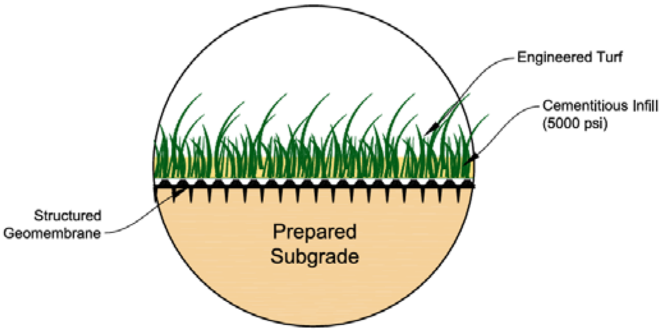


Figure 1. Section of Tufted-Geosynthetic Revetment System (TGRS)

TGRS was developed as an engineered revetment for use in preventing erosion for the following applications:

- Wave Overtopping on the Landward Side of Levees and Embankments;
- Overtopping and Spillway Protection of Dams;
- Lining of Channels, Steep Downchutes, Swales, and Canals; and
- Shoreline Protection within Basins, Impoundments, Lakes and Reservoirs.

TGRS has unique benefits over other revetment systems. These include the aesthetics of vegetation; exceptional hydraulic performance; minimal maintenance; smaller carbon footprint; low impact, rapid and scalable installation; and lower installed construction cost. Extensive performance testing has been performed on the TGRS, and this testing is presented in the remainder of this paper.

2. PERFORMANCE TESTING OF TGRS

2.1. Full-Scale Steady-State Overtop Testing

Full-scale, steady-state overtop testing was performed at Colorado State University – Engineering Research Institute (CSU). This testing was performed in accordance with ASTM D 7277 – Standard Test Method for Performance Testing of Articulated Concrete Block (ACB) Revetment Systems for Hydraulic Stability in Open Channel Flow. The results of the testing were analyzed in accordance with ASTM D 7276 - Standard Guide for Analysis and Interpretation of Test Data for Articulating Concrete Block (ACB) Revetment Systems in Open Channel Flow.

Testing of the TGRS occurred in April 2013 and September 2015. For both tests, the TGRS was installed in the flume over a sandy-loam compacted subgrade in general accordance with Watershed Geosynthetics' installation guidelines. The flume is 4-ft wide and is sloped at a 2H:1V. The geomembrane was placed over the soil subgrade. It was sealed with silicon caulk on the edges of the flume but was not physically restrained. The engineered turf was installed on top of the geomembrane. The engineered turf was attached to the sides of the flume with angle iron. Both the geomembrane and engineered turf were placed in such a way that the system was able to move, lift, and/or deform A horizontal (cross-flume) seam was placed in the synthetic turf layer near the bottom of the flume for both tests. The purpose of the seam was to test its strength under high flow velocity and shear stress conditions. Lastly, ¾-in of the cementitious infill was placed and brushed into the turf, and then it was hydrated. The completed installation of system is shown in Figure 2.

The TGRS was tested at 1.5, 3.0, and 5.0-ft steady-state overtopping depths for a total of 12 hours in April 2013 and at 1.5, 5.0, and 5.5-ft depths for a total of 12 hours in September 2015. Figure 3 shows a picture of testing at the 5.0-ft overtopping depth. After the completion of each overtopping event during both tests, bed elevation measurements were performed. Also, a detailed visual inspection of the TGRS and embankment flume was completed. The TGRS was examined for material damage, loss of turf and/or infill, cracked infill, lifting or deformation of the material, and/or any other changes to the system caused by the hydraulic testing. Based upon the bed measurements and the visual inspection, there was no deformation or lift of the system, no loss of intimate contact with the soil subgrade, and no damage to the system. The system and underlying soil were determined to be intact. Additionally, during the overtopping flows, there was no observed disturbance of the water surface further indicating that there was no deformation or lift of the TGRS. CSU calculated the velocity on the system using the methodology in ASTM D 7276. They reported stable performance values for velocity of 29.2 fps in the April 2013 test and 40 fps in the September 2015 test. Because no instability, deformation, loss of intimate contact or damage to the system occurred, and no erosion of the underlying subgrade occurred; these values of velocity are not maximum performance thresholds. They are the maximum capacity of the flume under the specific test conditions. The results of the full-scale flume testing are repeatable and demonstrate that the TGRS is capable of resisting extreme velocity. A summary of these results is shown in Table 1.

Figure 2. Installed TGRS

Figure 3. 5-ft Overtop Steady State Testing of TGRS

Table 1. Summary of the Steady-State Overtop Testing of the TGRS

Test Date	Overtop Depth ft (m)	Test Duration (hr)	*Q* cfs (cms)	Embankment Length ft (m)	Manning's "*n*" Value	Velocity fps (mps)
April 2013	1.5 (0.46)	4.0	20 (0.57)	30 (9.1)	0.017	21.4 (6.5)
April 2013	3.0 (0.91)	4.0	52 (1.47)	30 (9.1)	0.018	26.3 (8.0)
April 2013	5.0 (1.52)	4.0	117 (3.31)	30 (9.1)	0.020	29.2 (8.9)
Sept 2015	1.5 (0.46)	4.0	20 (0.57)	60 (18.3)	0.025	18.0 (5.5)
Sept 2015	5.0 (1.52)	4.0	119 (3.37)	60 (18.3)	0.021	37.0 (11.3)
Sept 2015	5.5 (1.68)	4.0	140 (3.96)	60 (18.3)	0.018	40.0 (12.2)

2.2. Hydraulic Jump Testing

Since there is no standard test method for measuring hydraulic jump, CSU developed a test program that would quantify the performance of the TGRS under a series of hydraulic jumps. A manually operated vertical sluice gate was installed approximately 22 feet from the top of the embankment in order to create a hydraulic jump on the TGRS. The TGRS extended beyond the gate by approximately 10-ft. The TGRS was not anchored at the bottom of the flume. It was just terminated with no anchor. A longitudinal section of the TGRS in the flume for the hydraulic jump test is shown in Figure 4. This gate was set so that it created the jump on the lower third of the TGRS installation in the flume. A test consisted of at least 1.5 hours of continuous flow at each discharge interval 1.5, 3.0, and 5.0-ft overtopping depths. Measurements of water surface were taken at the gate, at the beginning of the jump and at approximate 2-ft intervals upstream along the centerline of the slope. After at least 30 minutes of flow for a specific hydraulic jump, the sluice gate was adjusted to move the jump upstream. The procedure was repeated to collect data for three (3) hydraulic jumps at each overtop depth. Photograph of the Hydraulic Jump Testing is shown in Figure 5.

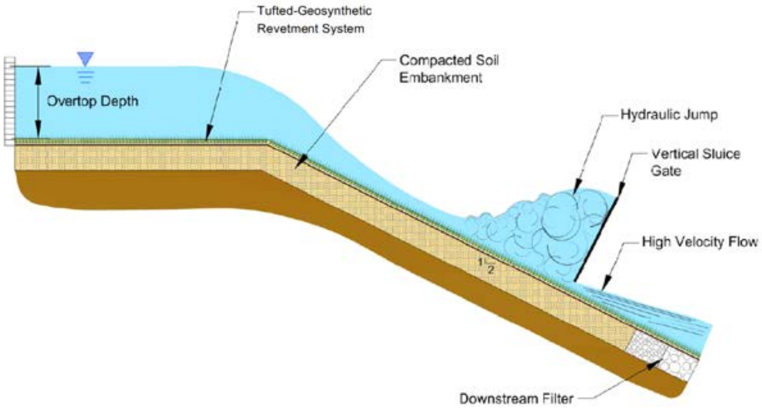


Figure 4. Longitudinal Section of the TGRS in the Flume for Hydraulic Jump Testing

Figure 5. Hydraulic Jump Testing of TGRS

The objective of the hydraulic jump test program was to quantify the performance of TGRS under the hydraulic loading caused by a range of hydraulic jumps at various overtopping depths. A performance threshold was not reached because there was no instability, deformation, loss of intimate contact, or damage of the TGRS System, and because there was no erosion of the underlying soil subgrade. However, a relationship between the energy lost in the jump and the ratio of the upstream and downstream Froude numbers was developed. This relationship is shown in Figure 6. Also, power dissipation was calculated for each hydraulic jump interval, and plotted as a function of specific energy upstream of the jump (See Figure 7). The TGRS System demonstrated the ability to withstand turbulent loading caused by hydraulic jumps dissipating as much as 30 horsepower per foot of width.

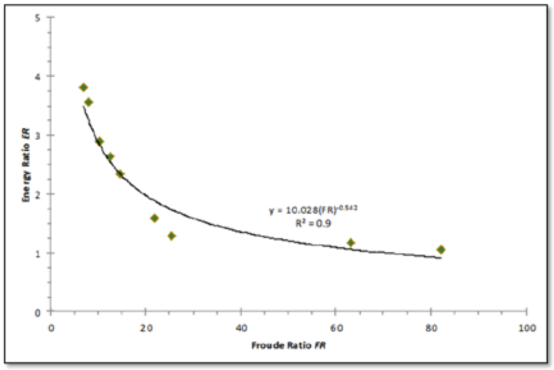


Figure 6. Envelope Curve for Energy Ratio as a Function of Froude Ratio

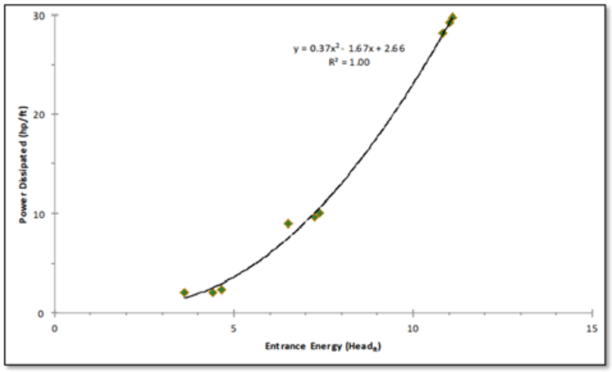


Figure 7. Power Dissipation per Foot of Width as a Function of Specific Energy at the Entrance to the Hydraulic Jump

2.3. Heavy Debris Loads

After the hydraulic jump testing was complete, an evaluation was performed to simulate heavy debris loads in June 2013. The purpose of this test was to qualitatively assess the resilience of the TGRS to impact and abrasion from large debris. The flow in the flume was brought to an overtopping depth of 5.0-ft. A Bobcat S850 front-end loader was filled with broken, angular concrete blocks ranging from approximately 3 to 15 inches in diameter. The front-end loader dumped two (2) full buckets of concrete debris into the flume at the top of the embankment from a height of approximately 12 ft (See Figure 8). The concrete debris caused a few minor surface impressions at the location of the 12-ft drop. The integrity of the TGRS System was not compromised. Also, there was no observed damage to the system downstream of the drop location. No instability, loss of intimate contact, or erosion was observed.

Figure 8. Broken Concrete Being Dumped into the Flume

2.4. Intentionally Damaged State

The next test was designed to evaluate the qualitative performance of the TGRS System in a damaged state. A pickaxe was intentionally driven through the TGRS and approximately 6-in into the underlying sandy-loam subgrade. This hole was located approximately 15-ft down from the embankment crest. Flow discharges were run at the 3.0-ft and 5.0-ft overtopping depths for the duration of 1 hour at each depth interval. During the testing, it was observed that there was no instability, loss of intimate contact, or discernible erosion. After the testing, the TGRS was inspected. It was noted that the hole was still intact and did not further unravel. Also, there was no erosion of the subgrade at the location of the hole, and the hole closed in. The condition of the hole and the subgrade under the hole are shown in the photographs of Figure 9. The velocity was calculated at the location of the hole in the flume to be 24.4 fps. The TGRS performed well after being subjected to puncture damage.

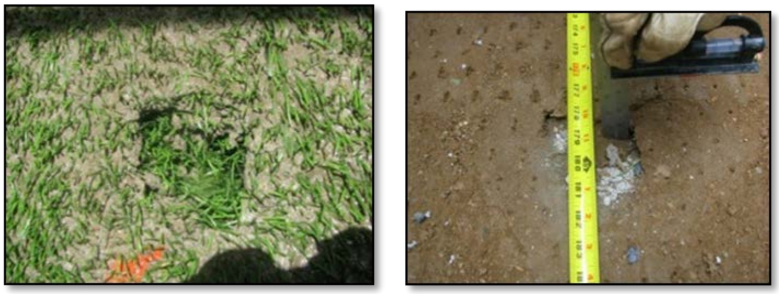


Figure 9. Intentional Damage: Hole from Pick Axe (After Testing)

2.5. Wave Overtop Testing for Levee Landward Side Slope Protection

Full-scale Wave Overtopping Tests for Levee Landward Side Slope Protection were performed on TGRS at CSU. Testing was performed in accordance with the methodology developed for the US Army Corps of Engineers. The TGRS Revetment System was installed in the flume over a highly-erodible silty sand subgrade on the 3H:1V slope that transitions to a 25H:1V slope at the toe. It was installed with a downstream seam down the centerline of the tray in order to evaluate the strength of the seam made between two adjacent panels of the synthetic turf component. The seam was sewn together using a similar machine and methodology as used for field installations.

Testing of the TGRS Revetment System was conducted in four (4) phases. The first phase tested the intact TGRS up to the limits of the Wave Overtopping Simulator. Figure 10 shows testing of the TGRS. At the completion of the first phase, the installed and tested TGRS was intentionally damaged before continuing with further testing. The intentional damage (Phases 2 –4) was to simulate conditions that might exist after a number of years of service without maintenance. This intentional damage consisted of the following:

Figure 10. Wave Overtop Testing

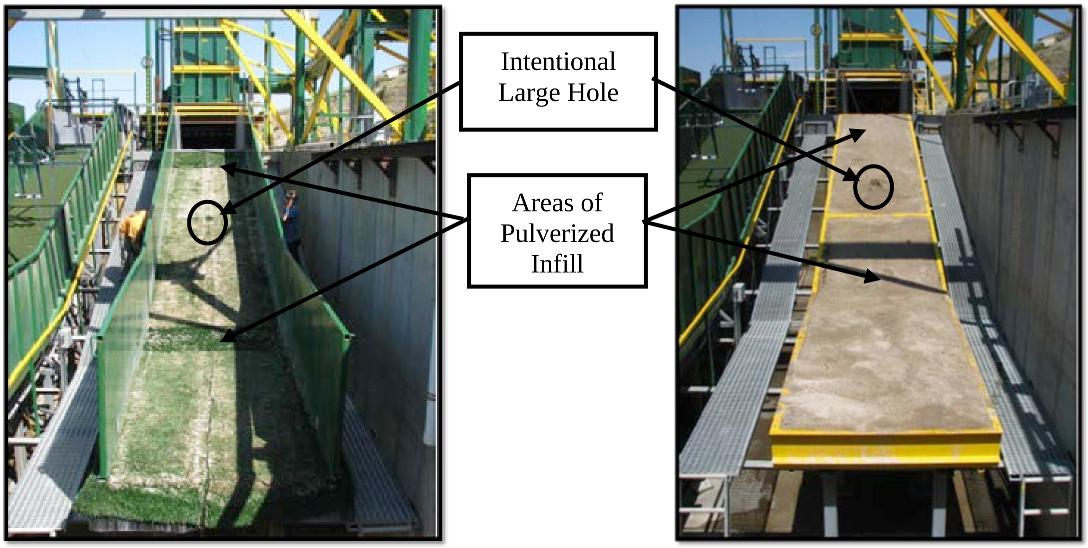
- Phase 2 - Pulverization of the hardened cementitious infill in order to simulate cracked mortar and portions of the surface that had been severely damaged. (See Figure 11)
- Phase 3 - A bullet hole was simulated by driving rebar through the TGRS into the underlying sandy subgrade. (See Figure 11)
- Phase 4 - A larger hole was created using a pick axe to expand the simulated bullet hole. This larger hole was approximately 4-inch diameter and 7-inches deep into the subgrade. (See Figure 11)

Figure 11. Intentional Damage to the TGRS: Pulverization, Simulated Bullet Hole, and Large Hole

The TGRS Revetment System withstood the largest wave overtopping flows of 4 $ft^3/s/ft$ that could be applied by the CSU Wave Overtopping Simulator. These flows are the most energetic wave overtopping conditions that can be produced in any existing wave overtopping experimental facility. They represent a generic 500-year hurricane (0.2

percent annual exceedance probability) in New Orleans, LA. The testing continued for a total of 13 hours with TGRS being subjected to 165,600 ft^3/ft of cumulative water volume.

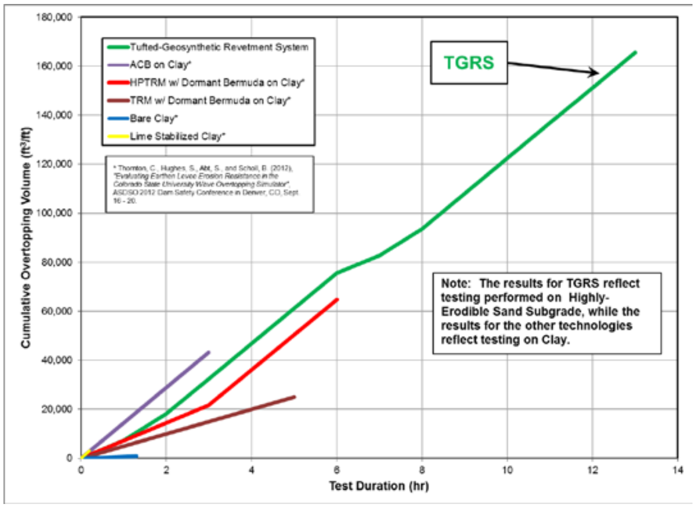
Upon completion of the tests, the TGRS was inspected to document the condition of the system. Then the TGRS was removed to document the condition of the underlying sand subgrade. The TGRS Revetment System performed well in maintaining the underlying, highly-erodible soils during these severe conditions, even in an intentionally damaged state. It should be noted that in the area of the large hole, which went through the system and into the subgrade, there was no head-cutting and very little erosion downstream of the hole. Figure 12 is a photograph of the condition of the TGRS System after the 13 hours of testing. Also, the photograph in Figure 12 shows the condition of the highly-erodible, silty sand subgrade which was underneath the TGRS.


Intentional Large Hole

Areas of Pulverized Infill

Figure 12. Condition of TGRS System and Soil Subgrade after Completion of Wave Overtopping Testing

The performance of TGRS in the wave overtopping simulator can be compared to the performance of other erosion control technologies tested in the same simulator. The graph in Figure 13 shows a comparison of armoring performance for levee landward-side protection for various technologies which have been tested in the CSU Wave Overtopping Simulator. TGRS outperformed these other systems by more than double. Also, note that the subgrade used for the other technologies was clay while the subgrade for the TGRS was highly-erodible silty sand.



* Thornton, C., Hughes, S., Abt, S., and Scholl, B. (2012), *"Evaluating Earthen Levee Erosion Resistance in the Colorado State University Wave Overtopping Simulator"*, ASDSO 2012 Dam Safety Conference in Denver, CO, Sept 16 - 20.

Note: The results for TGRS reflect testing performed on Highly-Erodible Sand Subgrade, while the results for the other technologies reflect testing on Clay.

Figure 13. Performance of Various Revetments for Levee Landward-Side Protection from Wave Overtopping

2.6. Aerodynamic Evaluation

TGRS will withstand high winds and not be lifted, dislodged or damaged. TGRS has features that help mitigate the forces of wind. These include a porous surface to break the vacuum, and turf blades that will increase the aerodynamic boundary conditions and react against the wind causing a resistance to the uplift component. Also, the infill of TGRS is cemented so it will not be dislodged.

In order to quantify these features, the TGRS System was evaluated in the Subsonic Model Test Facility Wind Tunnel at the Georgia Tech Research Institute (GTRI). Testing was performed to evaluate the aerodynamic properties and ballast requirements (infill thickness). The material was tested under two (2) different configurations - a perimeter condition (up to 18-in from the edge of the installation) and an interior condition (beyond 18-in from the edge). Wind speeds were increased up to 170 ft/s (approximately 120 mph). Figure 14 shows the test at 170 ft/s (120 mph). At velocities greater than 110 ft/s there is a downward force and not a lift force on the TGRS. During the hydraulic testing at CSU, a similar downward force was observed since there was no lift of the system even when punctured with a hole.

Based on these hurricane force wind speeds, the minimum infill ballast requirements are 0.40-in for the perimeter condition and 0.038-in for the interior condition. Since TGRS has a recommended cementitious infill thickness of ¾-in, it will resist wind speeds greater than 170 ft/s (120 mph) when properly designed, constructed, and maintained.

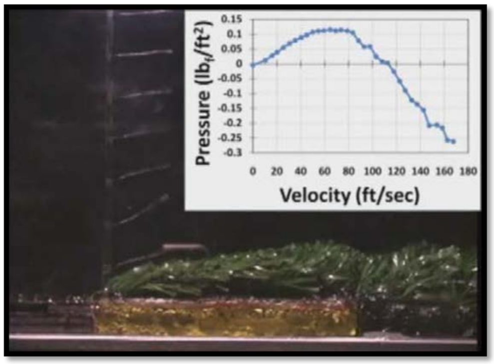


Figure 14. Aerodynamic Evaluation of TGRS at GTRI

Figure 15. Wind Gust Evaluation of TGRS at Vigyan

In addition to the testing that was performed at GTRI, wind gust testing was performed at Vigyan Laboratories. The synthetic component of the TGRS (no infill) was installed in Vigyan's wind tunnel (see Figure 15). The starting wind speed was approximately 26 mph. Then it was subjected to a wind gust with the top speed being attained in 2 to 3 seconds. The maximum top speed for the gusts was approximately 110 mph. 22 test runs were performed. The turf did not lift or pull away. It remained in place for the 22 test runs.

2.7. Weathering and Functional Longevity

TGRS is comprised of three (3) components – structured geomembrane, engineered synthetic turf, and high strength cementitious infill. In order to evaluate the longevity of the system, we evaluate the longevity of its three (3) components. This evaluation is as follows:

2.7.1. Structured Geomembrane

The structured geomembrane in TGRS is manufactured from polyethylene. The longevity of high density polyethylene (HDPE) geomembranes has been extensively evaluated for many years by the Geosynthetics Institute (GSI). In Keorner (2011), he projects that the half-life of a covered HDPE geomembrane is 445 years at an average annual temperature of 68 deg F (20 deg C). The structured geomembrane of the TGRS system has similar properties to the geomembranes researched by GSI, and therefore, it is projected to have a similar longevity of hundreds of years.

2.7.2. Engineered Synthetic Turf

The engineered synthetic turf fibers with the cementitious infill is the protection layer of the TGRS System. These components shield the underlying backing geotextiles and geomembrane from exposure. The synthetic turf yarns are the only synthetic component of the system that is directly exposed to the elements, specifically ultraviolet light (UV). Weathering tests of these yarns have been performed in accordance with ASTM G147 and G7 at Atlas Material Testing Laboratories in New River, AZ. Samples were exposed to direct UV by fastening them to a panel which faces south at a 45-degree angle.

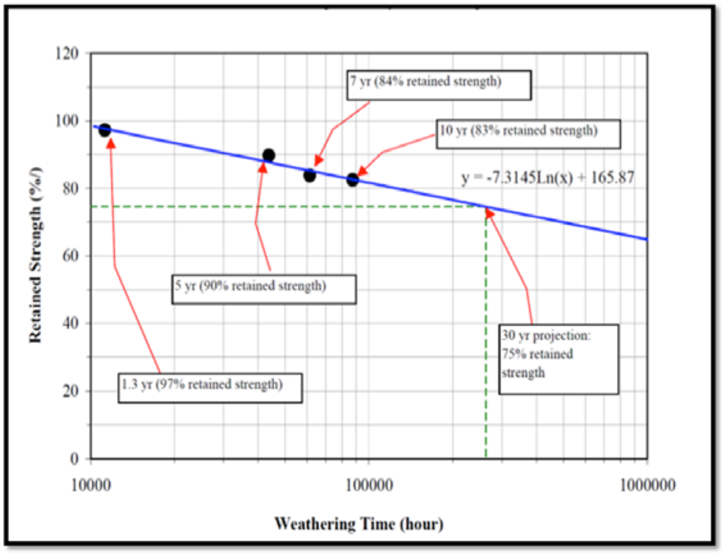


Figure 16. Retained Tensile Strength of Synthetic Turf Fibers vs. Weathering Exposure Duration

The samples were exposed for a given period and then the retained tensile strength was measured. To date, four (4) samples have been tested for the exposure periods of 1.3, 5, 7, and 10 years. The retained tensile strength at these exposure periods is 97.2%, 89.7%, 83.8%, and 82.5%, respectively. Retained tensile strength was plotted against exposure duration as shown in Figure 16.

A logarithmic line was fit to the four (4) points and extrapolated out to 1,000,000 hours. At 100 years (876,000 hours), the retained tensile strength of the synthetic turf yarn is projected out to approximately 65%. At 65% retained tensile strength, it will continue to function as designed and provide reinforcement for the infill, protection of the geotextile backing layers, and protection of the underlying geomembrane. Therefore, it can be projected that the engineered synthetic turf fibers will have a 100+ year functional longevity.

2.7.3. Cementitious Infill

As a rule of thumb, the American Concrete Institute (ACI) provides an average service life for reinforced (with steel) concrete of 75 years with a typical range between 50 and 100 years. The infill of the TGRS is a high-strength (5000 psi), cementitious concrete mortar which is reinforced with polyethylene fibers. These polyethylene fibers will not degrade / corrode in the applications where TGRS is used. Concrete with reinforcing steel will be more susceptible to degradation / corrosion in these applications. Therefore, the infill is conservatively predicted to have longevity of at least 50 years, if not up to 100 years, depending on exposure and environments.

It should also be noted that the cementitious infill is similar to a road repair mix which is formulated to be used as an overlay for patching, leveling, filling, repairing and topping concrete surfaces. On account of this, the HydroBinder is easily maintained, patched and repaired should it be damaged or degraded.

2.7.4. Summary of TGRS Longevity

The longevity of each of the components of TGRS is summarized as follows:

- Structured Geomembrane – 445 years to Half Life
- Engineered Synthetic Turf - 100 years to 65% Retained Strength
- Cementitious Infill – 50 to 100 years for Reinforced Concrete

Therefore, based on the longevity of each of the components of TGRS, it can be conservatively estimated that the TGRS System will have at least a 50-year functional longevity, if not up to 100 years. As with any engineered system, in order to achieve its maximum functional longevity, it is suggested that the TGRS system be properly maintained.

2.8. Flammability

The TGRS system was tested for surface flammability in accordance with ASTM D 2859 - Standard Test Method for Ignition Characteristics of Finished Textile Floor Covering Materials. This is the standard test method that is required by U.S. Consumer Product Safety Commission for Carpets and Rugs.

Eight (8) 12-in by 12-in samples of TGRS with cementitious infill and eight (8) 12-in by 12-in samples of TGRS without infill (engineered turf only) were prepared for testing. They were first preheated to dry them out. Then, a metal frame was placed over them. The metal frame has an 8-in diameter opening.

An ignition source (methenamine solid fuel tablet) was placed in the center of the sample. The methenamine tablet was then lit. It burned for approximately 2 minutes. After the flame had self-extinguished, the propagation of the flame was measured from the edge of the 8-in diameter metal frame. The criteria for a passing test is that the flame must self-extinguish before reaching a distance of 1-in from the frame in seven (7) out of the eight (8) samples tested.

Both the TGRS with cementitious infill and the TGRS without the infill (engineered turf only) passed this flammability test. The TGRS without the infill was evaluated as a worst case scenario. Pictures of one of the samples after testing are shown in Figure 17.

Figure 17. TGRS Sample after Flammability Testing

3. FACTOR OF SAFETY DESIGN METHODOLOGY

Using the results of the steady state overtop testing, one can calculate a factor of safety related to flow velocity in an overtopping event on the TGRS. Current industry standards incorporate only shear stress in factor of safety calculation methodologies. Although, evaluations of test results across numerous products show that velocity is a more appropriate indicator of system performance. While many discrete particle-based systems can utilize an overturning moment analysis for incipient motion, this method is not appropriate for continuous systems such as the TGRS.

As described in Section 2.1, CSU performed steady state overtop testing of the TGRS in accordance with ASTM D7277 in April 2013 and September 2015. The calculated results of this testing show that the maximum value of velocity for the TGRS is 40 fps. While the system did not reach its performance threshold, the maximum value of velocity quantified during testing can be considered critical design value. Erosion protection systems that are continuous surfaces are not susceptible to instability due to shear stress being applied parallel to the surface. However, the force of lift as generated from flow velocity can result in the revetment system being lifted into the flow field and potentially dislodged. Assuming that the density of water and coefficient of lift of the TGRS system are constant, the lift generated during the 2015 tests can be calculated. Comparing the lift generated at a critical velocity of 40 fps with values of lift computed at incremental velocities produces the relationship shown in Figure 18. Site specific flow conditions can be evaluated and compared to the relationship quantified in Figure 18 and a factor of safety computed.

It should be noted that the factor of safety relationship is conservative as it was developed with two major assumptions. First is that the value of 40 feet per second was the maximum capacity of the test facility and not a critical value since the TGRS system showed no signs of instability. Second, tests were conducted on a 2H:1V slope and no adjustment was made to recorded flow conditions. Realizing both these assumptions, applying the relationship shown in Figure 18 can therefore be assumed conservative when analyzed with slopes flatter than 2:1.

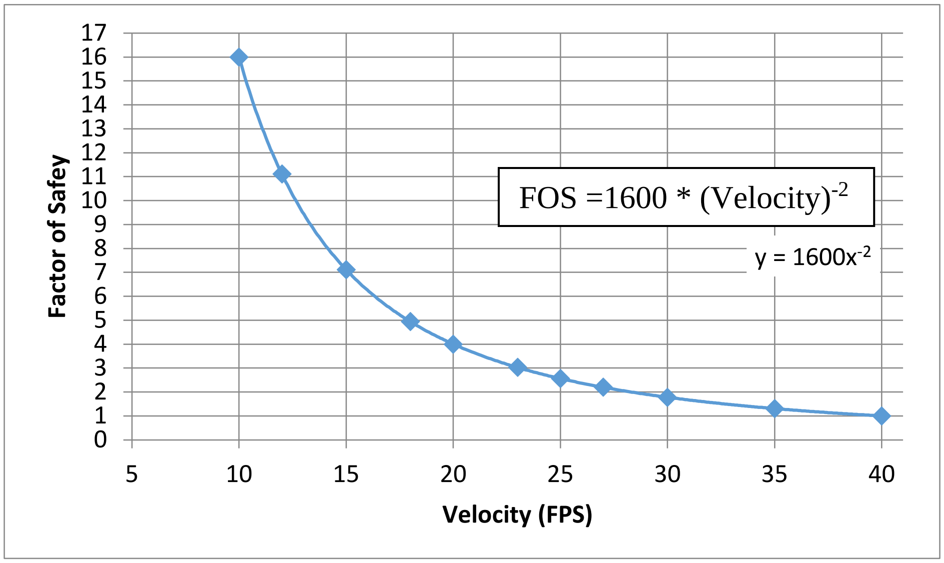


Figure 18. Factor of Safety for Overtopping Velocity on TGRS

4. SUMMARY AND CONCLUSION

The TGRS system is an innovative revetment technology which has use for protecting dams and levees from overtopping flows. It has been extensively tested for hydraulic performance at CSU in their full-scale facilities. CSU was not able to determine the performance threshold of the system prior to reaching the maximum of their flow and flume capacity. Testing included steady-state overtopping, hydraulic jump, unsteady wave overtopping, large debris evaluation, and intentional damage to the system (pulverized infill and puncture holes).

The steady-state overtopping was conducted in accordance with standard procedures for ACB revetment system testing. TGRS was tested in steady-state flow conditions for a total of 32 hours under various events. TGRS was able to withstand hydraulic loads resulting in a velocity exceeding 40 fps. The test program also demonstrated the ability of the system to withstand hydraulic loads caused by hydraulic jumps dissipating as much as 30 horsepower per foot of width. The qualitative tests demonstrated the capability for the TGRS system to withstand impact and abrasion caused by large debris, as well as to withstand damage associated with puncture. Instability or failure of the system did not occur, and erosion of the subgrade did not happen. Using the results of velocity from the steady state overtop testing, a methodology to calculate factor of safety was developed based on lift.

The unsteady wave overtopping tests were performed in accordance with the methodology developed for the US Army Corps of Engineers. The TGRS was able to withstand 13 hours of testing up to the maximum discharge of the simulator of 4 ft^3/s/ft for a cumulative overtop volume 165,600 ft^3/ft. This maximum discharge represents a generic 500-year hurricane (0.2 percent annual exceedance probability) in New Orleans, LA. The TGRS was tested under intact conditions and intentionally damaged conditions (pulverized infill, small hole, and large hole). Failure of the TGRS did not occur, and it protected the underlying, highly-erodible subgrade soil. A performance limit was not reached. TGRS outperformed other known revetment systems that have been tested in this wave overtop simulator.

Non-hydraulic evaluations have also been performed on the TGRS. These include aerodynamic testing, weathering and longevity, and flammability. The TGRS is able to withstand constant winds over 120 mph and wind gusts over 110 mph. The projected longevity of the system is conservatively estimated to be 50+ years. Lastly, the ignition source on the TGRS was did not propagate and was able to self-extinguish.

There are no known reports of other revetment technologies having undergone such an extensive testing program without system failure or subgrade erosion. The results of the hydraulic testing and the non-hydraulic evaluations of the TGRS system demonstrate that it is an appropriate technology for permanent revetment and armoring protection.

The TGRS can be used on numerous applications such as levees, dams, steep downchutes, outfall structures, and shorelines. Also, TGRS has several benefits over traditional revetment systems. These benefits include the aesthetics of vegetation; exceptional hydraulic performance; minimal maintenance; smaller carbon footprint; low impact, rapid and scalable installation; and lower installed construction cost.

5. ACKNOWLEDGMENTS

The authors would like to acknowledge and thank the individuals who have helped to develop and/or test the innovative TGRS Technology. These individuals include Michael Ayers, Jose Urrutia, Delaney Lewis, Steven Hughes, Brian Scholl, and Jason Berg.

6. REFERENCES

American Society for Testing and Materials (ASTM G7-13). “Standard Practice for Atmospheric Environmental Exposure Testing of Nonmetallic Materials”.
American Society for Testing and Materials (ASTM G147-09). “Standard Practice for Conditioning and Handling of Nonmetallic Materials for Natural and Artificial Weathering Tests”.
American Society for Testing and Materials (ASTM D 2859-15). “Standard Test Method for Ignition Characteristics of Finished Textile Floor Covering Materials”.
American Society for Testing and Materials (ASTM D7276-08). “Standard Guide for Analysis and Interpretation of Test Data for Articulating Concrete Block (ACB) Revetment Systems in Open Channel Flow”.
American Society for Testing and Materials (ASTM D7277-08). “Standard Test Method for Performance Testing of Articulating Concrete Block (ACB) Revetment Systems for Hydraulic Stability in Open Channel Flow”.
Henderson, F. M. (1966). “Open Channel Flow”, MacMillan Publishing Co., New York.
Koerner, R, G. Hsuan, and G. Koerner (2011), “GRI White Paper #6 – Geomembrane Lifetime Prediction: Unexposed and Exposed Conditions”, *Geosynthetics Research Institute, Philadelphia, PA, February 8.*
Thornton, C. I., Hughes, S., Abt, S., and Scholl, B. (2012), "Evaluating Earthen Levee Erosion Resistance in the Colorado State University Wave Overtopping Simulator", *ASDSO 2012 Dam Safety Conference in Denver, CO, Sept. 16 - 20.*
Thornton, C. I., Scholl, B. N., and Yaw, M.B. (2013). “Hydraulic Testing and Data Report for HydroTurf Revetment System,” *Engineering Research Center, Colorado State University, Fort Collins, Colorado*.