

TECHNICAL NOTE

FULL-SCALE HYDRAULIC TESTING OF THE HYDROTURF® ADVANCED REVETMENT TECHNOLOGY

Extensive independent, 3rd party hydraulic testing has been performed at Colorado State University – Engineering Research Center (CSU) in Fort Collins, CO on the HydroTurf® Revetment System. This technical note describes the full-scale testing that was completed. The information presented in this technical note is as follows:

- Introduction to HydroTurf® Revetment System
- Benefits
- Steady State Hydraulic Testing
 - Steady State Overtopping
 - Hydraulic Jump
 - Heavy Debris Loads - Assessment of Resilience to Impact and Abrasion
 - Assessment of Performance in an Intentionally Damaged State – Hole Created Using a Pick Axe
- Wave Overtopping Hydraulic Testing for Levee Landward-Side Slope Protection
- Assessment of Performance in an Intentionally Damaged State (Wave Overtopping)
 - Pulverized HydroBinder® Infill
 - Simulated Bullet Hole
 - Hole Created Using a Pick Axe

Non-hydraulic testing and evaluations have also been performed on the HydroTurf® System. This information is included in a separate Technical Note. Please contact Watershed Geosynthetics for this document.

INTRODUCTION TO HYDROTURF® REVETMENT SYSTEM

HydroTurf® was developed as an engineered revetment solution for use in preventing erosion in the following applications:

- Protection from Wave Overwash / Overtopping on the Landward Side of Levees and Embankments;
- Lining of Channels, Swales, Canals, and Spillways;
- Shoreline Protection within Basins, Impoundments, and Reservoirs; and
- Facings for Slopes and Mechanically Stabilized Earth Walls.

HydroTurf® is a unique flexible concrete erosion prevention solution consisting of a high-friction, impermeable geomembrane layer with an integrated drainage layer overlain by an engineered synthetic turf. The geomembrane is placed directly on the subgrade soil. It is covered with the engineered turf whose fibers provide reinforcement for the HydroBinder® cementitious infill. This infill is placed dry to a thickness of ¾-inch minimum. After placement, it is then hydrated with a light spray of water. A cross section of HydroTurf® is shown in Figure 1.

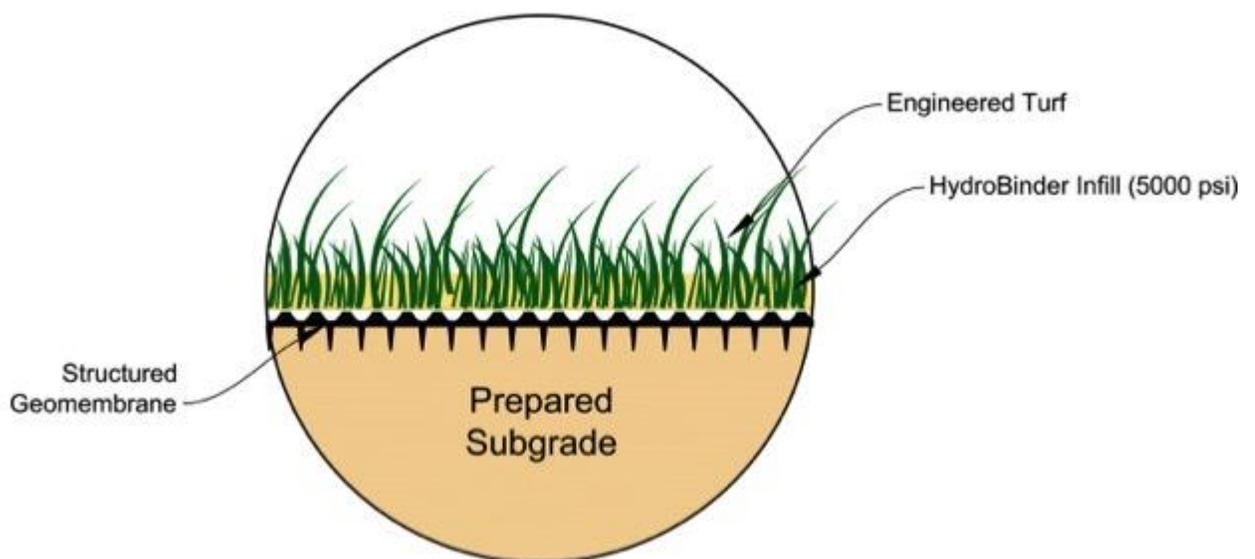


Figure 1 – Section of HydroTurf® Revetment System

BENEFITS

HydroTurf[®] has a number of benefits over other revetment solutions. These benefits include the following:

- ***Excellent Hydraulic Performance*** – HydroTurf[®] has been measured to have exceptional hydraulic performance over other hard armor revetment systems.
- ***50+ Year Functional Longevity*** – Through long term weathering tests, HydroTurf[®] is extrapolated to have a 50+ year functional longevity.
- ***Less Costly Construction*** – HydroTurf[®] is significantly less costly than hard armor revetment systems (i.e., concrete, rock riprap, and articulated concrete block (ACB)). The installed cost for HydroTurf[®] is typically up to 50% less than that for traditional hard armor systems.
- ***Rapid, Low Impact, and Scalable Construction*** – Construction and installation of the HydroTurf[®] System are rapid, low impact, and scalable. Only small, light construction equipment is needed to install the system. On large projects, one (1) experienced construction crew is able to install approximately 1 acre per day. Additional crews can be added to increase this rate. .
- ***Significant Long Term Maintenance Cost Savings*** – Vegetation management and erosion control are significant maintenance costs for Anchored Turf Reinforcement Mats (TRMs) products. Maintenance costs for these TRMs may be as high as \$1500/acre/year. HydroTurf[®] has minimal maintenance and will drastically lower long term maintenance costs.
- ***Reduction in Carbon Footprint*** - HydroTurf[®] has a significantly lower carbon footprint (1/4 to 1/8) than that of the other revetment solutions.
- ***Aesthetics*** – HydroTurf[®] looks and feels like natural vegetation.

STEADY STATE OVERTOP TESTING

CSU tested HydroTurf[®] 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.

HydroTurf® was installed in the flume in general accordance with Watershed Geosynthetics' installation guidelines. The flume is at a 2H:1V slope. First, a sandy-loam subgrade was compacted in place in the flume (See Figure 2). Next, a continuous sheet of the 50-mil structured geomembrane was placed with the "spike" side down (See Figure 3). This geomembrane serves as the underlayer of the system. Then, the engineered synthetic turf was placed on the geomembrane. A horizontal seam was placed in the synthetic turf layer near the bottom of the flume. The purpose of the seam was to test its strength under high flow velocity and shear stress conditions. This seam consists of two (2) sections of the synthetic turf which were heat-bonded together using similar equipment used for field installations. The next step in sample preparation was applying approximately a ¾-inch thick layer of dry HydroBinder® into the fibers of the synthetic turf. The dry mixture was placed using a drop spreader. It was broomed against the grain of the turf in order to pull the fibers up through the infill. The HydroBinder® infill was then hydrated by applying a light spray of water until saturation. The completed installation of the HydroTurf® System is shown in Figure 4.

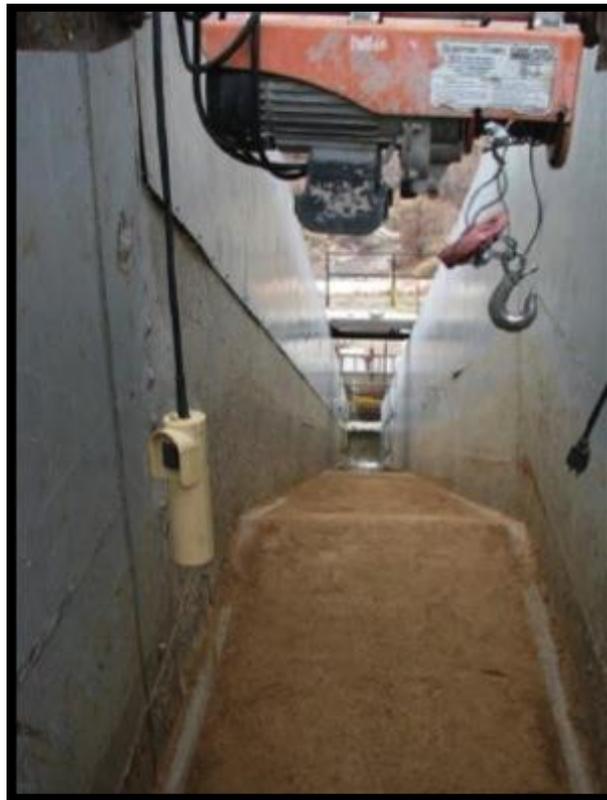


Figure 2 – Compacted Sandy-Loam Subgrade



Figure 3 – Installation of the Structured Geomembrane



Figure 4 – Completed Installation of the HydroTurf® System

The HydroTurf® was tested at 1.5, 3, and 5-ft steady-state overtop depths for a total of 12 hours. After testing, the embankment flume was inspected. The system and underlying soil were determined to be intact. CSU reported stable performance values of 29.2 fps for velocity. Since no instability, deformation, loss of intimate contact or damage to the system occurred, and since no erosion of the underlying subgrade occurred; this value of velocity is not a maximum performance threshold. A summary of these results is shown in Table 1. A profile of the testing section is shown in Figure 5, and photographs of the testing are shown in Figure 6.

Overtop Depth (ft)	Q (cfs)	Manning's "n" Value	Velocity (fps)
1.5	20	0.017	21.4
3	52	0.018	26.3
5	117	0.020	29.2

Table 1 – Results of Steady State Hydraulic Testing of HydroTurf®

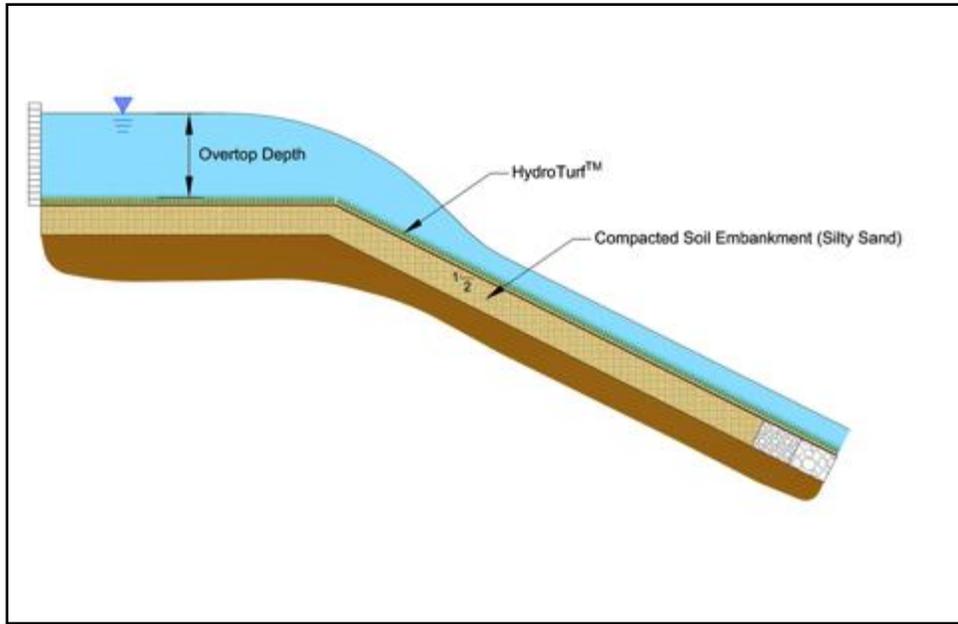


Figure 5 - Profile Section of the Installed HydroTurf® System in the Overtopping Flume



Figure 6 – Steady State Hydraulic Testing of HydroTurf® at CSU

The HydroTurf® performance value for velocity as measured in this steady state test is 29.2 fps at a 5-ft overtop depth. This value can be compared to the published maximum performance thresholds / permissible design values for various erosion and revetment technologies. This comparison shows that HydroTurf® outperforms these other systems (See Figure 7).

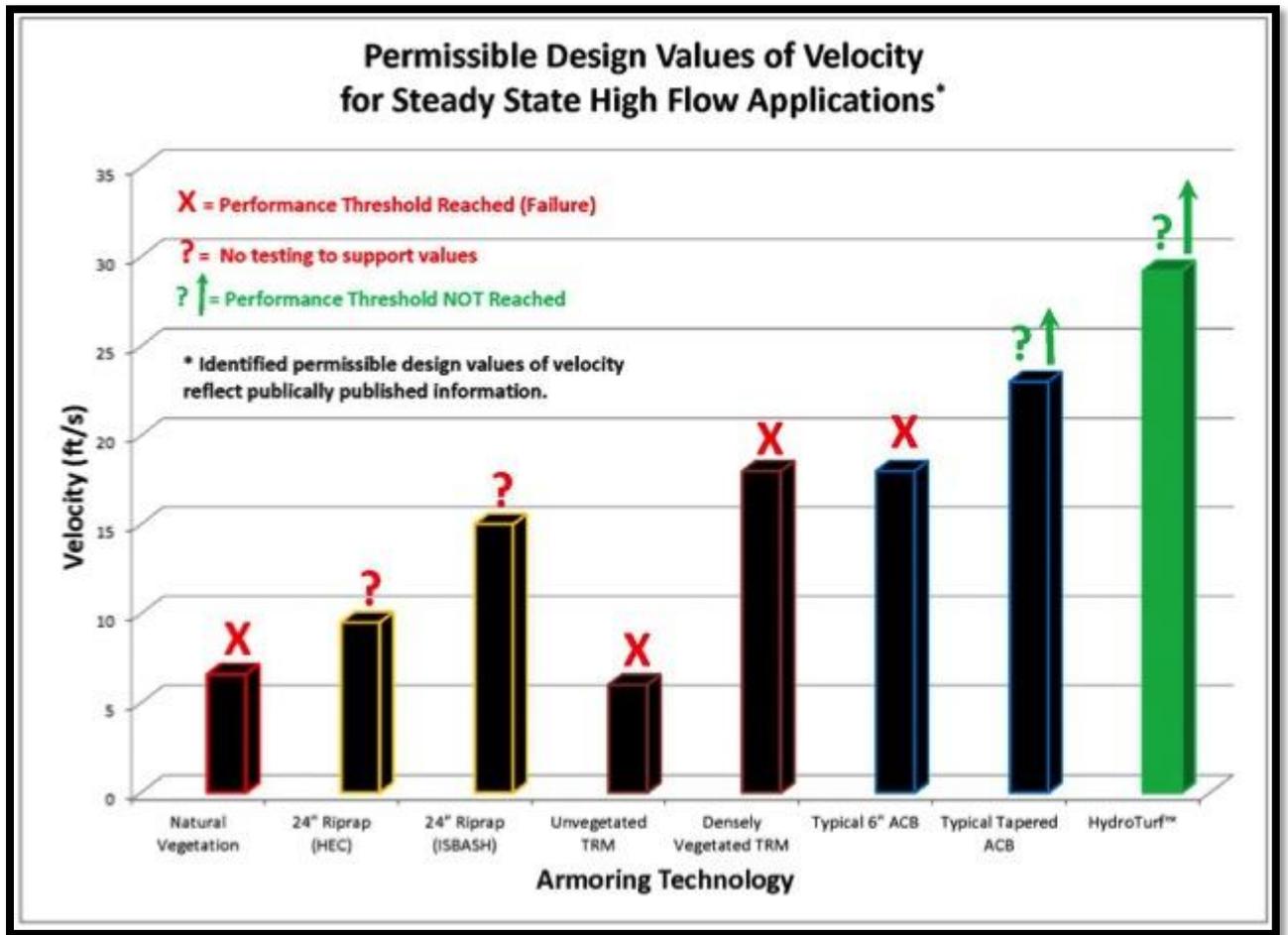


Figure 7 – Permissible Design Values of Velocity for Steady State High Flow Applications

Following completion of the first three (3) steady state tests, additional testing was performed on the same installed HydroTurf® material in the flume. This testing evaluated the performance of HydroTurf® to Hydraulic Jumps, Large Debris, and Intentional Damage. It is described in the following sections of the Technical Note.

Hydraulic Jump Testing - Since there is no standard test method for measuring hydraulic jump, CSU developed a test program that would adequately quantify the performance of the HydroTurf® 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 HydroTurf®. Figure 8 shows a picture of this sluice gate installed in the channel. This gate was set so that it created the jump on the lower third of the material in the flume. A profile section of the Hydraulic Jump test is shown in Figure 9.



Figure 8 – Sluice Gate Installed in Overtop Flume for Hydraulic Jump Testing

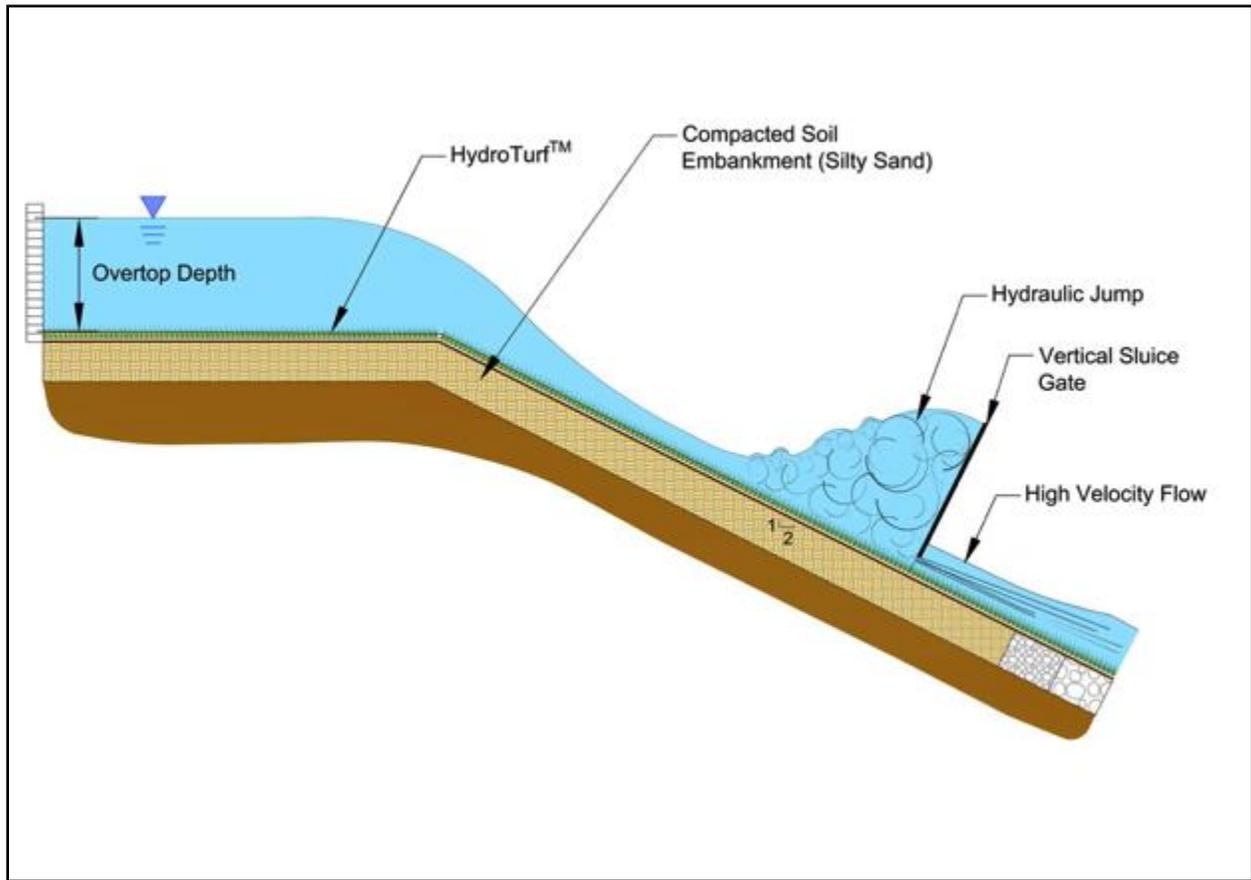


Figure 9 - Profile Section of the Installed HydroTurf® System in the Overtopping Flume for Hydraulic Jump Testing

A test consisted of at least 1.5 hours of continuous flow at each discharge interval (1.5, 3.0, and 5.0-ft overtop 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 under a 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. Photographs of the Hydraulic Jump Testing are shown in Figure 10.



Figure 10 – Hydraulic Jump Testing of HydroTurf® at CSU

The objective of the hydraulic jump test program was to quantify the performance of HydroTurf® under the hydraulic loading caused by a range of hydraulic jumps at various overtopping depths. A performance threshold was not reached since there was no instability, deformation, loss of intimate contact, or damage of the HydroTurf® system, and since there was no erosion of the underlying 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 11. Also, power dissipation was calculated for each hydraulic jump interval. It was plotted as a function of specific energy upstream of the jump (See Figure 12). The HydroTurf® System demonstrated the ability to withstand hydraulic loads caused by hydraulic jumps dissipating as much as 30 horsepower per foot of width.

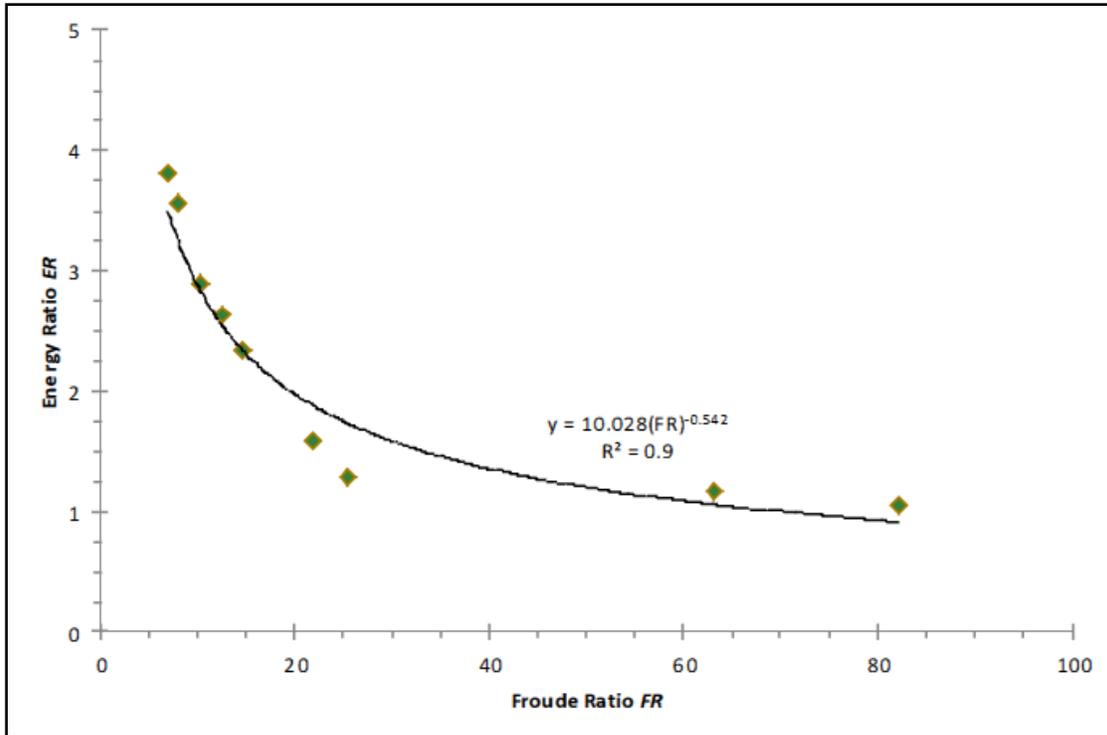


Figure 11 - Envelope Curve for Energy Ratio as a Function of Froude Ratio for HydroTurf®

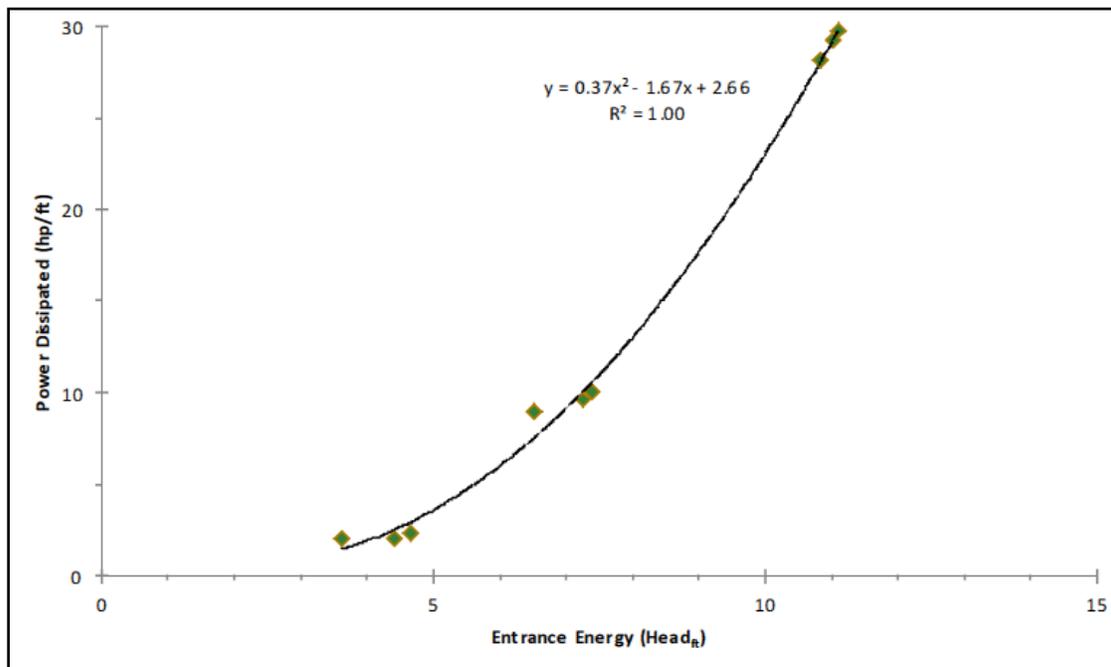


Figure 12 - Power Dissipation per Foot of Width as a Function of Specific Energy at the Entrance to the Hydraulic Jump for HydroTurf®

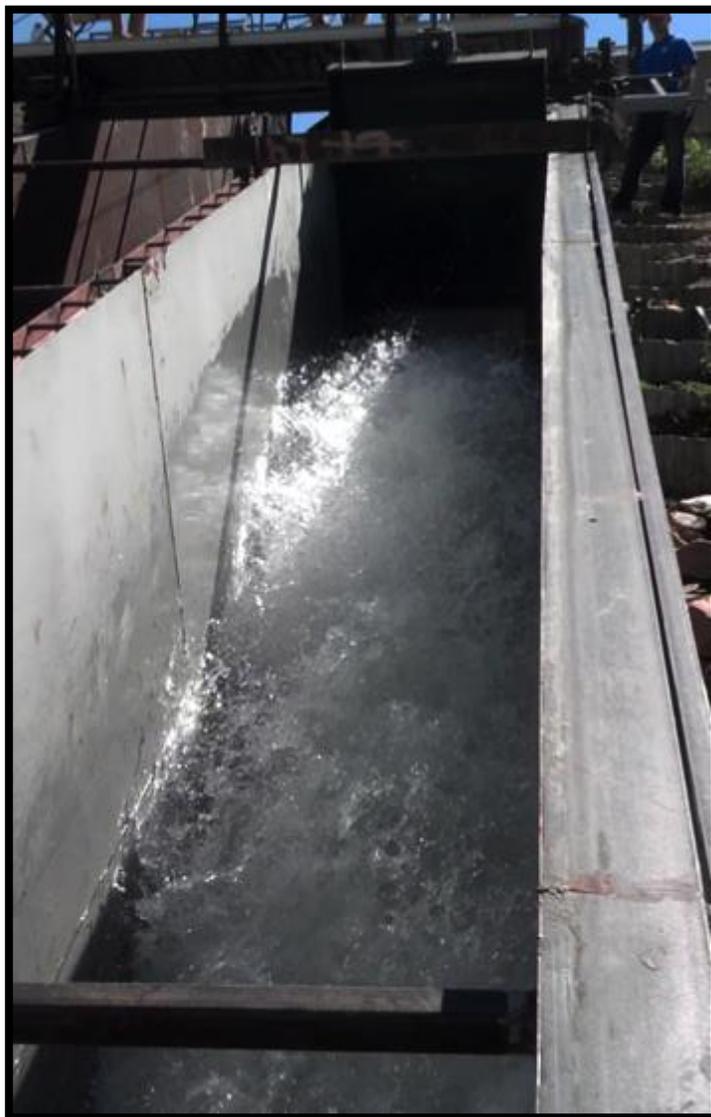


Figure 13 – Pressurized “Jet” from Under the Sluice Gate Surging onto the HydroTurf®

Since the sluice gate had a small opening at the base, the flow immediately downstream of it was a pressurized “jet” surging onto the HydroTurf® System. The extreme turbulence of the flow made it difficult to measure the velocity precisely, but the velocity of the jet of water exiting the hydraulic jump was approximately 35 fps. At the location of this jet, there was no instability, deformation, loss of intimate contact, or damage of the HydroTurf® system, and there was no erosion of the underlying highly-erodible subgrade. Figure 13 shows a photograph of the “jet” flow.

Heavy Debris Loads – After the hydraulic jump testing was complete, testing was performed to simulate heavy debris loads. The purpose of this test was to qualitatively assess the resilience of the HydroTurf® Revetment System 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 (See Figure 14). 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 feet (See Figures 15 and 16). The concrete debris caused a few minor surface impressions at the location of the 12-ft drop. The integrity of the HydroTurf® 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 14 - Broken Concrete in Bobcat Bucket

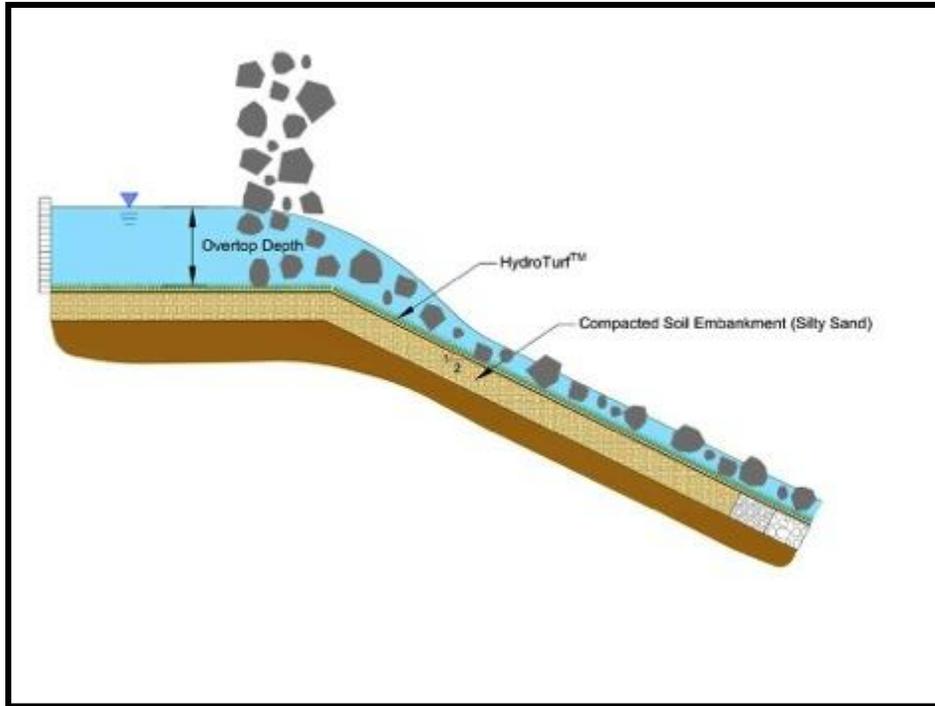


Figure 15 – Profile Section of Broken Concrete Being Dumped into the Flume



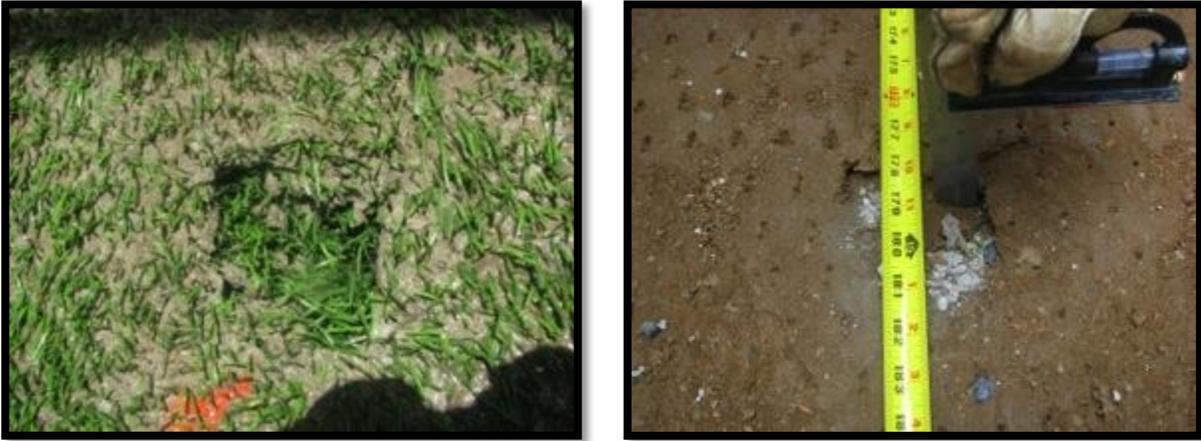
Figure 16 - Broken Concrete Being Dumped into the Flume

Intentionally Damaged State – The next test was designed to evaluate the performance of the HydroTurf® System in a damaged state. A pick axe was intentionally driven through the HydroTurf® system and approximately 6-in into the underlying sandy-loam subgrade. Figure 17 shows a photograph of this hole. Testing was performed at the 3-ft and 5-ft overtop depths for a duration of 1 hour at each overtop depth (total of 2 hours).

No instability or discernible erosion was observed. After removal of the HydroTurf® System, the subgrade was inspected. There was no erosion, and the initial hole closed. Also, the subgrade along the entire embankment showed no signs of erosion. Figure 18 shows a photograph of the intentional hole at the conclusion of testing and a photograph of the subgrade at the location of the hole after the system was removed.



**Figure 17 - Intentional Damage: Hole from Pick Ax
(Prior to Testing)**



**Figure 18 - Intentional Damage: Hole from Pick Ax
(After Testing)**

Full-scale hydraulic performance testing of the HydroTurf® Revetment Technology was completed at CSU in the steady state overtopping flume. Testing was conducted in accordance with standard procedures for ACB revetment system testing. HydroTurf® was tested in steady state flow conditions for a total of 20 hours under various events. HydroTurf® was able to withstand hydraulic loads resulting in a velocity exceeding 29.2 ft/s at a Manning's n value of 0.020. The test program has 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 ability for the HydroTurf® 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. Therefore, the HydroTurf® Revetment System was not tested to its performance threshold. A photograph of the condition of the soil subgrade post-test is shown in Figure 19.



**Figure 19 – Condition of the Soil Subgrade
(After Testing and Removal of HydroTurf® System)**

FULL-SCALE WAVE OVERTOPPING TESTS FOR LEVEE LANDWARD SIDE SLOPE PROTECTION

Full-scale Wave Overtopping Tests for Levee Landward Side Slope Protection were performed on HydroTurf® at CSU. Testing was performed in accordance with the methodology developed for the US Army Corps of Engineers. A schematic and a photograph of the wave overtopping simulator facility are shown in Figures 20 and 21, respectively.

Test Preparation

The testing tray set containing the HydroTurf® Revetment System was prepared at the CSU Wave Overtopping Test Facility. A 2-in thick layer of pea gravel was placed in the bottom of the trays and covered with filter geotextile that is manufactured using high tenacity polypropylene yarns, woven to form a dimensionally stable network. A highly-erodible soil (silty sand) was then placed into the trays in two (2) 5-in thick layers. Each layer was compacted to a minimum of 98% of the Standard Proctor (ASTM D698).

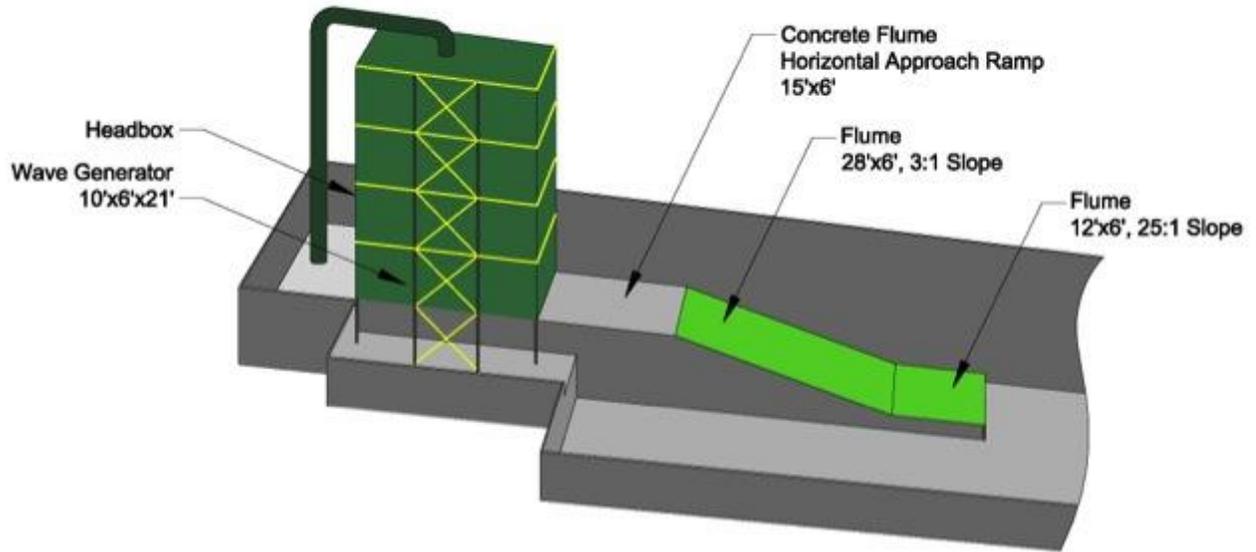


Figure 20 – Schematic of the CSU Wave Overtopping Test Facility



Figure 21 – CSU Wave Overtopping Test Facility

The HydroTurf® was installed on the soil in the trays. First, a continuous sheet of the 50-mil structured geomembrane was placed with the “spike” side down. This geomembrane serves as the underlayer of the system. Then, the engineered synthetic turf was placed on the geomembrane. One of the primary purposes of the experiment

was to test the strength of the sewn seam between two adjacent pieces of the synthetic turf component. Two (2) sections of the synthetic turf were sewn together using a similar machine used for field installations. This joined piece was placed on the trays so the seam was situated along the down-slope centerline of the trays. The next step in tray preparation was applying approximately a ¾-inch thick layer of dry HydroBinder® infill into the fibers of the synthetic turf. The dry mixture was placed using a drop spreader, and then it was broomed against the grain of the turf in order to pull the fibers up through the infill. The HydroBinder® mix was then hydrated. Installation photos are shown in Figure 22.



Figure 22 – Installation of the HydroTurf® System

Testing

Testing of the HydroTurf® Revetment System was conducted in four (4) phases. The first phase tested the installed HydroTurf® up to the limits of the Wave Overtopping Simulator. At the completion of the first phase, the installed and tested HydroTurf® 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:

- Phase 2 - Pulverization of the hardened HydroBinder® infill in order to simulate cracked mortar and portions of the surface that had been severely damaged. (See Figure 23)



Figure 23 – Intentional Damage: Pulverization of HydroBinder® Infill

- Phase 3 - A bullet hole was simulated by driving rebar through the HydroTurf® into the underlying subgrade. (See Figure 24)



Figure 24 – Intentional Damage: Simulated Bullet Hole through HydroTurf®

- 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. (See Figure 25)



Figure 25 – Intentional Damage: Large Hole through HydroTurf®

Photos of the testing are included in Figure 26.



Figure 26 – Wave Overtopping Testing of HydroTurf® at CSU

Results

The HydroTurf® Revetment System withstood the largest wave overtopping flows (4 cfs/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 HydroTurf® being subjected to 165,600 cf/ft of cumulative water volume.

Upon completion of the tests, the HydroTurf® was removed and the underlying soil condition was documented. The HydroTurf® Revetment System performed well in maintaining the underlying, highly-erodible soils during these severe conditions, even in an intentionally damaged state. Figure 27 is a photograph of the condition of the HydroTurf® System after the 13 hours of testing. Figure 28 is a photograph of the condition of the highly-erodible, silty sand subgrade which was underneath the HydroTurf®.

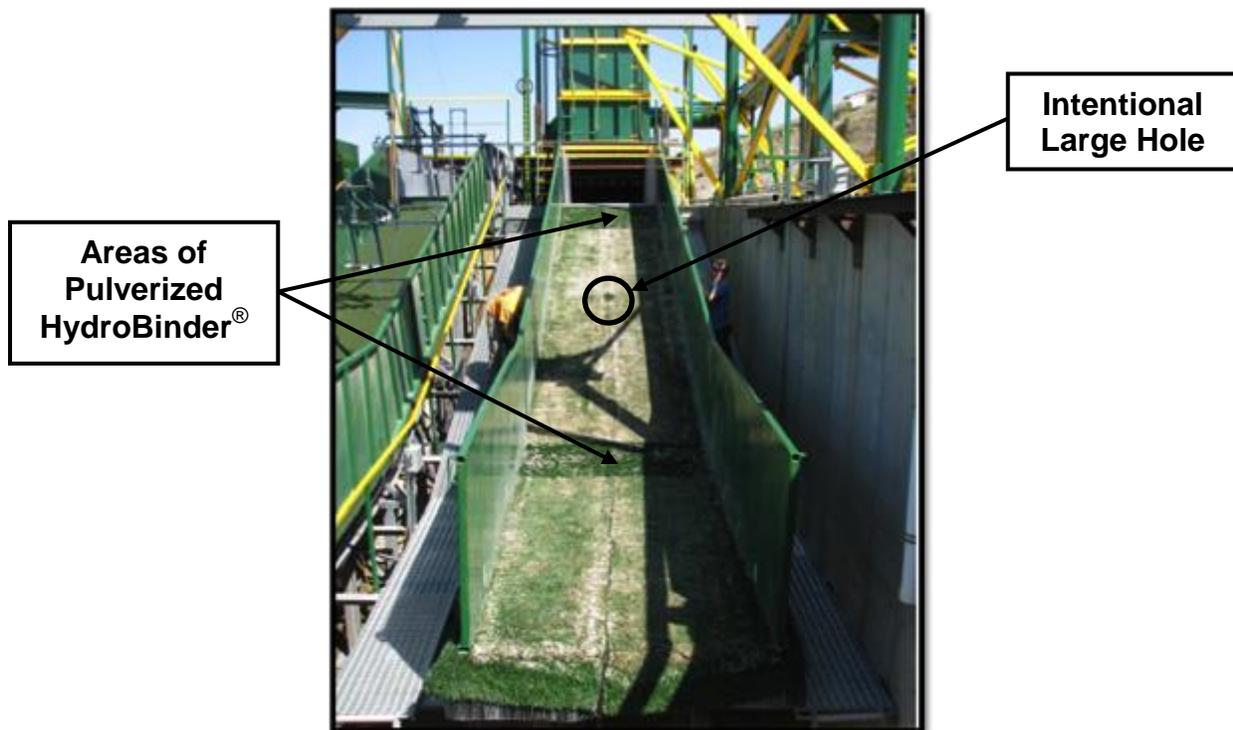


Figure 27 – Condition of HydroTurf® System after Completion of Wave Overtopping Testing

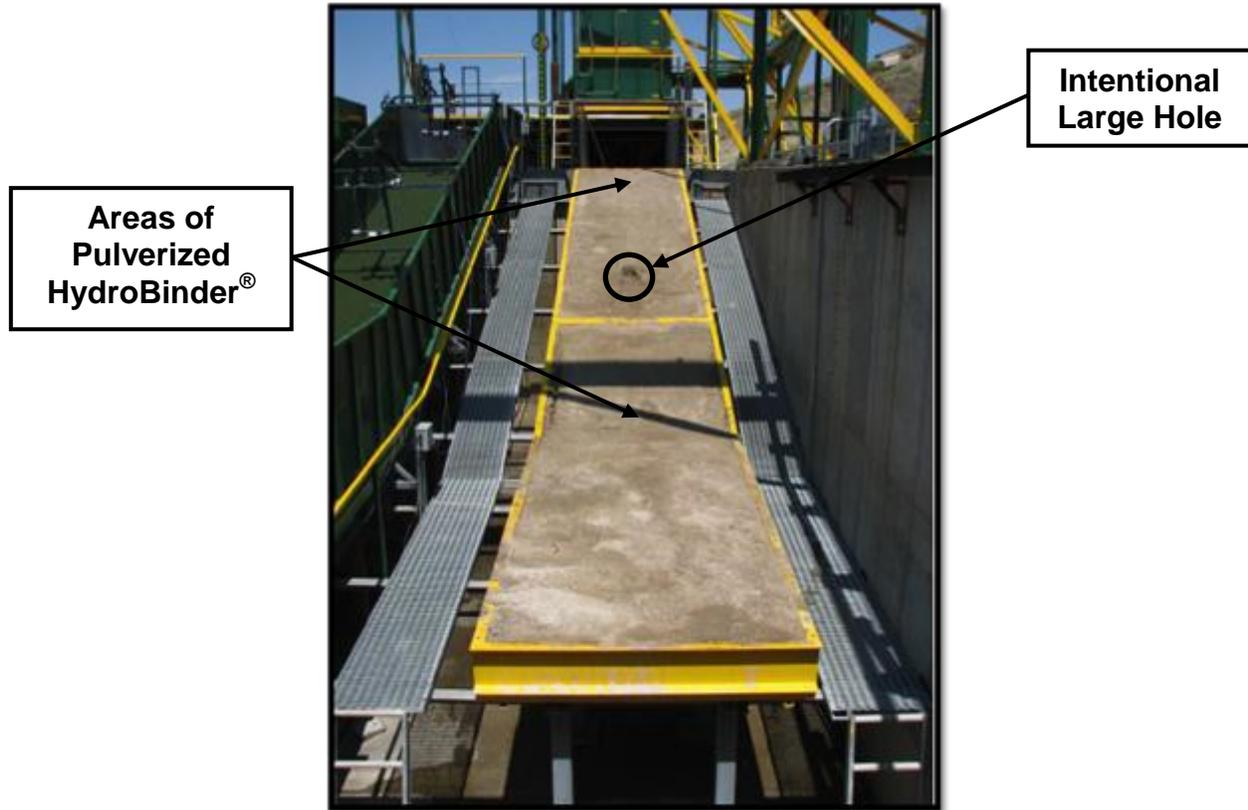


Figure 28 – Condition of Silty Sand Subgrade after Completion of Wave Overtopping Testing

Detailed results for each of the testing Phases are as follows:

- *Phase 1 – Intact HydroTurf®*: For the six (6) hours of testing with four (4) being at the maximum capacity of 4.0 cfs/ft, there was no observed erosion of the silty sand under the HydroTurf®.
- *Phase 2 – Pulverized HydroBinder® Infill*: For the additional five (5) hours of testing with three (3) being at 4.0 cfs/ft, there was no observed erosion of the silty sand under the damaged HydroTurf®.
- *Phase 3 – Pulverized HydroBinder® Infill and Simulated Bullet Hole*: For the additional one (1) hour of testing at 4.0 cfs/ft, there was no observed erosion of the silty sand under the damaged HydroTurf®. The simulated hole did not expand or cause localized erosion.
- *Phase 4 – Pulverized HydroBinder® Infill and Large Hole*: For the additional one (1) hour of testing at 4.0 cfs/ft, minimal erosion of the silty sand was observed in

a localized area around and downstream of the large hole. No head-cutting was observed at the location of the hole.

- The field sewn seam adjoining the adjacent panels of engineered turf proved successful throughout the high stresses exerted during the 13 hours of testing.
- A graph of Cumulative Wave Overtopping Volume vs. Test Duration is shown in Figure 29.

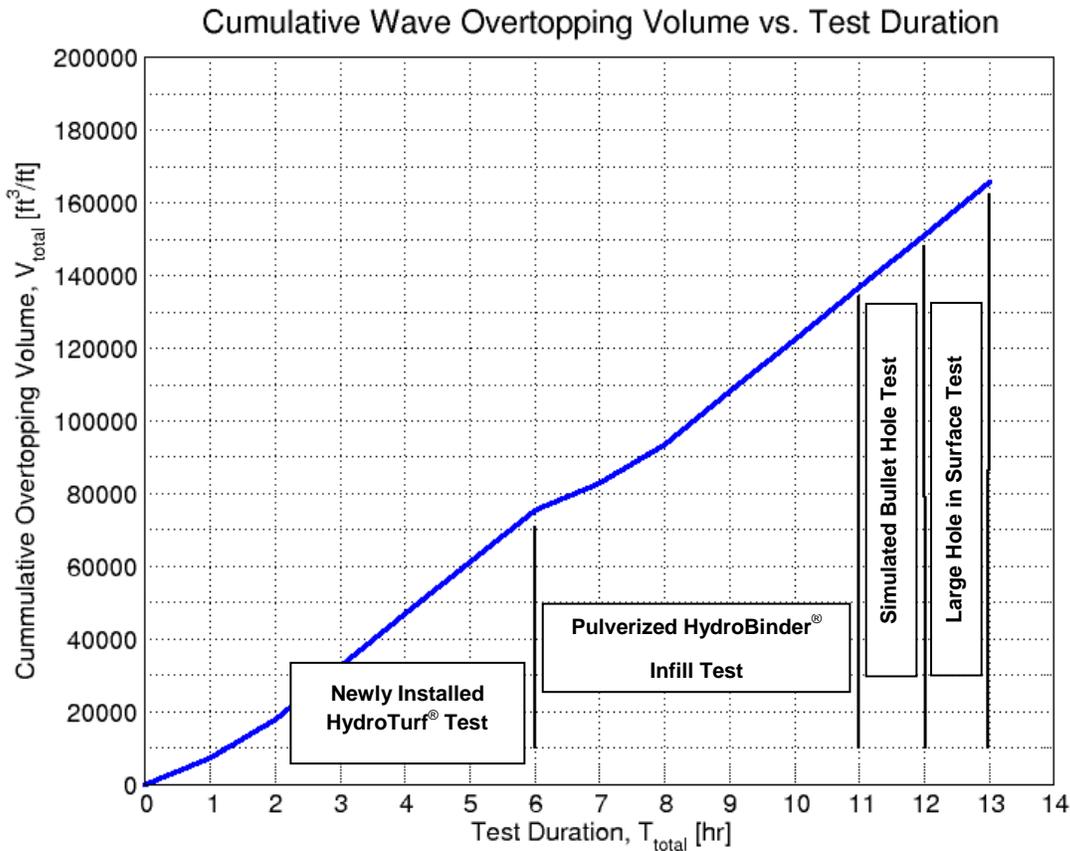


Figure 29 – Cumulative Wave Overtopping Volume vs. Test Duration for HydroTurf®

The performance of HydroTurf® in the wave overtopping simulator can be compared to the performance of other erosion control technologies. The graph in Figure 30 shows a comparison of armoring performance for levee landward-side protection for various technologies which have been tested in the CSU Wave Overtopping Simulator. HydroTurf® outperformed these other systems. Also, note that the subgrade for the other technologies was clay while the subgrade for the HydroTurf® was highly-erodible silty sand.

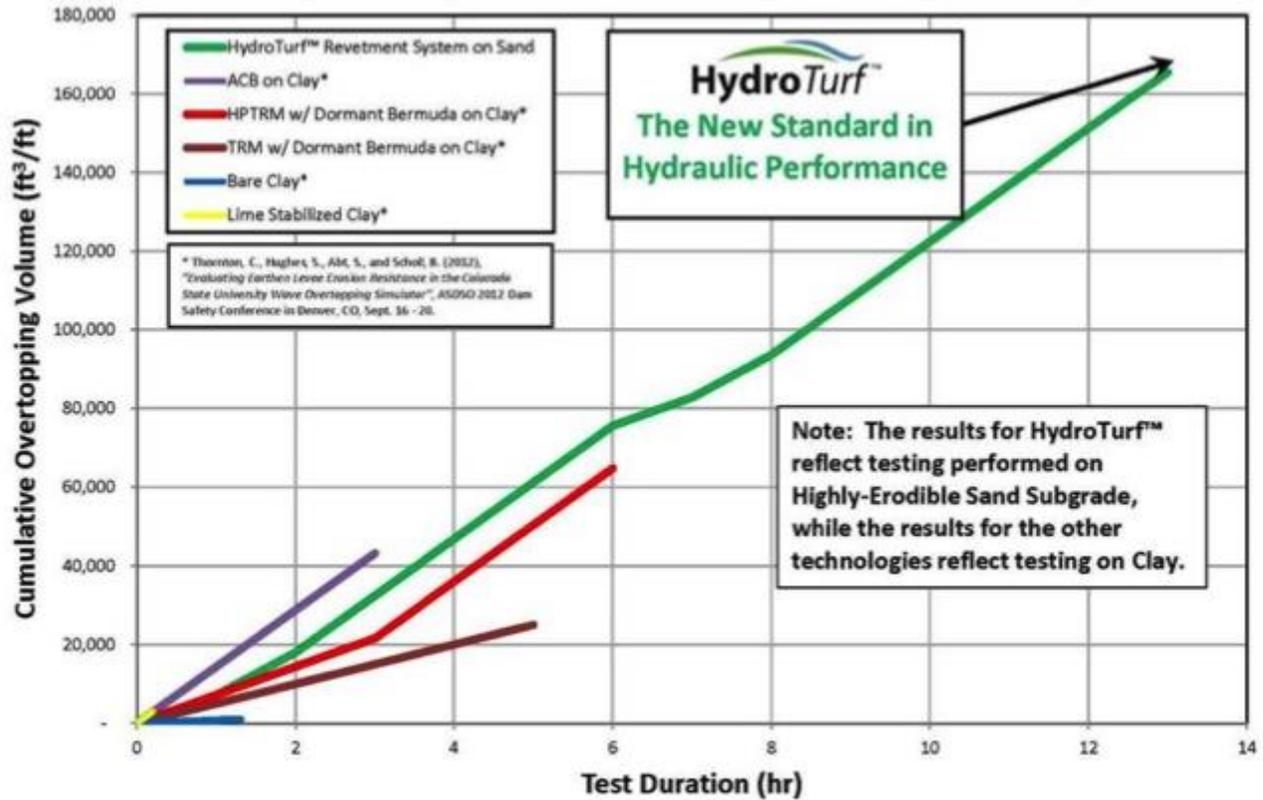


Figure 30 – Armoring Performance for Levee Landward-Side Protection from Wave Overtopping

LIMITATIONS

HydroTurf® product (US Patent No. 7,682,105; Canadian Patent No. 2,663,170; and other Patents Pending) and registered trademark are the property of Watershed Geosynthetics LLC. All information, recommendations and suggestions appearing in this literature concerning the use of our products are based upon tests and data believed to be reliable; however, this information should not be used or relied upon for any specific application without independent professional examination and verification of its accuracy, suitability and applicability. Since the actual use by others is beyond our control, no guarantee or warranty of any kind, expressed or implied, is made by Watershed Geosynthetics LLC as to the effects of such use or the results to be obtained, nor does Watershed Geosynthetics LLC assume any liability in connection herewith. Any statement made herein may not be absolutely complete since additional information may be necessary or desirable when particular or exceptional conditions or circumstances exist or because of applicable laws or government regulations. Nothing herein is to be construed as permission or as a recommendation to infringe any patent.