Wave Overtopping Resiliency of Grass and Turf Reinforcement Mats on Sandy Soils

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Summary

Full-scale wave overtopping tests conducted in the CSU Wave Overtopping Test Facility examined the resiliency of grass and reinforced grass slopes founded on sandy soils. Soil loss was quantified by comparing surveys of the slope surface to the initial survey. Grass failure is shown to correlate with the cumulative excess work done by the individual overtopping wave volumes, even though the hydraulic loading sequences between test samples were significantly different in time. Grass strengthened with turf reinforcement mats can sustain 2-4 times the hydraulic loading of grass-only slopes. These results are strictly limited to the soils and grass species tested in the wave overtopping simulator.

Introduction

The state of Florida in the United States builds dikes, levees, and embankments using native soil high in sand content that often contains shell fragments. Erosion resistance of these soils is improved by vegetation, but generally the improvement is less than erosion resiliency of grass-covered cohesive slopes. One of the most significant flood protection structures in Florida is the 9-m-high Herbert Hoover Dike that almost completely surrounds the 1,900 km^2 area of Lake Ockeechobee. Seiching of the lake, and waves caused by hurricanes passing over the lake, can be extreme. At least 2,800 people perished during the late 1920s due to lake surges overtopping the previous inadequate dikes.

The Jacksonville District, Corps of Engineers, sponsored full-scale wave overtopping tests at Colorado State University's Wave Overtopping Test Facility (Thornton et al. 2011; Van der Meer et al. 2011). The purpose of the testing was to determine acceptable wave overtopping limits that could be tolerated by South American Bahiagrass (*Paspalum notatum Flüggé*) planted on the sandy soils typically used for construction of dikes and embankments in Florida. These resiliency limits will be used to set levee and embankment crest elevations. In addition, two wave overtopping tests examined the increased slope stability afforded by turf reinforcement mats (TRMs) populated with Bahiagrass.

This paper presents erosion results and initial analyses that relate the cumulative eroded sediment volume to the cumulative hydraulic loading represented by the excess work in the individual overtopping waves above a critical threshold. After a brief overview of the test tray preparation and testing procedures, the concept of cumulative excess work is introduced. Results are presented for two grass-only tests and two grass+TRM tests, and the observed erosion is related to the applied hydraulic loading for each test. Preliminary limits for tolerable grass damage for this specific soil and grass species are presented in terms of cumulative excess work. The steep landward-side slope caused the unsteady overtopping flow to be supercritical most of the time.

Test Sample Preparation

The fixed-in-place Wave Overtopping Simulator requires that representative dike slopes be prepared in special planter trays for simulator testing. Four soil types were transported from Florida to Colorado for use in establishing representative grass-covered slopes within each tray. Generally, the soils contained high percentages of sand and silt (classified as SM). Soil properties are given in Table 1.

Table 1. Soil Properties.

Soil ID	Dry Density (kg/m^3)	Med. Grain Size (mm)	Description
1	1,490	0.17	Brown, black silty sand with organics (SM)
2	1,866	0.23	White, silty, clayey sand/w shells, and slight organics (SM)
3	1,906	0.30	Tan, silty sand with trace gravel, and shells (SM)
4	1,906	0.17	Tan, silty sand with trace gravel (SM)

The landward dike slope geometry was reproduced using a straight levee tray and a bent berm tray having dimensions as shown in Figure 1. Pea gravel was placed in the bottom 5 cm of the 30.5-mm-deep trays, and the remaining depth was filled with compacted soil.

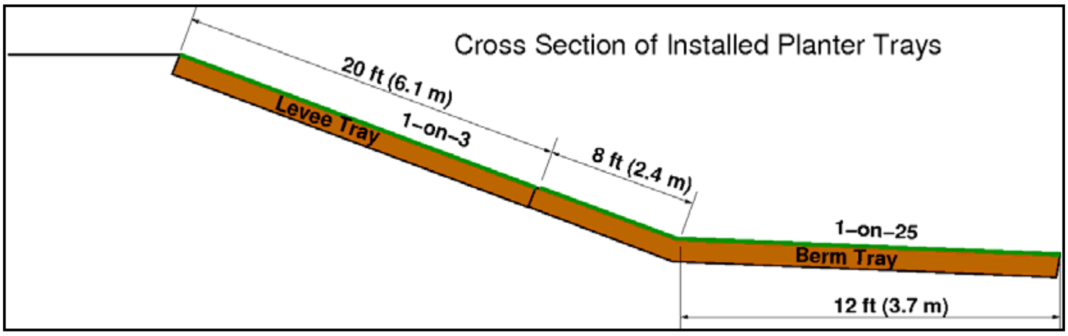


Figure 1. Planter tray dimensions and slope geometry.

After the soil was placed in the trays and compacted, Bahiagrass (*Paspalum notatum Flüggé*) sod harvested in Florida and shipped to Colorado was installed and grown under greenhouse conditions at temperatures and humidity typical of Florida's climate. A process was developed to cut back the grass coverage on the trays to 50% (± 5%) of the surface area to replicate expected dike conditions in Florida. The left-hand photograph of Figure 2 shows several of the planter tray sets in the greenhouse one week after sod installation, and the right-hand photograph illustrates an overhead close-up of a tray reduced to 50% (± 5%) grass coverage. Turf reinforcement mats (TRMs) were installed in two of the tray sets prior to sod establishment.

Greenhouse One Week After **Fifty-Percent Grass Coverage**

Figure 2. Test tray preparation.

Bahiagrass is a warm-season grass species characterized as having a deep root system for greater drought resistance associated with highly sandy soil in subtropical climate.

Testing Procedures

Generally, the testing procedure for each planter tray set was structured as a series of one-hour wave overtopping simulations with increasing values of average overtopping discharge for each successive hour. The overtopping wave volume distribution was determined using the same Weibull distribution used by the Dutch in-situ simulator. The first two tests started with very low average overtopping rates because engineers were uncertain of the grass and soil resiliency. Subsequent tests proceeded with more aggressive hydraulic loading sequences based on observed grass resiliency shown in earlier tests. Topographic data on the slope were acquired using conventional total station survey techniques throughout the testing sequences. Initially, surveys were conducted after each 1-hour segment, but in subsequent tests surveys were acquired whenever visual changes to the slope surface had occurred.

Three tests were conducted for each of the four soil types. Incident wave characteristics and percent grass cover are given in Table 2. The seaward levee slope was assumed to be 1V:3H (Cot α = 3). Testing continued until it was visually observed that grass failure had occurred. Determination of grass/soil failure sometimes included soil erosion to the bottom of the tray, or excessive soil loss beneath the TRMs. Two grass-only tests (4 and 5) and the two TRM tests (6 and 12) are analyzed in this paper. The other tests had not yet been completed when this paper was prepared.

Table 2. Testing Parameters.

#	**Specimen**	**H_{m0} (m)**	**T_p (s)**	**#**	**Specimen**	**H_{m0} (m)**	**T_p (s)**
Soil Type 1				**Soil Type 2**			
1	50% Grass Coverage	2.44	7.7	7	50% Grass Coverage	2.04	4.5
2	30% Grass Coverage	2.44	7.7	8	50% Grass Coverage	2.20	6.0
3	30% Grass Coverage	1.52	7.7	9	Bare Soil	2.20	6.0
Soil Type 4				**Soil Type 3**			
4	50% Grass Coverage	1.43	3.4	10	50% Grass Coverage	1.43	3.4
5	50% Grass Coverage	2.04	4.5	11	50% Grass Coverage	2.04	4.5
6	TRM with 50% Grass	2.04	4.5	12	TRM with 50% Grass	2.04	4.5

Concept of Cumulative Excess Work

Dean et al. (2010) examined whether flow velocity (u), shear stress ($\propto u^2$), or work ($\propto u^3$) above a given threshold was the best parameter for relating design nomograms of grass stability derived from steady overtopping measurements to the case of unsteady wave overtopping. They concluded flow work ($\propto u^3$) above a certain threshold provided the best estimator of erosion, and the concept was named "*erosional equivalence*". Dean et al. applied the concept to irregular wave overtopping.

Dutch researchers independently developed similar methodology for evaluating grass cover damage and dike resiliency. Van der Meer et al. (2010) proposed that dike erosion and damage occurs from accumulated "hydraulic loading" caused primarily by the impact by the leading edge of the overtopping wave. Hughes (2011) suggested that cumulative hydraulic loading can be thought of as erosional equivalence based on excess specific energy or excess energy density at the peak of the overtopping wave; whereas Dean et al.'s approach is erosional equivalence based on excess work over the entire overtopping wave. In essence, the two approaches are quite similar.

Hughes (2011) expanded Dean et al.'s concept of cumulative excess work (CEW) by assuming the distributions of velocity and flow thickness in individual overtopping waves could be approximated as triangular saw-tooth shapes. The instantaneous discharge in an overtopping wave was assumed to be the product of the velocity and flow thickness as shown in Figure 3. Thus, the volume of an overtopping wave (V_W) was estimated to be

$$V_W = \frac{q_p\, T_o}{3} \qquad (1)$$

where q_p is the peak discharge and T_o is the duration of individual wave overtopping. The excess work in the overtopping wave is represented by the sum of the discharge (i.e., wave volume) above a critical discharge as indicated in the idealized wave shown in Figure 3. Based on Dean et al. (2009), Hughes (2011) derived the critical discharge (q_c) as a function of critical velocity (u_c), landward-side slope angle (θ), Fanning friction factor (f_F), and gravity (g) as

$$q_c = \left(\frac{f_F \, u_c^3}{2g \sin\theta} \right) \tag{2}$$

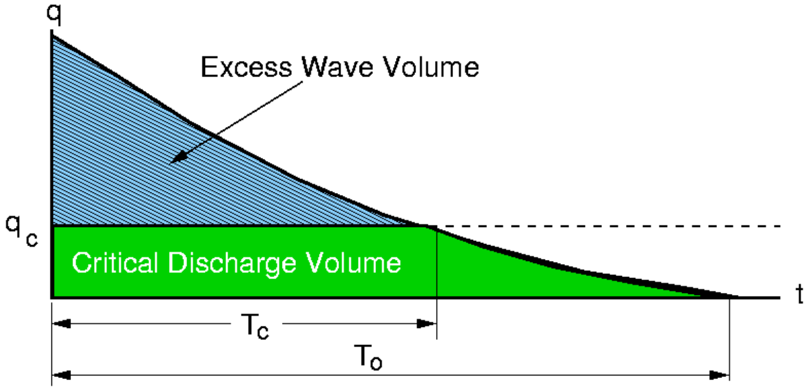


Figure 3. Excess wave volume above the threshold for an idealized wave.

The total cumulative excess work (or excess wave volume) for a distribution of overtopping waves was given by Hughes (2011) as the summation of the excess work contribution per wave, i.e.,

$$V_{ET}(t) = \sum_{n=1}^{N} V_{Wn} \left[1 - \left(\frac{q_c \, T_{on}}{V_{Wn}} \right) + \frac{2}{3^{3/2}} \left(\frac{q_c \, T_{on}}{V_{Wn}} \right)^{3/2} \right] \tag{3}$$

where the subscript n refers to the parameter values for individual waves. Further details and suggested implementation into a predictive model are given in Hughes (2011). Erosion results measured during the experiments were analyzed using the cumulative excess work concept, and this analysis provided the first validation of the methodology.

Test Results

Analyses were performed on two grass-only tests and two tests of grass reinforced with TRMs. The two grass-only tests (Tests 4 and 5) had the same sod and soil type. The only differences between the tests were incident waves (see Table 1) and wave overtopping loading sequences. The two tests with TRMs (Tests 6 and 12) were subjected to the same incident wave condition with the only variation being the manufacturer of the TRM and the overtopping loading sequence. Different, but similar, soil (see Table 1) was used for the two TRM tests; however, the sod was the same species and age.

Each test consisted of multiple one-hour test sequences during which time the average overtopping rate was held constant. Survey data were acquired after some (but not all) one-hour sequences. Survey points were measured using conventional survey equipment. The advantage of conventional surveying was being able to acquire measurements in higher density at locations were erosion occurred. The disadvantage was the time required to measure enough points to provide a reasonable representation of the three-dimensional levee surface. Terrestrial LiDAR was considered and tested, but the LiDAR results were heavily biased by the standing grass blades, and accurate erosion depths could not be measured. Also, the LiDAR could not measure soil loss beneath the TRM, whereas a survey rod could push the TRM down until TRM contact was made with the underlying soil.

Figure 4 shows a three-dimensional surface constructed from survey points at the end of grass-only Test 5 when grass failure was declared. The photograph in Figure 4 shows the actual grass surface represented in the survey. Note the transition mat of artificial turf located at the junction between the two trays. This transition mat helped to reduce potential edge effects caused by the necessary use of two adjoining trays.

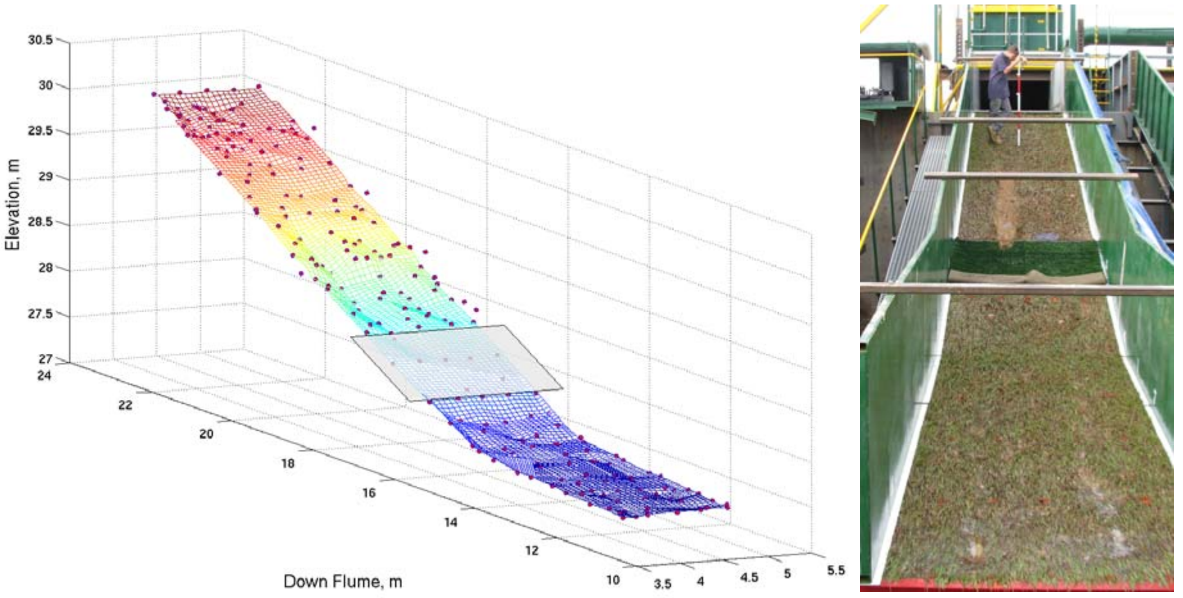
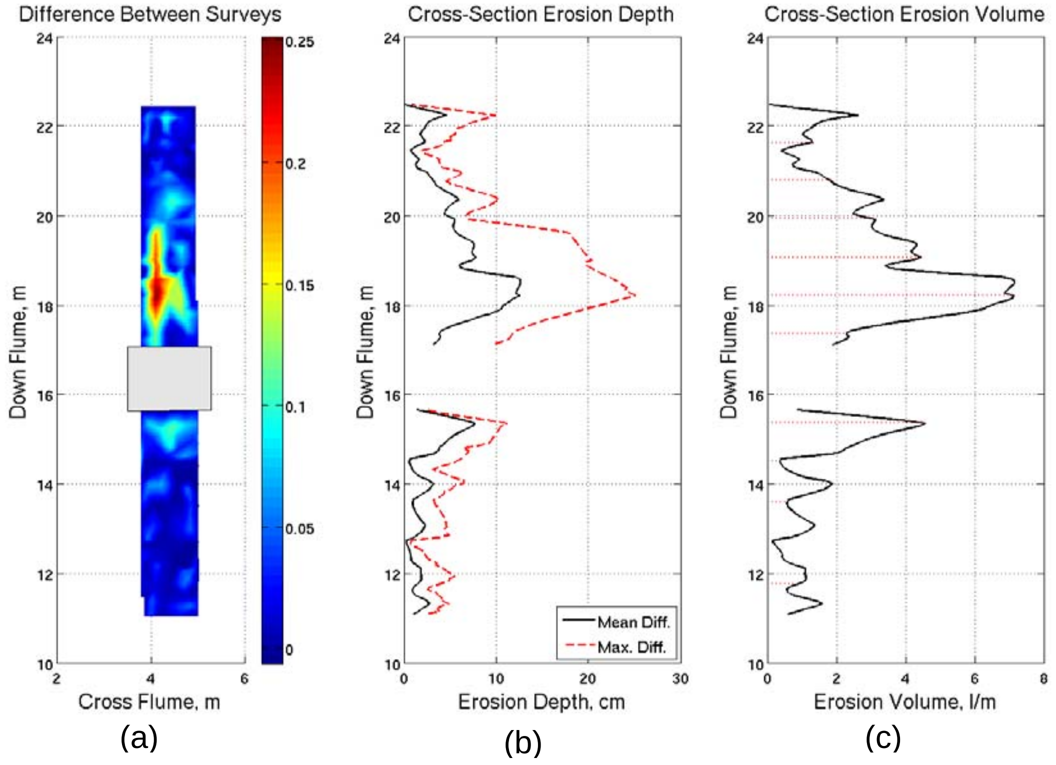


Figure 4. Uniform mesh fitted to survey data (left) and grass damage (right).

Figure 5(a) shows the difference (m) between initial and final Test 5 surveys. Figure 5(b) indicates the variation in cross-flume mean and maximum depths (cm). The cross-flume eroded volume per unit flume width (l/m) in shown in Figure 5(c). Similar comparisons were made for all intermediate surveys for each test sequence.

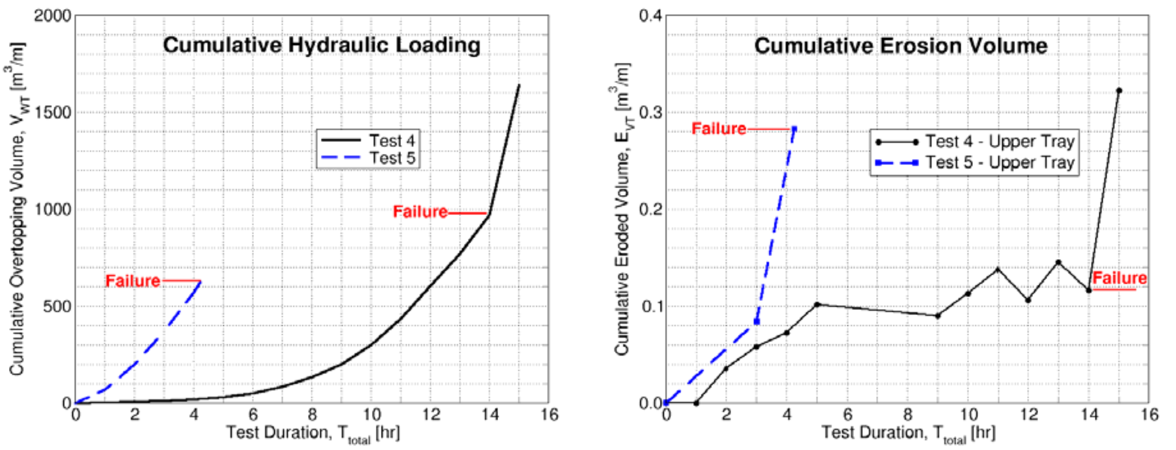


(a) (b) (c)

Figure 5. Cumulative erosion at end of Test 5.

Grass-Only Test Comparison (Tests 4 & 5)

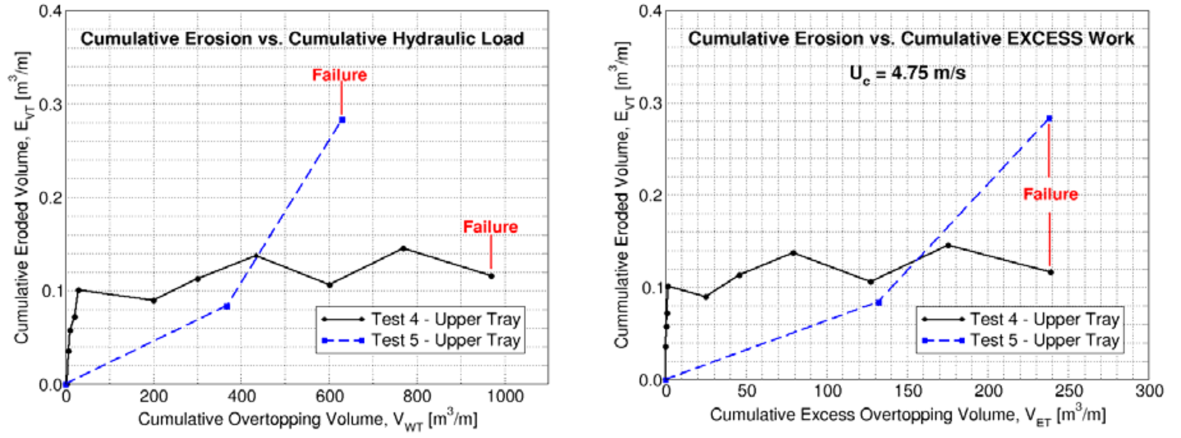
Test 4 was the first test conducted with the sandy soil, so the wave overtopping loading was initially very low (0.9 l/s/m), and then increased slowly for each subsequent hour of testing. The cumulative overtopping water volume for Test 4 is shown as a function of time by the solid line in Figure 6(a). Grass failure (subjective opinion of the researchers) occurred after 14 hours as indicated on the plot. Test 5 hydraulic loading was more aggressive as indicated by the dashed line in Figure 6(a), and grass failure occurred after just 5 hours. The progression of cumulative eroded volume per unit width over the entire upper tray length (6.1 m) is shown in Figure 6(b) for both grass-only tests. The cumulative erosion lines should be monotonically increasing, but errors associated with fitting a geometric surface to limited survey data resulted in some surveys calculating less erosion volume than the previous survey. Nevertheless, the erosion trend appears to be reasonable, and the similar shape of cumulative hydraulic loading and cumulative erosion in time suggests a direct relationship between loading and erosion.



(a) (b)

Figure 6. Grass-only cumulative loading (left plot) and cumulative erosion (right plot).

Figure 7(a) plots cumulative erosion volume as a function of cumulative overtopping water volume for the two grass-only tests. Both tests follow similar trends despite the fact that the wave conditions and the loading sequences were different. Test 5 had more total eroded volume at the declared point of failure, and this was probably due to different development of the scour areas caused by local variation in grass and soil resiliency.



(a) (b)

Figure 7. Erosion vs. hydraulic load (left plot) and excess work (right plot).

Van der Meer et al. (2010) applied their cumulative hydraulic loading model to in-situ wave overtopping tests on sandy soil. They reported that a critical velocity of U_c = 4.0 m/s provided positive damage correspondence between wave overtopping tests conducted using different incident wave conditions. In a similar manner, the cumulative EXCESS wave volume was calculated for the different wave conditions of Tests 4 and 5 using several different values of U_c in the CEW method. Assumed friction factor was f_F = 0.015, and the landward-side slope was 1V:3H. The best match was obtained for U_c = 4.75 m/s as shown in the plot of Figure 7(b) where grass failure is associated with a cumulative excess overtopping volume of about V_{ET} = 240 m^3/m.

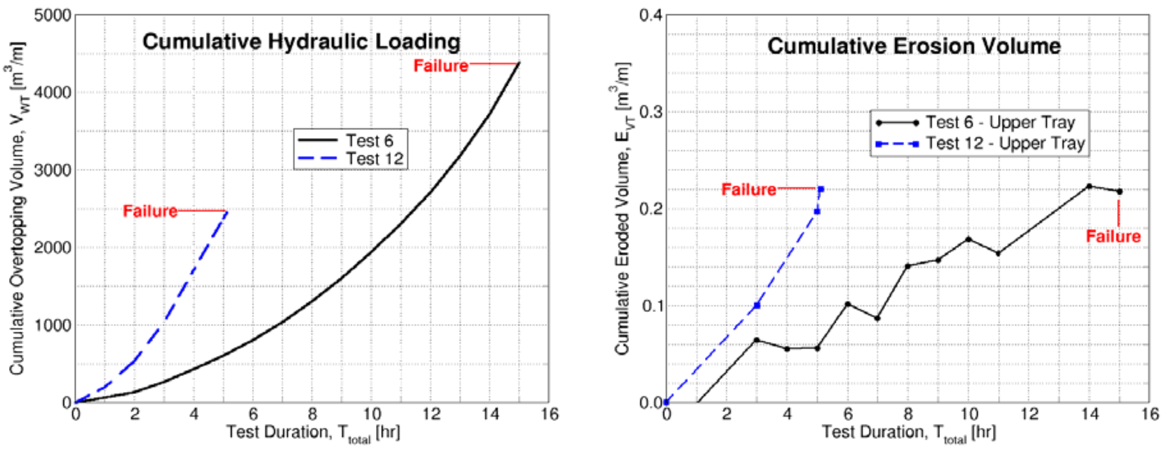
Turf Reinforcement Mat Test Comparison (Tests 6 & 12)

The two tests of grass sod reinforced with turf reinforcement mats varied only in TRM manufacturer, loading sequence, and slightly different soil type. The same sod species was used in each test. The left-hand photograph in Figure 8 shows the relatively intact grass on the upper levee tray at the conclusion of Test 6. The rest-hand photograph shows an area just down-slope of the transition fabric where sod and grass were separated and soil loss occurred beneath the TRM. Note the depression in the mat from the survey rod during soil surface erosion measurements.

Figure 8. Grass reinforced with TRM (Test 6).

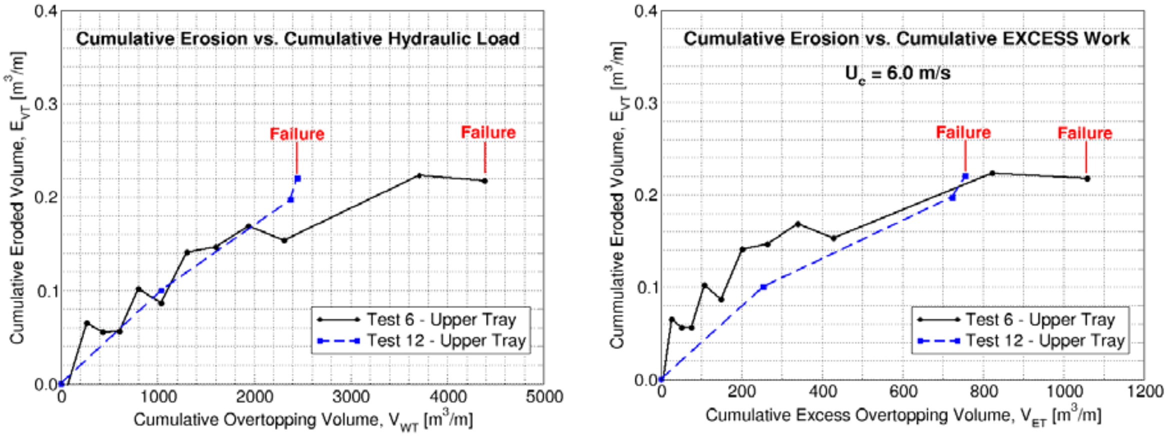
The cumulative overtopping water volume for Tests 6 and 12 are shown as a function of time in the Figure 9(a). Failure due primarily to loss of soil beneath the TRM is indicated on the plot for both tests. Test 12 hydraulic loading was more aggressive, and failure occurred after 5.1 hours compared to failure at 15 hours for Test 6. The progression of cumulative eroded volume per unit width over the entire upper levee tray length (6.1 m) is shown in Figure 9(b) for both tests.

Figure 10(a) shows the correlation between cumulative erosion volume and cumulative overtopping water volume for the two grass+TRM tests. The erosion progression of each test was more closely aligned with each other compared to the grass-only tests. Even though the wave conditions were the same, the applied loading sequence was different, soil types were slightly different (see Table 1), and the TRMs were made by different manufacturers. At declared failure, the total eroded volume on the upper tray was nearly the same for the two tests. The additional protection provided by the TRM appears to have reduced the influence of soil/grass local variations and contributed to erosion being more consistent between tests.



(a) (b)

Figure 9. Grass+TRM cumulative loading (left) and cumulative erosion (right).



(a) (b)

Figure 10. Erosion vs. hydraulic load (left plot) and excess work (right plot).

Application of the cumulative excess work methodology for a reasonable range of critical velocities failed to provide a good match between the two tests. A comparison of cumulative excess work for the two tests with U_c = 6.0 m/s is shown in Figure 10(b). Whereas the two cumulative erosion volume lines show similar trends, it is tentatively concluded that the difference in cumulative excess work at failure may be related to root-holding differences between the TRM products. If this was the case, then the cumulative excess work methodology cannot be calibrated for these tests because more than just incident wave condition and loading contributed to damage. It should be noted that both TRMs would continue to provide levee slope protection well beyond the level indicated here without jeopardizing the levee crest. The TRM proved to be very effective in limiting head-cutting (upstream erosion progression), even when grass has been damaged and soil has been eroded beneath the mat.

Discussion

Despite significant differences in the hydraulic loading sequences, reasonable comparison between the grass-only tests was achieved when cumulative eroded volume (per unit width) over the entire upper slope was correlated to the cumulative overtopping wave volume. Application of the cumulative excess work concept revealed that the points of perceived grass-only failure coincided when the critical velocity for soil loss was about 4.75 m/s. This critical velocity is higher than the critical velocity of 4.0 m/s determined by Van der Meer et al. (2010) for sandy soils in The Netherlands. A possible explanation for the larger critical velocity might be the fact that the CSU trays contained no structured soil that might occur on mature Dutch dikes, or it may just be application of different (but similar methodologies. The cumulative excess work concept was attempted for the two grass+TRM tests, but it was not possible to achieve correspondence between the cumulative excess work at failure. A possible reason for this unsuccessful calibration might be difference in the root-retention capability of the TRMs.

Figure 11 summarizes the cumulative eroded volume all four tests as a function of cumulative overtopping water volume. The ranges of perceived grass failure are shown on the figure. Bahiagrass reinforced with a TRM was able to sustain between 2 and 4 times the cumulative hydraulic loading as Bahiagrass without reinforcement. It seems reasonable that grass+TRM should have greater erosion resistance than grass alone because the TRM is integrated with the grass to provide greater plant stabilization as well as functioning as a direct barrier between the soil and fast-flowing water. Admittedly, the declaration of grass failure was based on engineering judgment rather than a defined criterion; but the indicated grass failure levels fell considerably short of a condition that would jeopardize the levee crest integrity.

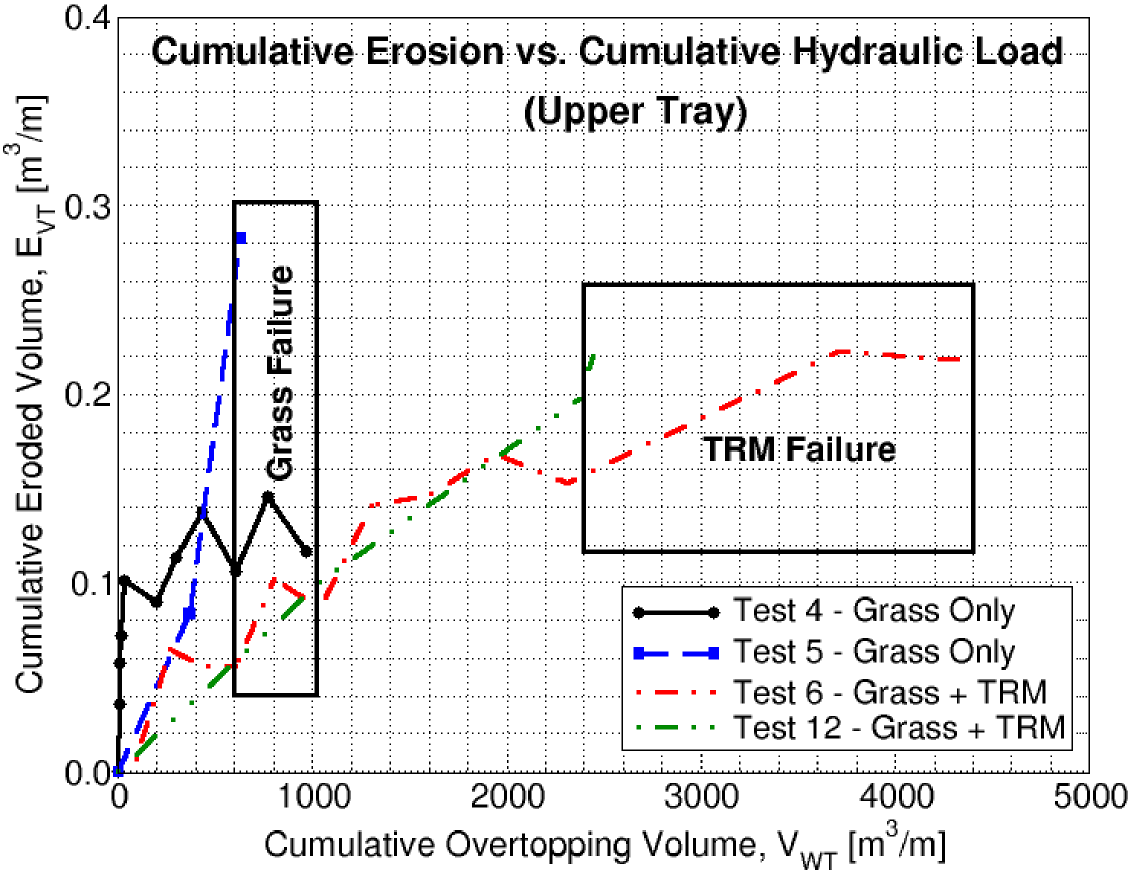


Figure 11. Summary of grass-only and grass+TRM test performance.

These results were obtained for grass coverage of 50%. Therefore, the use of a TRM provides increased slope resiliency and a more robust system in areas where climate or management practices may result in grass coverage of 50%. The difference shown in Figure 11 between grass-only slopes and grass reinforced with TRM maybe not be the same when grass coverage is substantially greater than 50%.

Cumulative excess work for wave conditions and loading scenarios different from those tested for grass-only slopes can be calculated to determine if the grass failure limit would be exceeded for a variety of loading conditions. Without question, the above results are strictly limited to Bahiagrass sod placed atop sandy soils closely matching the characteristics of the soil used in the tests. Attempts to extrapolate or extend these results to different soil types or grass species would be inappropriate.

Conclusions

Wave overtopping tests conducted in the CSU Wave Overtopping Test Facility examined the performance of Bahiagrass sod placed on the sandy soil and Bahiagrass sod reinforced with a turf reinforcement mat (TRM) overlying sandy soil. The wave overtopping was simulated by a sequence of progressively larger values of average wave overtopping discharge until such time the grass reached a state of damage that was subjectively considered to be unacceptable. Incident wave parameters and hydraulic loading sequence were different for the two grass-only tests. The main differences between the two grass+TRM tests were the TRM manufacturer, the hydraulic loading sequence, and the sandy-soil type.

It was concluded that Bahiagrass sod atop sandy soil having the same characteristics of the tested soil can resist wave overtopping until the cumulative EXCESS wave volume exceeds V_{ET} = 240 m^3/m (calculated using a critical velocity of U_c = 4.75 m/s). When turf reinforcement mats are used under the Bahiagrass sod, the grass tolerated cumulative overtopping wave volumes 2 to 4 times greater depending on TRM manufacturer.

This paper presented results from the first 4 of 12 planned tests. A comprehensive technical report detailing all 12 Jacksonville District tests, along with similar CEW analyses between additional tests will be completed and available before the end of 2013. These results, combined with results from the other 8 tests will be used by Jacksonville District to assess overtopping risk for existing levees and embankments and to establish tolerable overtopping criteria for future levees built using sandy soils.

Future testing and analyses conducted using the CSU Wave Overtopping Simulator and the Dutch Mobile Overtopping Simulator will expand our understanding of grass resiliency to wave overtopping for a wider range of grass species, soil types, and percent grass coverage. In addition, wave overtopping resiliency criteria will be established for a greater variety of manufactured slope erosion products.

Acknowledgements

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