ESTIMATING GRASS SLOPE RESILIENCY DURING WAVE OVERTOPPING: RESULTS FROM FULL-SCALE OVERTOPPING SIMULATOR TESTING

Christopher Thornton[1], Steven Hughes[1], Bryan Scholl[1], and Natalie Youngblood[1]

This paper summarizes full-scale laboratory wave overtopping simulation test results from three years of testing conducted at the Colorado State University wave overtopping test facility. These results are specific to the tested soils and grass cover, so direct application to coastal dikes and levees built using different soils and grass species, or to locations subjected to different wave overtopping conditions, is not advisable. For this reason, robust design guidance will require significantly more data than are presently available. Tentative design methods are proposed for extension of the relatively few full-scale test results to other situations having different levee geometry, different wave conditions, and different grass/soil parameters. The intention is to provide a viable framework that can be extended as more knowledge is gained from additional testing with different grass/soil combinations.

Keywords: wave overtopping; earthen dikes; grass resiliency; overtopping simulator; turf reinforcement mats

INTRODUCTION

Increasing awareness of climate change, and the consequences of inevitable sea level rise, has elevated the importance of earthen dikes and levees in their role as protective coastal structures. In the future, existing dikes could experience more wave overtopping than originally envisioned, and new dikes must be built with sufficient overtopping resiliency to withstand anticipated future storm events. A key reality faced by engineers is that earthen dikes and levees must be constructed with locally-available soils; and the protective grass cover quality can vary widely depending on climate, grass species, and dike maintenance as illustrated by the photographs in Figure 1.

Figure 1. Variations in grass quality on the Herbert Hoover Dike, Florida, USA.

The capability of earthen levees, dikes, and embankments to withstand sustained wave overtopping is a function of hydraulic loading severity, duration of wave overtopping exposure, and

[1] Department of Civil and Environmental Engineering, Colorado State University, 1320 Campus Delivery ERC, Fort Collins, Colorado 80523, United States

the robustness of the levee grass/soil system. Existing design guidance for tolerable wave overtopping of grass-covered slopes is given as an average overtopping discharge without any mention of the duration over which the overtopping occurs (e.g., Pullen *et al*. 2007). In other words, the duration of wave overtopping is implicit in the guidance. Clearly, wave overtopping that persists for 10 hours has the potential to be far more damaging than overtopping at the same rate that occurs for only 2 hours. Furthermore, the existing tolerable wave overtopping rates are considered to be quite conservative as shown by in-situ tests conducted in Europe using the Dutch Wave Overtopping Simulator (Van der Meer *et al*. 2008).

Recent developments in the area of levee grass resiliency have begun to incorporate overtopping duration into the evaluation of tolerable wave overtopping. Van der Meer *et al*. (2010) formulated the concept of "*Hydraulic Loading*", and the similar concept of "*Cumulative Excess Work*" was introduced by Dean *et al*. (2010) and further developed by Hughes (2011). Both methods consider overtopping duration through the cumulative effect of overtopping waves on the stability of the grass and soil.

Over the past three years Colorado State University (CSU) has investigated the resiliency of grass levee slopes by conducting full-scale wave overtopping tests using the world's largest wave overtopping simulator (Van der Meer *et al*. 2011). However, overtopping test results are specific to the soil/grass combinations tested and to the range of incident wave conditions simulated. Direct application of the test results to dikes or levees having different grass/soil and different overtopping characteristics would be unwise.

This shortcoming is being addressed by three parallel efforts. First, variation in erosion resulting from different incident wave conditions can be factored into the analysis using methods that seek equivalent overtopping impacts arising from different hydraulic conditions. Second, observed wave overtopping resiliency of specific soil and grass combinations is being expressed in terms of grass root and soil parameters to gain better understanding of how local variations in grass roots affect overtopping resiliency. Finally, practical design methods are being developed that accomodate realistic overtopping events where average overtopping discharge varies in time as storm intensity and surge level increase to a peak and then abate with passage of the storm.

This paper summarizes full-scale wave overtopping simulation test results, and presents tentative design methods for initial extension of the test results to other situations having different levee geometry, different wave conditions, and different grass/soil parameters. Our intention is to provide a viable framework that can be extended as more knowledge is gained from additional testing with different grass/soil combinations.

TEST FACILITY AND EXPERIMENT PREPARATION

The CSU Wave Overtopping Simulator is the largest in the world with total wave reservoir capacity of 31 m^3. The left-hand photograph in Figure 2 shows a large wave volume being released in

a) Wave Overtopping Simulator   b) Slope damage   c) Erosion estimate

Figure 2. CSU Wave Overtopping Simulator and typical grass cover damage.

the simulator. The middle photograph and contour plot on the right in Figure 2 show slope damage and soil erosion at the end of a testing sequence. The simulator can release overtopping wave volumes

approaching 17 m^3/m, and it can simulate wave overtopping events having average overtopping discharges as high as 370 l/s per m. During wave overtopping simulations, water enters the simulator vessel at a constant rate, and the release of prescribed wave volumes is controlled by a computer program that operates the release valve according to a concise set of instructions. A description of the simulator calibration and operation is given by Van der Meer *et al*. (2011).

The fixed-in-place Wave Overtopping Simulator requires that representative levee slopes be prepared in special "planter trays" for simulator testing. The trays have been fabricated to mimic the landside geometry and vegetated surfaces of typical U.S. levees and embankments. The landside grass slope geometry used in the testing to date consisted of a 8.5-metre-long section on a 1-on-3 slope that transitioned to a 3.6-metre-long berm section on a 1-on-25 slope as shown in Figure 3. The trays are 30 cm deep. The slope transition in the lower tray allows continuous soil/grass to be installed over this problematic region where increased erosion occurs due to hydraulic centrifugal forces. Trays installed in the simulator are shown in Figure 2.
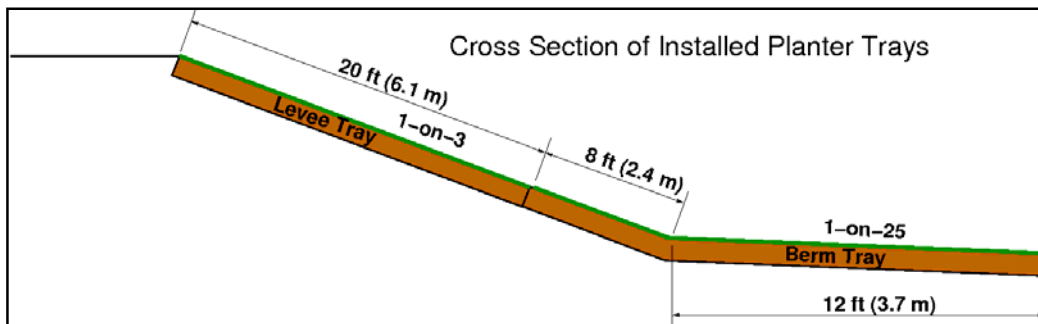

Figure 3. Grass slope planter tray geometry.

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

Representative photographs of planter tray preparation are shown in Figure 4. The photograph in the upper left shows compaction of the first lift of a sandy soil. The upper right photograph shows installation of Bahiagrass sod on a sandy soil. The photograph on the lower left side of Figure 4 shows completed and trimmed trays placed in one of the grasshouses shown on the lower right photograph.

TEST RESULTS
Wave overtopping tests completed thus far include healthy and dormant grass on clay (11 tests) and healthy grass with 50% or 30% coverage on sandy soil (11 tests). Some of the tests examined the increased resiliency provided by turf reinforcement mats. The tests of grass on clay were sponsored by the U.S. Army Corps of Engineers' New Orleans District to support strengthening of the New Orleans levee system, and the tests on sandy soil were sponsored by the Corps of Engineers' Jacksonville District to support a risk analysis of the Herbert Hoover Dike in Florida, USA.

New Orleans District Tests (Stiff Clay)
Nine planter tray sets for the New Orleans tests were fabricated and prepared at the Corps of Engineers' Coastal and Hydraulics Laboratory in Mississippi. The same stiff clay being used to reconstruct New Orleans levees was shipped to Mississippi and placed in two 13-cm-thick layers and compacted according to levee specifications. Finally, mature Bermuda or Bahiagrass sod was placed on the clay, and the trays were fertilized and watered extensively to compensate for the short growing period (6 months) prior to testing and to assure strong root systems. When ready, the trays were shipped to CSU for testing. One tray set had only bare clay, two sets had Bermuda grass, and two tray sets had Bahiagrass. Two tray sets had medium-strength turf reinforcement mats installed under Bermuda sod, and two of the tray sets had HPTRM under the Bermuda sod.

Figure 4. Preparation of planter trays.

All wave overtopping tests for the New Orleans District simulated an incident wave condition having significant wave height of $H_{m0} = 2.4$ m and peak spectral wave period of $T_p = 9.0$ s impinging on a levee seaward slope of 1V:4H. Tests were conducted in 1-hr segments during which time the average wave overtopping was held constant. Usually, the overtopping discharge was increased for the next 1-hr segment. The 11 tests are summarized in Table 1.

The middle column in Table 1 is the cumulative overtopping water volume that spilled over the levee slope during the entire test. Complete test details are given in Thornton *et al*. (2010).

Well-maintained and healthy Bermuda grass did not fail under extraordinary levels of wave overtopping. Superior resiliency of the Bermuda grass was attributed to a dense root system and ample thatching of the grass. Subsequent comparison of the

Table 1. New Orleans test summary.		
Specimen	**Cumulative Overtopping Volume (m³/m)**	**Result**
Bare clay	56	Failed
Bermuda	16,522	No Damage
Bahiagrass	13,244	No Damage
Bermuda w/TRM	10,034	No Damage
Bermuda w/HPTRM	9,632	No Damage
Bermuda w/Ruts	11,338	Minor Damage
Lime-Stabilized Clay	237	Failed
Articulated Concrete Blocks	4,013	Minor damage
Dormant Bermuda	**2,175**	**Failed**
Dormant Bermuda w/TRM	**2,207**	**Significant Damage**
Dormant Bermuda w/HPTRM	**6,187**	**No Damage**

grass root structure cultivated in the trays to similar root parameters found on actual New Orleans levees indicated that the grass in the trays had roots that were twice as dense as typical levee grass. In other words, the extreme performance of the healthy grass in the test trays was not representative of field performance that might be expected.

Fortunately, relevant performance data were obtained from trays (shown in bold font in Table 1) in which the healthy grass had gone dormant (or possibly died) over the harsh Colorado winter. During these tests, dormant Bermuda grass sustained significant damage at substantially reduced wave overtopping hydraulic loads, and trays containing an open-weave, medium-strength turf reinforcement mat were also damaged after similar reduced cumulative overtopping hydraulic loading. The most

interesting results occurred for dormant Bermuda grass reinforced with the HPTRM. This test specimen was able to sustain nearly three times the cumulative loading hydraulic loading of the other dormant-grass tests without any perceived damage. Grass root parameters obtained from the dormant Bermuda were similar to root parameters at various locations throughout the New Orleans levee system. Hence, the dormant tests simulated grass root systems that could be considered similar to the actual levees.

Figure 5a plots the cumulative overtopping volume per unit crest length as a function of overtopping duration for both the healthy and dormant grass. The slopes of the curves indicate rates of average overtopping discharge during each hour of testing. Steeper slopes correspond to tests in which the overtopping rates were higher. The curves that end with no damage indicate that testing ended at that point, and damage had not occurred. The lower left corner of the plot in Figure 5a contains two interesting results, and an expanded view of this portion of the plot is shown in Figure 5b.
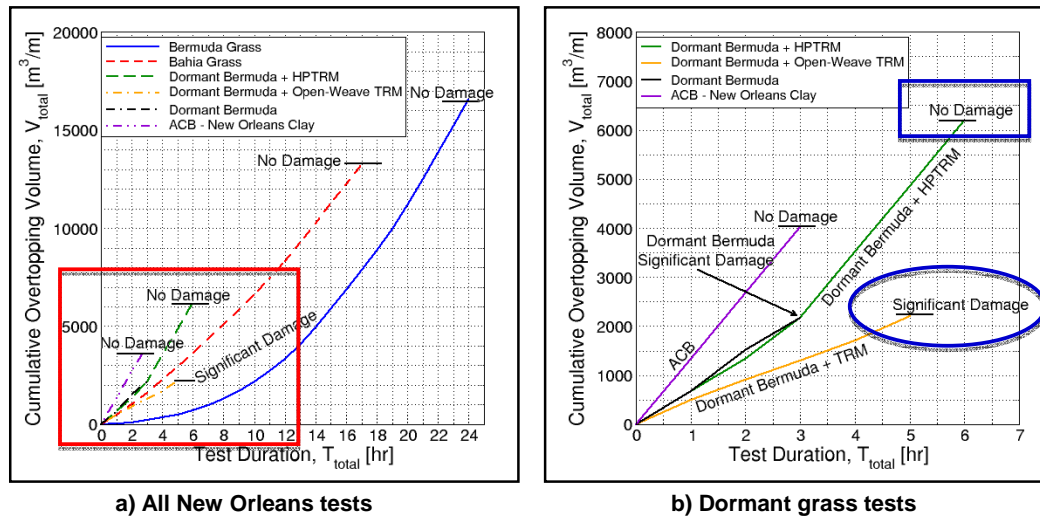

a) All New Orleans tests   b) Dormant grass tests

Figure 5. New Orleans tests cumulative overtopping volume per unit crest length versus time.

First, the dormant Bermuda grass test and the dormant Bermuda grass with the open-weave TRM both suffered significant damage at nearly the same cumulative overtopping volume. Because of the loading rate, the dormant Bermuda grass tray reached the damage point sooner. It appears that the open-weave TRM provided minimum additional resiliency when the grass was in a dormant state. Second, the tray containing dormant Bermuda grass strengthened with the HPTRM was able to resist cumulative loading that was 2.8 times greater than the damaged dormant grass tray. In fact, the upper limit of cumulative loading that might be withstood by the dormant grass with the HPTRM is unknown because testing was ended before damage occurred.

Jacksonville District Tests (Sandy Soil)
Florida levees and embankments are constructed using native soils with high percentage of sandy material, and Bahiagrass appears to be well suited to the subtropical and tropical climate. Twelve planter tray sets were prepared at CSU for the Jacksonville District tests. Four different soil types having similar grain-size distributions were acquired from Florida borrow sites targeted for use in levee and embankment construction, and the soil was 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. Each soil type was used in three planter tray sets. The sandy soil was placed in two compacted 13-cm lifts on top of the pea gravel layer, and Bahiagrass sod was placed over the soil (see Figure 4). Bahiagrass is a warm-season grass species characterized as having a deep root system for greater drought resistance associated with sandy soil in subtropical climate. Nine of the planter tray sets were grass-only, and two sets had HPTRMs installed prior to sod placement. All the grass trays were nurtured (watered and fertilized) during the Colorado winter inside special greenhouses that maintained temperature and humidity typical of Florida. Prior to testing, the grass in the trays was purposely distressed to result in grass coverage of about 50% of the surface area for nine tray sets and 30% for two tray sets).

The Jacksonville District test series featured five different incident wave parameters, four soil types, and two levels of grass coverage as indicated in Table 2. The seaward levee slope was assumed to be 1V:3H. Wave overtopping loading was applied in 1-hr segments with the average overtopping discharge increasing from one segment to the next. All tests resulted in failure of the grass surface, and the right-hand column of Table 2 lists the cumulative wave overtopping volume at the point of failure. The root parameters in Table 2 are discussed later in the paper.

Test	Grass Coverage	Wave Parameters		Root Parameters		Cumulative Overtopping Volume at Failure (m^3/m)
		H_{m0} (m)	T_p (s)	Length (cm)	Volume (cm^3)	
Table 2. Summary of test parameters and cumulative overtopping volume at grass failure.						
Soil Type 1						
1	50%	2.44	7.7	1,150.9	2.80	651
2	30%	2.44	7.7	610.1	6.52	551
3	30%	1.52	7.7	484.1	8.84	376
Soil Type 4						
4	50%	1.43	3.4	572.8	18.00	967
5	50%	2.04	4.5	478.0	14.95	630
6	50%	2.04	4.5	540.4	17.58	4,383
Soil Type 2						
7	50%	2.04	4.5	543.6	15.49	1,354
8	50%	2.20	6.0	707.2	13.73	301
9	-	2.20	6.0	-	-	3
Soil Type 3						
10	50%	1.43	3.4	549.7	12.02	552
11	50%	2.04	4.5	896.9	14.20	998
12	50%	2.04	4.5	537.8	11.87	2,447

The hydraulic loading during the initial two tests (Tests 4 and 6) proceeded very cautiously because of uncertainty about the grass resiliency on sandy soil. The surprising robustness of the grass cover indicated that subsequent tests could have more aggressive loading characterized by larger initial wave overtopping discharge with larger incremental increases with each passing test hour. Figure 6 shows the range of hydraulic loading sequences. Test 12 had the most rapid loading, and the other tests not shown on the plot had loadings similar to Test 5. The curves in Figure 6 terminate at the cumulative overtopping volumes at failure noted in the rightmost column of Table 2. An important outcome from the testing was that cumulative overtopping volume appears to be more important than the rate at which the hydraulic loading is applied. In other words, wave overtopping at higher average discharge rates will result in grass failure sooner, but the cumulative overtopping volume at failure is similar to the cumulative volume for failure that occurs from wave overtopping at lower discharge rates acting for longer durations.

Cumulative overtopping volume per unit crest length at failure is shown for all Jacksonville sandy soil tests in Figure 7. The horizontal dashed line proposes a "coarse" failure criterion of V_{WT} = 560 m^3/m for Bahiagrass on sandy soil having about 50% coverage. As seen in Figure 7, failure for some tests fell below this coarse criterion, and some failure cumulative volumes some are above it. Note that the coarse criterion does not account for differences in incident wave condition or grass root parameters. For the grass-only tests, soil type could be a factor in the test results variation, but the best explanation was found in terms of differences in grass root parameters as discussed later in this paper.

Importance of Dike and Levee Soil Type on Grass Slope Resiliency

The wave overtopping test series for New Orleans and Jacksonville Districts provided wave overtopping resiliency performance data for two vastly different soil types. Grass roots are expected to better resist hydraulic forces in lean clay if there are sufficient nutrients in the soil to foster dense root development. Generally, grass sod nurtured on clay was more resilient than sod placed on sandy soil. Nevertheless, the sandy soil tests exhibited a surprisingly high level of erosion resistance.
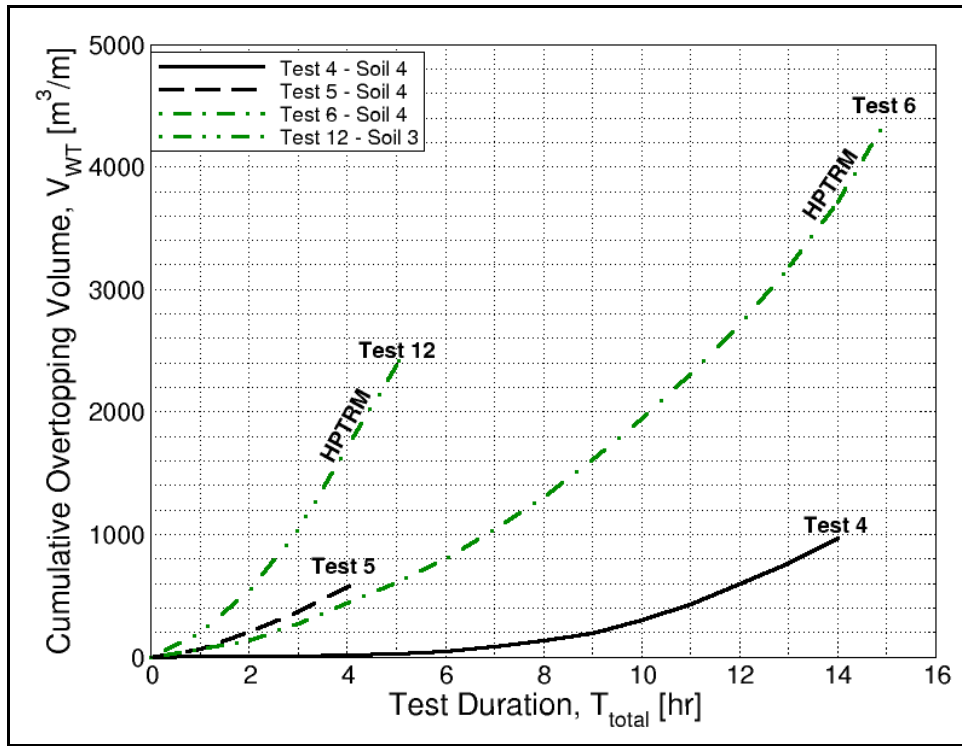
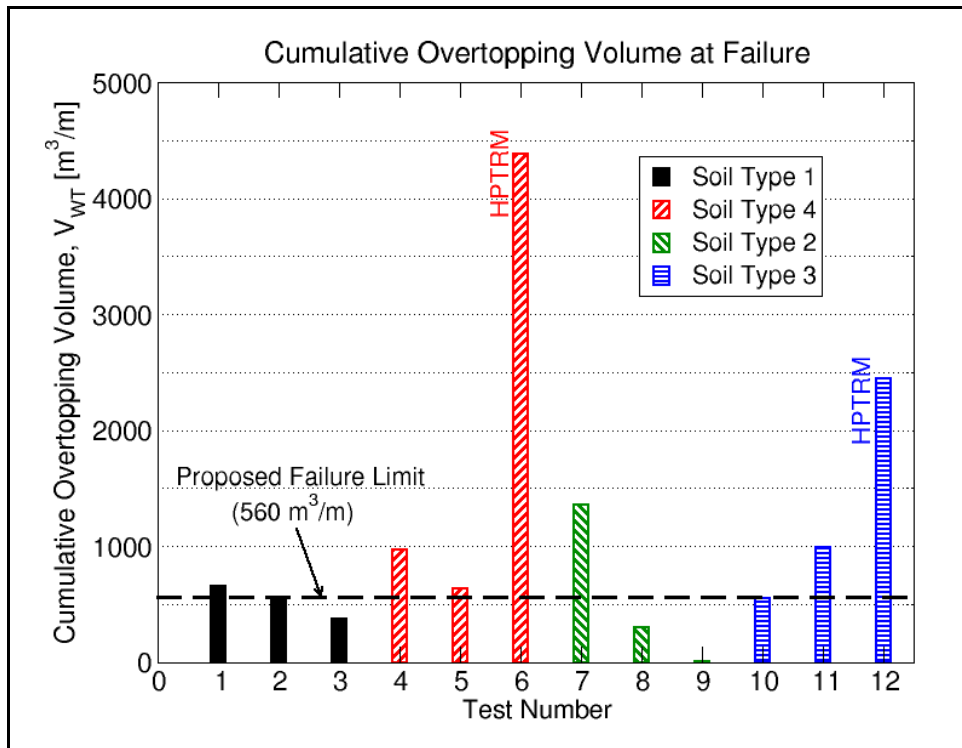**Figure 6. Jacksonville tests cumulative overtopping volume per unit crest length versus time.**

Figure 7. Cumulative overtopping volume per unit crest length at failure.

Figure 8a compares the failure of the New Orleans clay-soil test of <u>dormant</u> Bermuda grass to the failure levels of the Jacksonville sandy-soil tests of <u>healthy</u> Bahiagrass. The box on Figure 8a indicates the range of cumulative hydraulic loading over which failure occurred during the Jacksonville sandy soil tests. The New Orleans dormant grass test withstood more than twice the cumulative hydraulic loading of the Jacksonville tests. Some of the greater resiliency of the New Orleans test could have been caused by superior root density, but much of the grass strength appears to be related to better holding of the roots by the clay.

a) Grass-only tests   b) HPTRM+grass tests
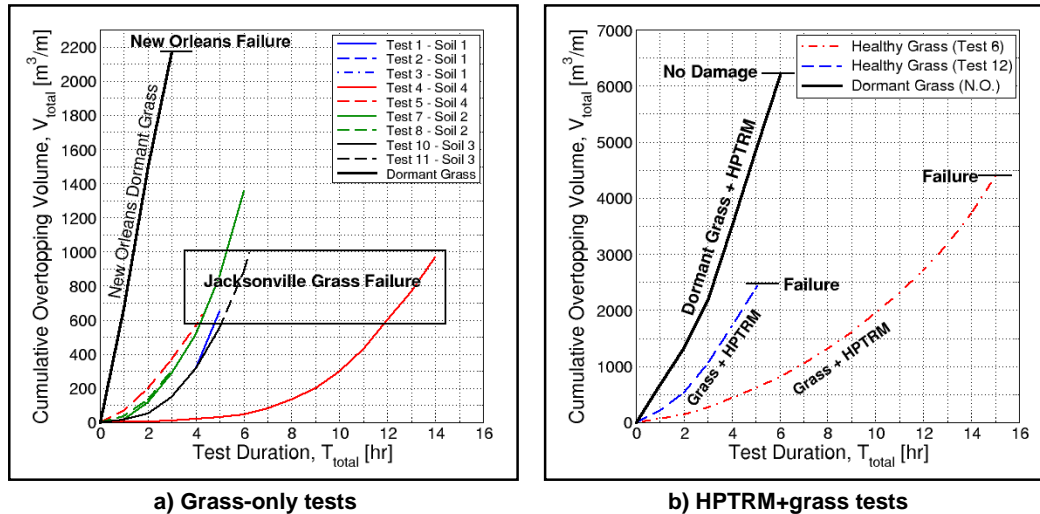
Figure 8. Influence of soil type on grass slope resiliency.

A comparison of resiliency of grass reinforced by HPTRMs is given for the two diverse soil types in Figure 8b. In this case, the ultimate damage level for the New Orleans dormant grass test is unknown, so it is not possible to conjecture on the degree of increased resiliency found for HPTRMs placed on clay as opposed to sandy soils. However, the resiliency increase is at least 2.5 for one brand of HPTRM and 1.5 for the other. The difference between the two HPTRMs installed on sandy soil was the percentage of openings in the mat; 15 percent openings for Test 6 and 30 percent openings for Test 12.

ESTIMATING GRASS-SLOPE RESILIENCY

Full-scale wave overtopping tests conducted using the Dutch-developed mobile simulator (Van der Meer *et al*. 2008) and the fixed-in-place CSU simulator have revealed several insights into grass-slope resiliency. However, the relatively few number of tests do not begin to cover the vast range of overtopping conditions, dike geometries, or soil/grass combinations needed for development of robust design guidance. Engineering techniques are needed for applying existing simulator results to other locations having different conditions. Three essential components are: (1) characterizing the wave overtopping hydraulic loading; (2) linking grass hydraulic resistance to the parameters of the grass root system; and (3) considering realistic overtopping discharge hydrographs caused by coastal storm surges. These components are discussed in the following subsections.

Characterizing Hydraulic Loads

Results from the Jacksonville District tests indicated that coarse tolerable overtopping limits for a specific grass/soil combination can be given in terms of the cumulative volume of the overtopping waves. However, the coarse criterion is tied to a narrow range of incident wave conditions and dike geometry. A multitude of different wave conditions and dike geometries could produce the same cumulative overtopping volume; but the characteristics of the individual overtopping wave velocity, $v(t)$, and flow thickness, $h(t)$, could be quite different. Thus, we should expect different erosional responses even if the soil/grass is the same.

Grass resiliency for wave conditions different than those tested could be estimated if there were a method to determine the erosional equivalence between the difference overtopping conditions. Two similar, independently-developed methods are being considered with the hope of using the methods to

find equivalent conditions (waves + overtopping duration) that can be tolerated for a specific grass/soil.

Van der Meer *et al.* (2010) proposed that dike erosion and damage occurs from accumulated "hydraulic loading" caused primarily by the impact by the overtopping wave leading edge (first 1 to 3 s of the wave). The hydraulic loading is the excess shear stress contained in the leading edge of the overtopping wave volume which is proportional to $(u^2 - u_c^2)$ where u is instantaneous velocity, and u_c is some threshold velocity. Figure 9a graphically portrays the hydraulic loading concept of Van der Meer *et al.*

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 cumulative excess flow work, proportional to $(u^3 - u_c^3)$, provided the best estimator of erosion; and the concept was named "*erosional equivalence*".

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, and the excess work was shown to be the excess wave volume above a critical discharge level. Figure 9b illustrates the cumulative excess work concept.

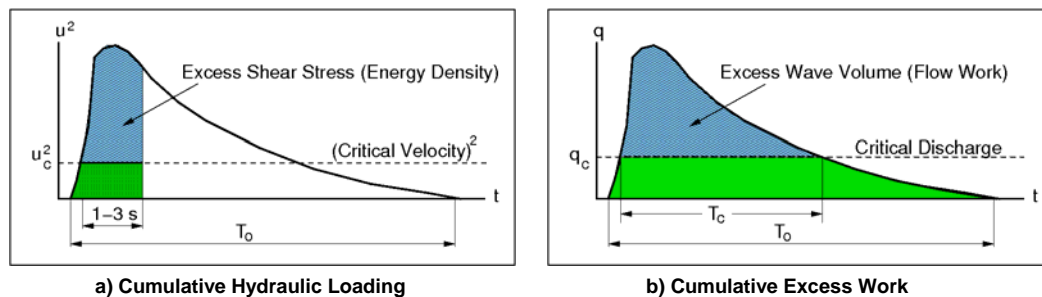| a) Cumulative Hydraulic Loading | b) Cumulative Excess Work |

Figure 9. Models for determining equivalent wave overtopping loading that have similar resiliency impacts.

In essence, the two proposed methods illustrated in Figure 9 are quite similar; and either one should prove to be a viable analysis candidate. Application of either method requires a minimum of two overtopping simulator tests simulating different wave overtopping conditions (incident waves + seaward dike slope) on identical grass slopes. Both tests must be continued until grass failure. Once this calibration has been performed, tolerable overtopping durations for other overtopping conditions can be estimated that give the equivalent hydraulic loading or cumulative excess work.

Hughes *et al.* (2012) applied the cumulative excess work method to Tests 4 and 5 from the Jacksonville District sandy soil series under the assumption that the only difference between the two tests was the simulated wave condition. Subsequent analysis of the grass root parameters (see Table 2) indicated this assumption was not correct. The following subsection shows that variation in grass root parameters has substantial effect of grass slope erosion resistance. Thus, a caveat when applying the equivalent hydraulic loading methods is that grass/soil parameters be the same.

Linking Hydraulic Resistance to Root Parameters

Engineers have long recognized that grass-slope resiliency during hydraulic flows is a function of various parameters of the grass stems and roots. Temple *et al.* (1987) characterized the hydraulic resiliency potential of grass in terms of a *retardance curve index* that is a function of representative grass stem length and stem density (stems per unit area). They also specified a *vegetal cover factor* to describe the protection provided by denser grass cover. These two parameters were used in application of effective shear stress concepts for determining stability of erodible channels during steady flow.

Dutch guidance (VTV 2006) for dike safety assessment stated that grass hydraulic resistance capability is strongly correlated to the depth variation of root area (mm^2) per m^2 of grass cover. Classification of grass between *very poor* and *good* was shown in a chart giving number of roots per m^2 surface area for depth variations between 0 and 20 cm. Steendam *et al.* (2010) analysed grass slopes tested during in-situ wave overtopping simulator tests according to the VTV guidance and

concluded the tested grass during winter months was good. Hoffmans *et al*. (2008) developed a theoretical *turf-element* model for analysing dike grass erodibility. This model included practically all of the physical processes at a macroscopic level including air entrainment and turbulent flow fluctuations. Hoffmans *et al*. stated that the development should be considered a *conceptual model* until detail measurements can be acquired.

The analysis contained in this subsection pertains only to the Jacksonville District tests conducted with grass sod on sandy soil. All but two of the CSU sandy-soil wave overtopping tests experienced gradual grass slope failure due to a combination of loss of supporting soil and, to a lesser extent, breakage of grass stems by hydraulic drag forces acting on the plants. The two aforementioned exceptions were tests where the Bahiagrass sod was stripped off in large sections by the flowing water.

After completion of the Jacksonville District wave overtopping tests, soil cores were collected from the planter trays to a depth of 20 cm, preserved in capped polycarbonate tubes, and shipped to Louisiana State University's AgCenter Soil Testing and Plant Analysis Laboratory for analysis. The samples went through a process to remove excess biomass and soil before being scanned at high resolution. The images were analysed to produce various root parameters including: total root length, root surface area, average root diameter, and root volume.

Each of the individual average root parameters of all nine grass-only Jacksonville District tests were plotted versus the cumulative overtopping water volume at failure. Good correlations were found for both average root length and average root volume. The volume of roots per unit surface area is an indicator of grass root density, and the total root length per unit area indicates the penetration of the roots into the soil. Both of these parameters are somewhat similar to the parameters given by Temple *et al*. (1987) and the Dutch guidance (VTV 2006). It seemed appropriate that a combination of these two root parameters might correlate well with the cumulative overtopping volume at failure.

The product of average root length and average root volume is shown in Figure 10 versus cumulative overwash volume at failure for all nine of the grass-only tests. Values of the root parameters are given in Table 2, and corresponding test numbers are indicated by each marker on the plot. The coarse criterion based on Figure 7 is shown by the horizontal dashed line in Figure 10.
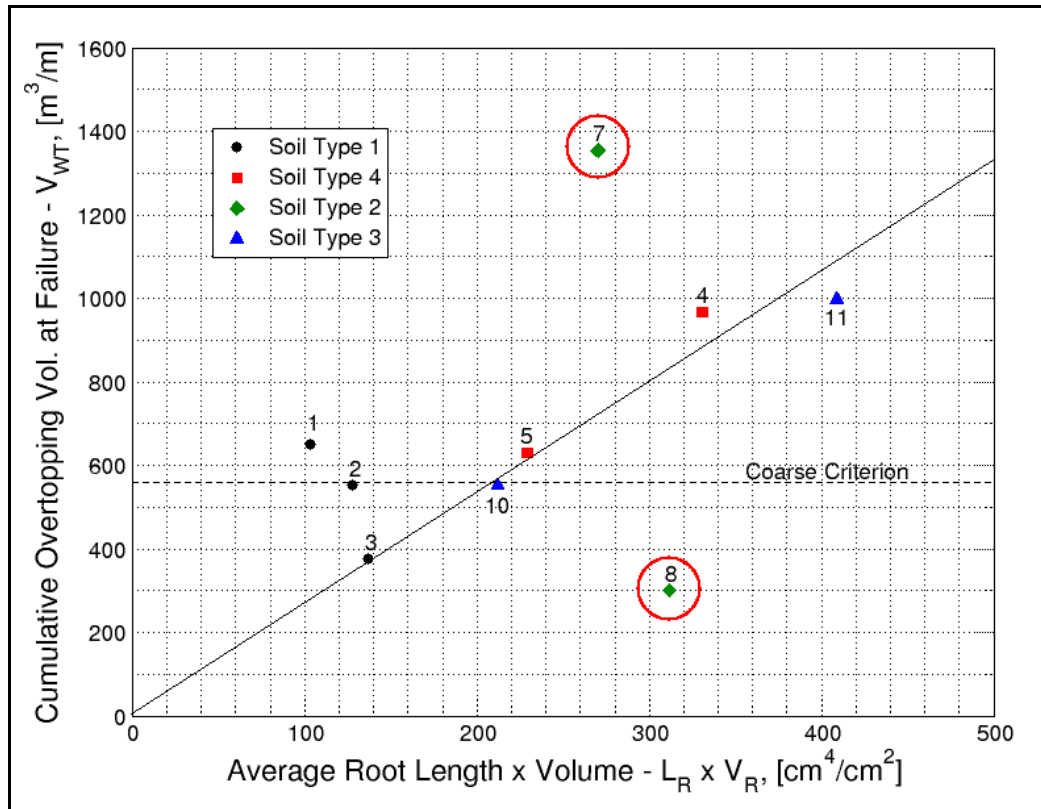

Figure 10. Root length times root volume per unit area versus cumulative overtopping volume at failure.

Five of the tests (3, 4, 5, 10, and 11) exhibited a good trend as indicated by the solid line in Figure 10. The two tests for soil type 2 (circled diamonds) did not follow this trend because the soil was more calcareous than the other soils, and the soil particles cemented together when water was applied during cultivation of the grass. Consequently, the roots had difficulty penetrating into the soil (as indicated by the post-test sampling). Grass failure for both Test 7 and 8 occurred when large sections of the sod were separated from the underlying soil and swept down the slope. This failure method is entirely different than the progressive erosion of soil supporting the grass plants seen for all the other tests. Thus, it seems understandable that Tests 7 and 8 fail to follow the clear trend seen for soil types 3 and 4. Tests 1, 2, and 3 (soil type 1) also deviate from the trend indicated by the solid line. Soil type 1 had significant organic content compared to the other soil types. Interestingly, the average root volume was lower than for the other soils, but the root lengths tended to be longer, which would give more holding power (see Table 2). On the other hand, the higher organic content of soil type 1 likely made the soil more easily eroded, and this could have offset the advantage of deeper rooting.

Figure 11 combines the nine grass-only tests shown on Figure 10 with the two tests of grass reinforced with HPTRM (Tests 6 and 12). The main difference between the two HPTRMs was the percentage of openings in the mat. The HPTRMs would be expected to tolerate a limited amount of overtopping volume without any grass cover, and the hypothetical lines drawn on Figure 11 are meant only to illustrate the potential design information that could be acquired with additional tests. An interesting result was the HPTRM with smaller openings (Test 6) managed to develop a better root system than the HPTRM with larger openings (Test 12).
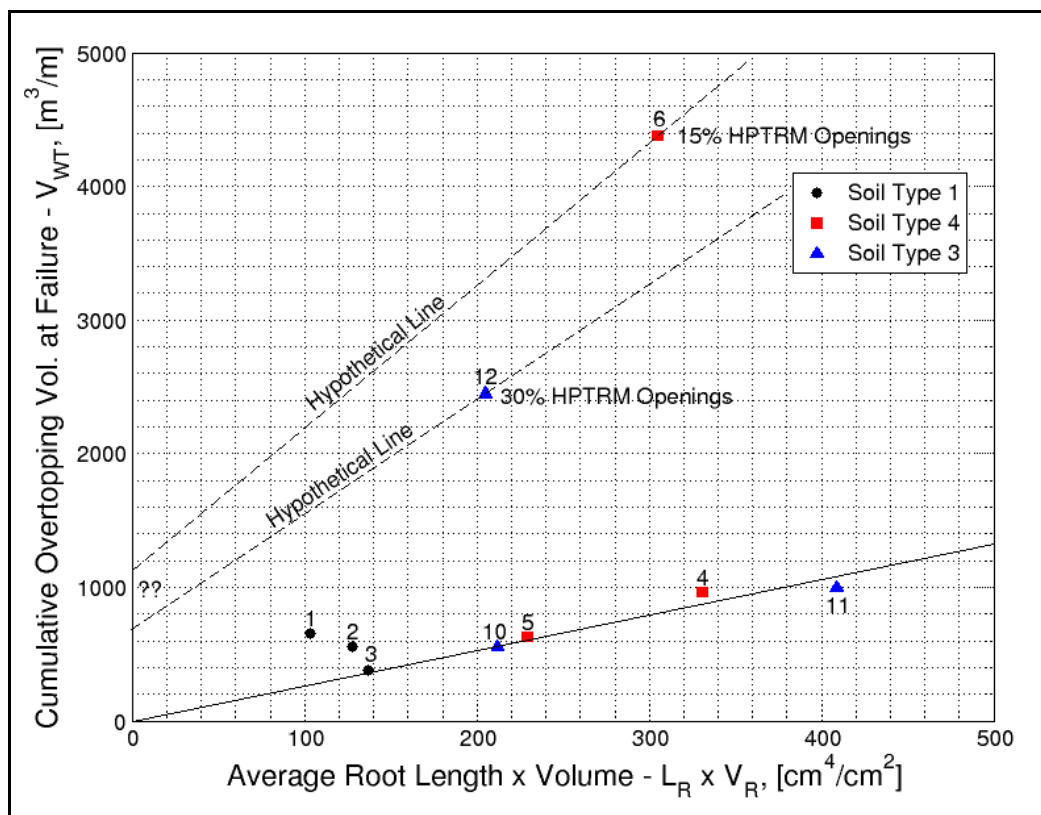

Figure 11. Root parameter versus cumulative overtopping volume at failure including HPTRM tests.

Variation of Overtopping Discharge in Time

Present guidance for tolerable wave overtopping is given in terms of an average overtopping discharge magnitude without any mention of overtopping duration. This conservative guidance is contrary to the accepted guidance for steady overflow (Hewlett *et al*. 1987) where the magnitude of the hydraulic forces (i.e., maximum flow velocity on the slope) is tied to the duration of overflow. A

second important aspect for coastal dikes and levees is the fact that the average overtopping discharge can slowly vary in time as the surge level increases to a peak and then decreases with the passing of the storm. During this realistic scenario, the landward-side slope is subjected to increasing hydraulic loading up to some maximum discharge before the discharge begins to decrease. The cumulative overtopping volume is essentially the integration of the area under the overtopping discharge hydrograph. The upper plot of Figure 12 shows three idealized discharge hydrographs having the same peak discharge, but different overtopping event durations. The lower plot presents the corresponding cumulative overtopping volumes, and a horizontal line has been drawn to represent the coarse sandy-soil criterion discussed previously. The overtopping lasting only 1 hr does not surpass this criterion. However, the 3-hr event reaches the criterion after about 1.5 hrs, and continued severe erosion would be expected for the final 1.5 hrs. Naturally, the 5-hr overtopping event would be the most damaging.
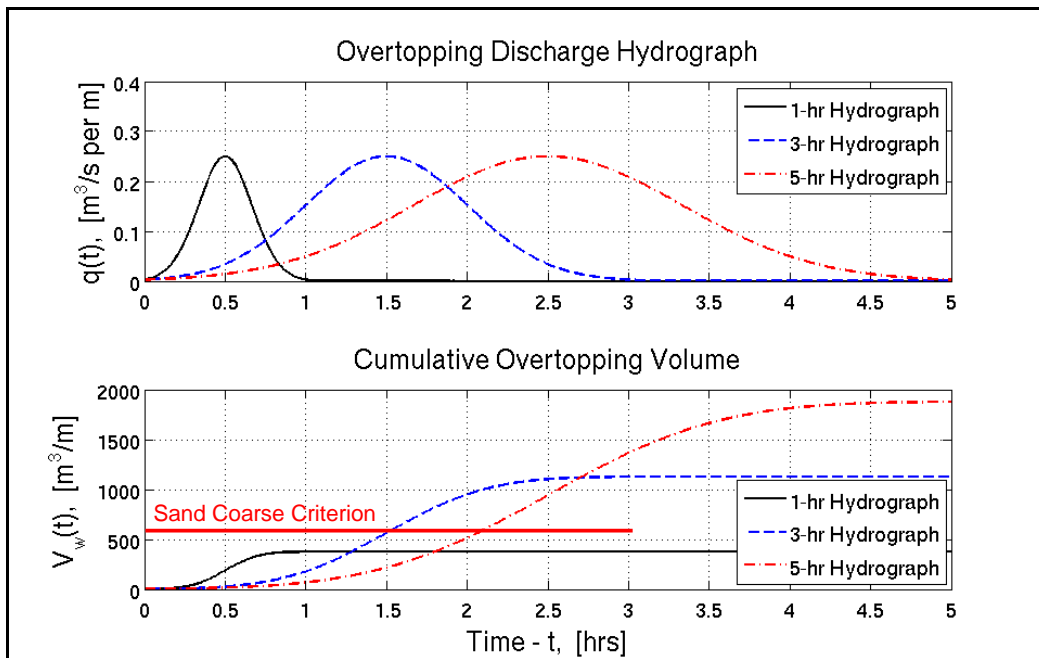

Figure 12. Three discharge hydrographs having the same peak discharge but different overtopping durations.

Figure 13 presents three idealized overtopping discharge hydrographs having different durations, and different peak discharges. The cumulative overtopping volume per unit dike length is equal to the sandy soil coarse criterion (560 m^3/m) for all three hydrographs. The solid line in Figure 14 represents the possible combinations of peak discharge and overtopping duration that result in the same cumulative overtopping volume (560 m^3/m) when using the idealized hydrograph shapes shown in Figure 13. The fact that vastly different discharge hydrographs result in the same cumulative overtopping volume implies that longer durations can be tolerated provided the peak discharge is lower. In other words, both duration and discharge peak magnitude are equally important.
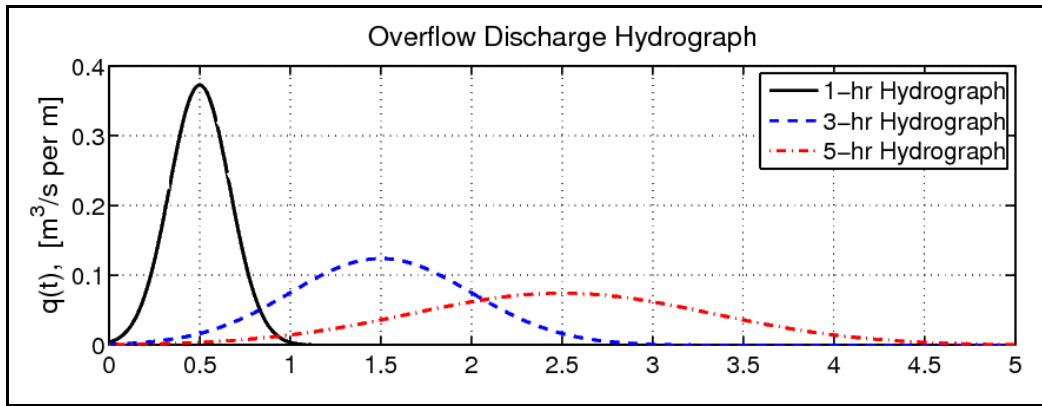
Figure 13. Three discharge hydrographs having the same cumulative volume but different durations.
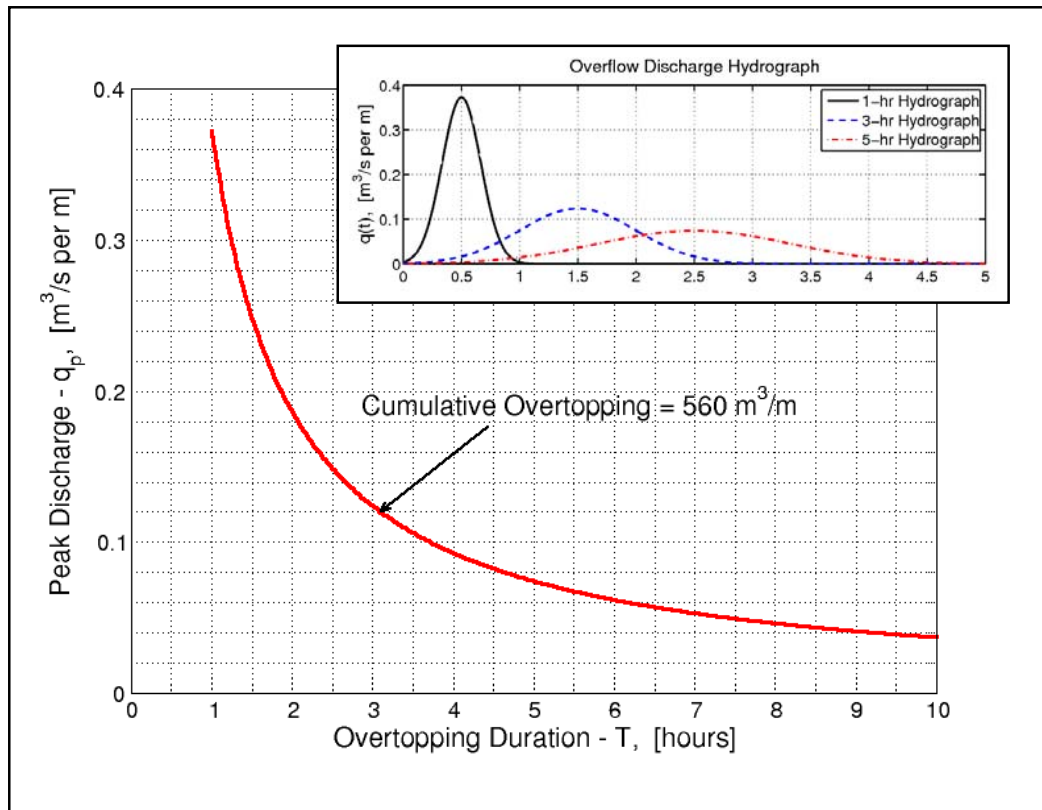

Figure 14. Combinations of peak discharge and overtopping duration producing same cumulative volume.

The main (as yet, unproven) hypothesis in this development is that damage to the grass slope should be similar for all hydrographs having the same cumulative volume. However, a key assumption in this hypothesis is that accumulation of overtopping volume (more correctly, excess work) does not depend on how the discharge slowly varies in time. For example, an unrealistic overtopping event where the average overtopping discharge increases instantaneously to 50 l/s per m and remains constant for 3.1 hr would also give the same cumulative overtopping volume of 560 m^3/m as the three hydrographs shown in Figure 13. A final consideration is that all of the different discharge hydrographs may not have the same hydraulic loading or cumulative excess work, and that aspect must be included in the analyses.

Proposed Resiliency Analysis Framework
    The following analysis framework is proposed for assessing tolerable wave overtopping for a specific dike grass/soil/geometry.

1. Use full-scale wave overtopping simulator tests (fixed or mobile simulator) to establish the grass cover resiliency as a function of grass root parameters for that specific wave overtopping incident wave condition.
2. Apply either the *hydraulic loading* or *cumulative excess work* methodology to translate results full-scale simulation results to other wave loading conditions.
3. Analyze grass failure risk using realistic overtopping discharge hydrographs that better represent the expected time variation of overtopping over the course of a storm event. Generally, more severe storms, such as hurricanes in the U.S., have higher surge levels but shorter durations compared to longer winter storms, such as the Northeasters in the U.S.

SUMMARY
    This paper summarized full-scale laboratory wave overtopping simulation test results from three years of testing conducted at the Colorado State University wave overtopping test facility. The results included 11 tests of healthy and dormant grass sod placed over clay soil and 11 tests of healthy grass sod founded on sandy soil. Grass failure was shown to be correlated to the cumulative wave overtopping water volume per unit dike crest length, and the clay soil showed significantly greater erosion resistance than the sandy soil. These results are specific to the tested soils and grass cover, so direct application to coastal dikes and levees built using different soils and grass species, or to locations subjected to different wave overtopping conditions, is not advisable.

    Tentative design methods are proposed for extension of the relatively few full-scale test results to other situations having different levee geometry, different wave conditions, and different grass/soil parameters. The intention is to provide a viable framework that can be extended as more knowledge is gained from additional testing with different grass/soil combinations.

    Resiliency of a specific grass/soil combination appears to be related to parameters of the grass root system. Correlations between the cumulative hydraulic loading at grass failure and the root parameters would allow other locations having different root parameters to be assessed for tolerable overtopping. This initial assessment would assume simulator incident wave conditions as used during the simulator testing. However, if the root parameters are correlated to the accumulated *hydraulic loading* or *cumulative excess work*, it should be possible to account for different wave conditions as well as different root parameters. Finally, the overtopping event should be analysed using a realistic overtopping discharge hydrograph that better represents how overtopping actually occurs during storm events.

    An important next step is to verify the hypotheses and assumptions given in this paper, namely:

1. The correlation of grass root parameters to cumulative hydraulic loading needs to be confirmed and expanded,
2. The concepts of equivalent hydraulic loading need to be verified (and perhaps united); and
3. The assumptions given for time-varying discharge hydrographs need to be confirmed.

    If and when the above steps are accomplished, the final step toward robust design guidance for overtopping resiliency of grass-covered slopes is expanding the knowledge base to include different soil/grass types, different maintained grass conditions, strength of repaired grass covers, and increased resiliency offered by turf reinforcement mats.

REFERENCES

Dean, R. G., Rosati, J. D., Walton, T. L., and Edge, B. L. 2010. Erosional equivalences of levees: Steady and intermittent wave overtopping, In: Demirbilek (editor), *Special issue of Ocean Engineering,* Elsevier, **37,** pp 104-113.

Hewlett, H. W. M, Boorman, L. A., and Bramley, M. E. 1987. Design of reinforced grass waterways," CIRIA Report 116, Construction and Industry Research and Information Association, London.

Hoffmans, G., Akkerman, G. J., Verheij, H., Van Hoven, A., and Van der Meer, J. W. 2008. The erodibility of grassed inner dike slopes against wave overtopping, *Proceedings of the 31st International Conference Coastal Engineering*, American Society of Civil Engineers, Vol 4, pp. 3224-3236.

Hughes, S. A. 2011. Adaptation of the levee erosional equivalence method for the Hurricane Storm Damage Risk Reduction System (HSDRRS), ERDC/CHL TR-11-3, U.S. Army Engineer Research and Development Center, Vicksburg, Mississippi**.**

Hughes, S. A., Thornton, C. I., Van der Meer, J. W., and Scholl, B. N. 2012. Improvements in describing wave overtopping processes," *Proceedings of the 33rd International Conference Coastal Engineering*, American Society of Civil Engineers.
Available at http://journals.tdl.org/icce/index.php/icce/article/view/6684/pdf_659.

Pullen T., Allsop, N.W.H., Bruce, T., Kortenhaus A., Schüttrumpf H., van der Meer, J. W. 2007. EurOtop: Wave overtopping of sea defences and related structures: Assessment Manual, www.overtopping-manual.com.

Steendam, G. J., Van der Meer, J. W., Hardeman, B., and Van Hoven, A. 2010. Destructive wave overtopping tests on grass covered landward slopes of dikes and transitions to berms, *Proceedings of the 32nd International Conference Coastal Engineering*, American Society of Civil Engineers. Available at: https://journals.tdl.org/icce/index.php/icce/article/view/1478/pdf_135.

Temple, D. M., Robinson, K. M., Ahring, R. M., and Davis, A. G. 1987. Stability design of grass-lined open channels, Handbook No. 667, Agricultural Research Service, U.S. Department of Agriculture, 175 pp.

Thornton, C. I., Scholl, B. N., and Abt, S. R. 2010. Wave overtopping simulator testing of proposed levee armoring materials, Engineering Research Center, Colorado State University, Fort Collins, Colorado.

Van der Meer, J. W., Steendam, G. J., de Raat, G., and Bernardini, P. 2008. Further developments on the wave overtopping simulator, *Proceedings of the 31st International Conference Coastal Engineering*, American Society of Civil Engineers, Vol 4, pp. 2957-2969.

Van der Meer, J. W., Hardeman, B., Steendam, G. J., Schüttrumpf, H., and Verheij, H. 2010. Flow depths and velocities at crest and inner slope of a dike, in theory and with the wave overtopping simulator, *Proceedings of the 32nd International Conference Coastal Engineering*, American Society of Civil Engineers. Available at: http://journals.tdl.org/ICCE/article/view/1239.

Van der Meer, J. W., Thornton, C., and Hughes, S. 2011. Design and operation of the US wave overtopping simulator, *Proceedings of 6th International Conference on Coastal Structures,* World Scientific, Singapore.

VTV. 2006. Safety assessment of the primary flood defences (in Dutch), Ministry of Transport, Public Works and Water Management, Rijkswaterstaat, Delft.