TESTING LEVEE SLOPE RESILIENCY AT THE NEW COLORADO STATE UNIVERSITY WAVE OVERTOPPING TEST FACILITY

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Resilient levee design requires guidelines developed using controlled experiments conducted at full scale to avoid significant scale effects related to grass strength and soil erosion. Colorado State University was commissioned by the New Orleans District, Corps of Engineers to (1) design, build, and calibrate a large Wave Overtopping Simulator, and (2) conduct extensive resiliency tests of grass slopes and other erosion protection alternatives subjected to very high irregular wave overtopping rates. The landward-side levee slope was replicated for the experiments using "planter boxes" prepared in the same manner as actual levee slopes. The grass proved to be surprisingly resilient at average discharges up to 370 l/s per m without failure, but dormant grass did fail at lower discharge rates. Bare clay exhibited little resiliency to wave overtopping. Hydraulic measurements quantified the degree of air entrainment at the lower end of the levee slope, and the measurements indicated a centrifugal force contribution at the transition between the levee and toe berm slopes.

INTRODUCTION

During Hurricane Katrina that struck New Orleans in 2005, the most common cause of earthen levee or dike failure was attributed to severe wave overtopping and erosion of the landward (or protected) side slope. In the absence of reliable design guidance for assessing levee slope resiliency, Task Force Hope of the New Orleans Corps of Engineers recognized the need to conduct full-scale tests of levee slopes to evaluate the performance of grass and various slope armoring alternatives. Colorado State University (CSU) was commissioned to design and build a unique testing facility that would be capable of simulating full-scale wave overtopping having maximum average overtopping discharges between 200 and 300 l/s per m. CSU designed and constructed a large wave overtopping test facility styled after the successful Dutch mobile overtopping simulator design. The design and calibration of the new CSU wave overtopping simulator is described in detail by Van der Meer, et al. (2011).

FACILITY CAPABILITIES

The primary functional design requirements for the Wave Overtopping Test Facility included the following: (a) capable of simulating wave overtopping associated with large average overtopping discharge, (b) replicate the primary

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features and attributes of levee grass slopes typical of New Orleans levees including the underlying clay soil, and (c) able to test alternative slope protection products such as turf-reinforcement mats (TRM) and articulated concrete blocks (ACB). The design issues associated with fulfilling the functional requirements included: design of the wave overtopping simulator; realistic representation of levee grass/soil in planter trays; development of consistent operating protocols; and design of a measurement scheme to quantify the hydraulic regime.

The CSU Wave Overtopping Test Facility was constructed as a fixed-in-place machine because of its large size. Thus, instead of transporting the simulator to an actual levee, it was necessary to *"take the levee to the simulator"* in the form of "planter boxes" or trays that were specially prepared to mimic the vegetated surfaces of typical New Orleans levees. The facility design (Figure 1) features structural steel supports for two side-by-side 1.8-m-wide test channels that support the levee trays. The wave overtopping simulator machine (large vertical container shown in Figure 1) can be easily moved to either channel. An overhead gantry crane facilitates placement and removal of the test planter trays.

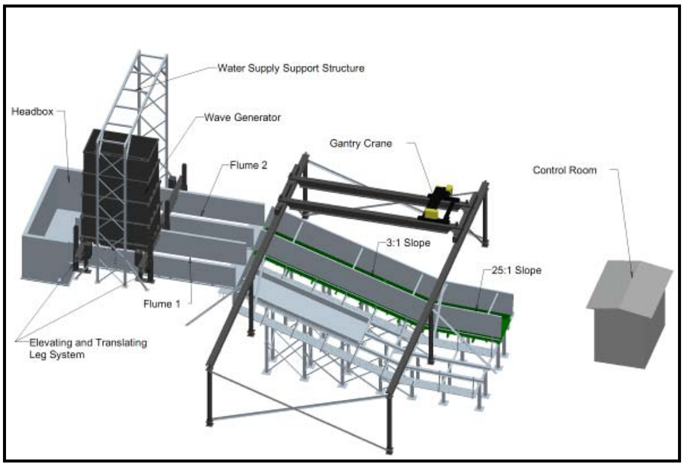

Figure 1. Schematic of Wave Overtopping Test Facility.

The CSU Wave Overtopping Simulator is the largest in the world with total wave reservoir capacity of 31 m^3. The simulator can release overtopping wave volumes up to 17 m^3/m, and it can simulate wave overtopping events having average 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. (See Van der Meer, et al. 2011 for description of calibration and operation). The facility can also produce steady overflow of at least 1.4 m^3/s per m over the levee test section.

The levee geometry tested for the New Orleans District consisted of a 8.5-m-long section on a 1-on-3 slope that transitioned to a 3.6-m-long berm section on a 1-on-25 slope as shown in Figure 2.

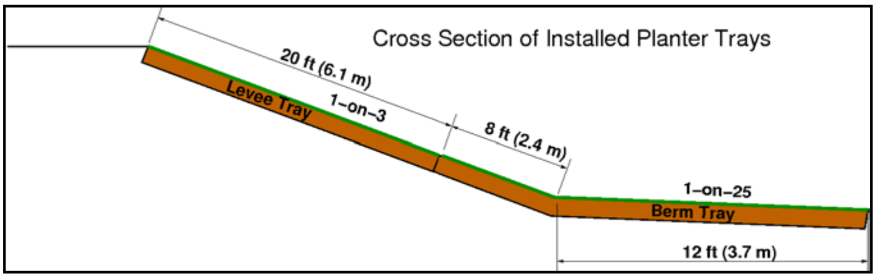

Figure 2. Schematic of planter trays used for New Orleans test.

PLANTER TRAY PREPARATION

Full-scale levees are simulated by “planter boxes” or trays that have been specially prepared to mimic the geometry and vegetated surfaces of typical New Orleans levees. The tested levee geometry was constructed using two steel trays as shown in Figure 2. The upper portion of the levee slope is represented by a straight tray having a length of 6.1 m. The tray for the lower portion of the levee has a bend with dimensions and slopes as shown on Figure 2. The reason for locating the slope transition at the interior of the tray was to assure soil and grass continuity at the transition where erosion is known to occur. Both planter trays making up a “set” had width of 1.8 m and depth of 30 cm.

A total of nine planter tray sets were fabricated and prepared at the U.S. Army Engineer Research and Development Center in Vicksburg, Mississippi. A 5-cm-thick layer of pea gravel was placed in the bottom of the trays and covered with filter cloth. The same clay being used to construct New Orleans levees was placed in two 12-cm-thick layers with each layer being thoroughly compacted according to New Orleans District levee specifications. Finally, mature 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. Figure 3 illustrates tilling of the clay, placing of the sod, and nurturing the grass prior to shipping the trays 2,000 km to Colorado. One tray set had only bare clay, two sets had Bermuda grass, and two tray sets had bahia grass. The four remaining tray sets had turf reinforcement mats installed under Bermuda sod.

The trays were installed into the test facility with an overhead crane, and side walls were bolted on to confine the flow. Installed trays were watered as needed if testing did not begin immediately or if the testing sequence was interrupted.

Figure 3. Planter tray preparation in Vicksburg, Mississippi.

LEVEE SLOPE RESILIENCY TESTS

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. Following each one-hour test segment, the surface of the test levee was surveyed, visually inspected, and photographed. No intrusive instrumentation was mounted in the levee test channel because of the possibility of inducing erosion farther downstream.

Nine distinct levee resiliency tests were conducted during the period September 2010 – March 2011. Table 1 summarizes the key parameters and end result for these tests. Several of the tests are discussed below. More comprehensive results for all tests are given in Thornton, et al. (2010).

Table 1. Summary of levee resiliency tests.

Levee Slope Surface	Hrs	Max. Ave. Discharge		End Result
		l/s per m	ft^3/s per ft	
Bare Clay	1.3	19	0.2	Severe Erosion
Bermuda Grass	24	370	4.0	No Damage
Bahia Grass	17	280	3.0	No Damage
Bermuda w/TRM	9	370	4.0	No Damage
Bermuda w/HSTRM	9	370	4.0	No Damage
Bermuda w/Ruts	9	370	4.0	Minor Erosion
Lime-Stabilized Clay	2	370	4.0	Severe Erosion
Articulated Concrete Block	3	370	4.0	Minor Erosion
Dormant Bermuda Grass	3	230	2.5	Erosion

For all tests, the simulations corresponded to an incident significant wave height of H_{mo} = 2.44 m and a peak spectral wave period of T_p = 8.0 s impinging on a seaward-side slope of 1-on-4. Each one-hour test at specific average wave overtopping discharges up to q_w = 200 l/s per m took one hour to complete. Average overtopping rates between 200 and 370 l/s per m required run times greater than one hour to simulate one hour of overtopping because of the time needed to fill the reservoir for the greater number of larger wave volumes.

Bare Clay

The bare clay levee surface was tested for a total of 80 min. During the first hour of testing the average overtopping discharge was 9.3 l/s per m. At the end of the first hour significant soil loss had occurred. For the second hour of testing the lower 6.1 m of the test (i.e., the berm tray) was covered with a geotextile to prevent further erosion, and the upper 6.1 m (straight tray) was subjected to increased average overtopping discharge of 18.6 l/s per m. The second hour of testing was suspended after 20 min because the upper levee slope failed catastrophically and the lower slope and berm suffered additional significant erosion.

Bermuda Grass

The Bermuda grass resiliency tests consisted of one 12-hour test sequence and two 6-hour test sequences. The first sequence simulated wave overtopping in one-hour segments at progressively higher average wave overtopping rates of q_w = 9, 19, 28, 37, 47, 56, 74, 93, 112, 130, 149, and 167 l/s per m. Visual inspection and comparison surveys indicated little to no damage to the Bermuda grass after the first 12-hour sequence.

Nearly two weeks later, the second 6-hr test sequence was run on the Bermuda glass slope. The 6 hours consisted of 6 tests, with each test taking longer than one hour to simulate and "equivalent" one hour of overtopping at the higher rates. Tested average overtopping rates over one-hour durations were q_w = 204, 242, 260, 280, 280, and 280 l/s per m. Even at this extreme hydraulic loading, the Bermuda grass was nearly unscathed by the water. The final 6-hr test sequence was conducted almost two weeks later with 1-hr average overtopping rates of q_w = 307, 334, 370, 370, 370, and 370 l/s per m. Once again, the grass showed little damage and the soil was relatively intact.

The well-established and dense Bermuda grass root system, combined with extensive thatching of the grass proved to have sufficient erosion resiliency under fairly extreme conditions. The key finding from this test series was that nearly perfect Bermuda grass that has been carefully maintained can withstand substantial wave overtopping without damage.

Bahia Grass

The bahia grass resiliency test lasted a total of 17 hours. The sequence simulated wave overtopping in 1-hr segments at progressively higher average wave overtopping rates of q_w = 130, 149, 167, 186, 186, 186, 204, 204, 204, 223, 223, 241, 260, 279, 279, 279 and 279 l/s per m. Visual inspection and comparison surveys indicated little damage to the Bermuda grass and little soil loss at the completion of the 17-hr test sequence.

Bermuda Grass with Wheel Ruts

Wheel ruts were intentionally created in a previously untested Bermuda grass tray. The tray set was tested for 9 hrs at the following 1-hr average wave overtopping discharges: q_w = 279, 307, 334, 370, 370, 370, 370, 370, and 370 l/s per m. Grass and soil erosion in the wheel ruts was considered to be minor.

Articulated Concrete Blocks

A fairly typical articulated concrete block (ACB) system was tested using available blocks. The bare clay surface in the trays was covered with a geotextile, and the blocks were placed in a pattern according to the particular ACB system specifications. Voids in the blocks were filled crushed rock having $D_{50} \approx 25$ mm. The left-hand photograph of Figure 4 shows the ACB tray set in the overtopping facility prior to testing.

Before **After test at 370 l/s per m**

Figure 4. Articulated concrete block test.

The ACB installation was tested for 3 one-hour equivalents with average wave overtopping discharge of q_w = 370 l/s per m. At the completion of testing, the blocks and geotextile were carefully removed revealing only minor loss of clay soil as shown in the right-hand photograph in Figure 4.

Dormant Bermuda Grass

The previously-tested planter tray set containing Bermuda grass went dormant during winter, and the grass underwent freezing. The left-hand photograph of Figure 5 shows the installed dormant Bermuda grass trays. The testing sequence for dormant Bermuda grass consisted of three 1-hr segments with average wave overtopping discharges of q_w = 186, 232, and 186 l/s per m. Minor erosion was noted at the end of the first 1-hr segment, and the amount of noticeable erosion increased during the second hour segment at higher discharge. The overtopping discharge was decreased for the third hour of testing; and at the end of the third hour, significant damage had occurred as illustrated by the right-hand photograph of Figure 5. The trench in the grass had a cross-flume width between 15 and 30 cm, a depth between 5 and 15 cm, and a length of approximately 2.7 m. Testing was continued after the third hour at the rate of q_w = 186 l/s per m, but the test was suspended after 20 waves due to complete failure of the grass.

Before **At end of 3rd hour**

Figure 5. Dormant Bermuda grass test.

HYDRAULIC MEASUREMENTS

The intrusive native of instrumentation installed in the test channels could potentially influence the downstream erosion processes, so additional tests were scheduled that focused on the hydrodynamic processes associated with the resiliency tests. A non-erodible artificial turf material was used to replicate the surface roughness of turf grass. Figure 6 shows the location of instruments used to document the hydrodynamic flow conditions on the levee slope.

Instantaneous velocity and flow thickness were measured using “surfboards” located on the horizontal levee crest, immediately upstream of the slope transition, and at the downstream end of the 1-on-25 slope. The surfboard device was developed by the Dutch. When an overtopping wave propagates down the slope, the surfboard is raised as it follows the surface of the water. A rotational potentiometer at the surfboard mounting point measures the deflection angle that is then converted to flow thickness using a previously-established calibration equation. Velocity at the surface of the overtopping flow is measured by calibrated paddlewheel velocimeters that are mounted on the underside of the surfboard with only the paddlewheel protruding into the flow.

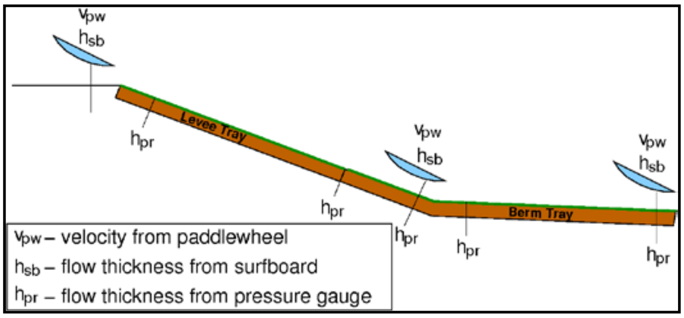

Figure 6. Instrument locations for hydraulic measurements.

Instantaneous flow thickness was calculated using measurements from five flush-mounted pressure transducers installed in the slope surface. The pressure transducers were located approximately 0.6, 5.5, 7.9, 9.1, and 11.6 m downstream from the landward edge of the horizontal crest. Three of the transducers were aligned with the velocity paddlewheels in the three surfboards. Synoptic time series data were collected from all instruments at a 50-Hz rate. Two interesting aspects of the measurement are discussed below.

Bulk Air Entrainment

Entrainment of air into the flowing water column increases the overall flow thickness, but the entrained air does not increase the pressure being exerted on the levee surface by the flow because the weight of the entrained air mass is negligible. This "bulking" of the flow volume can be characterized by a representative fluid density or fluid specific weight that is less than that of un-aerated water. The amount of entrained air could increase downstream from the point of initial entrainment until entrainment equilibrium is reached.

The amount of air entrained into the flow during wave overtopping was quantified by comparing flow thickness determined by different instruments located at the same position at the end of the 1-on-25 berm slope (see Figure 6). One time series of flow thickness was derived from the bottom-mounted pressure sensor by converting the instantaneous pressures to flow thickness perpendicular to the slope using the equation given by Henderson (1966) as $h = (p/\gamma_w) / \cos\theta$, where h is flow thickness perpendicular to the slope, p is bottom pressure, γ_w is the un-aerated water specific weight, and θ is the angle of the landward-side slope to the horizontal. Because the bottom pressure is due only to the weight of the aerated water mass, the flow thickness time series derived from pressure measurements represents the equivalent flow thickness without aeration.

The second flow thickness time series was obtained directly from the surfboard displacement as measured by the rotational potentiometer. These measurements represented the actual flow thickness of the aerated flow assuming the surfboard skimmed over the surface of the aerated flow. This assumption might not be strictly valid because it is possible that compressibility of the aerated flow allowed the surfboard to ride a bit below the surface of the flow rather than on the (ill-defined) flow surface.

Figure 7 compares a typical segment of flow thicknesses from the surfboard and pressure transducer. The surfboard measurements of aerated flow thickness are shown by the solid line; and at the wave peaks, the thickness of the aerated flow is substantially greater than estimates of un-aerated flow thickness (dashed line) from the pressure transducer. The difference between the two lines over much of the wave represents the "bulking" of the flow due to air entrainment. Note that the pressure gauge measured flow thicknesses of about 6 – 8 cm between waves. This is a measurement of standing water on the 1-on-25 slope that did not have time to drain between waves. The surfboard did not record this standing water because the surfboard weight caused it to sink to the bottom as flow velocity decreased with the passage of the wave.

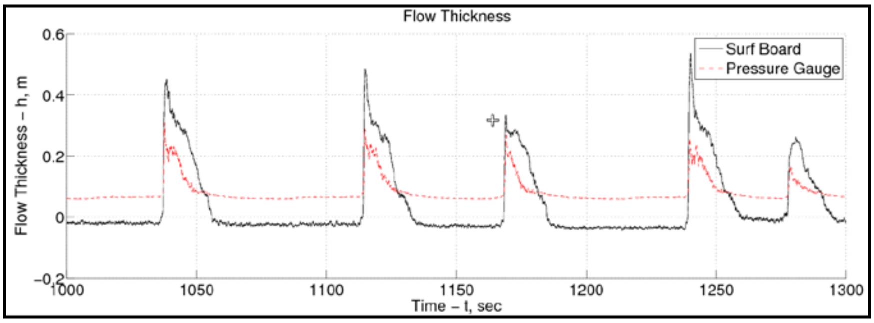

Figure 7. Measured "bulking" of flow thickness due to air entrainment.

Time series of instantaneous flow discharge were computed by multiplying the flow thickness time series by the synoptic velocity time series measured by the surfboard at the same location. The volumes of all 96 individual waves in the test run were estimated by integration of the discharge over the duration of the individual overtopping waves. A comparison of individual wave volumes based on pressure and surfboard flow thickness estimates is shown in Figure 8. For all but the smaller waves, the surfboard-based wave volumes were larger indicating the degree of air entrainment at that location in the flume. The largest wave volumes determined using the surfboard flow thicknesses exceed the known 17 m^3/m maximum capacity of the simulator vessel. The trend of the data in Figure 8 suggests the largest wave volumes contained about 35 percent air by volume.

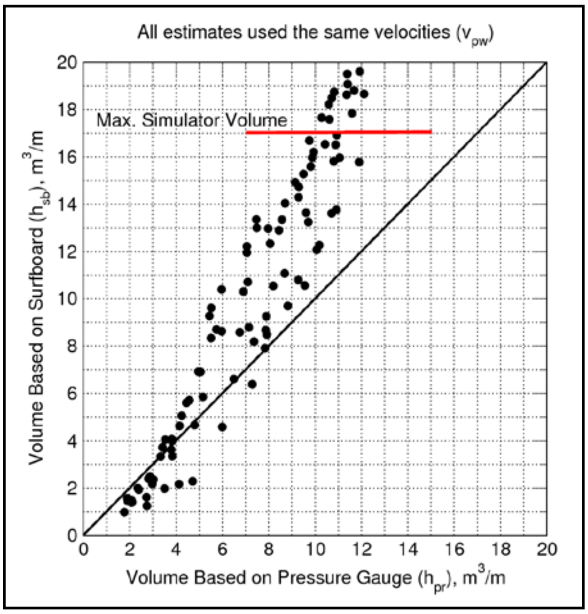

Figure 8. Individual wave volumes from pressure gauge and surfboard.

Effect of Centrifugal Acceleration at Slope Transition

Tests conducted in The Netherlands with the mobile Wave Overtopping Simulator resulted in damage at the toe of the landward-side dike face where the slope transitioned to a nearly horizontal surface (Van der Meer, et al. 2008; Steendam, et al. 2010). The location of this damage is not surprising because supercritical flow on the steep dike must be redirected at the slope transition. This redirection creates a centrifugal force on the levee surface in the immediate vicinity of the slope transition that is added to the pressure exerted on the bottom by the weight of the water. In other words the total acceleration acting on the water mass at the transition is the sum of gravitational and centrifugal accelerations.

Figure 9 compares the flow thickness recorded near the slope transition by the surfboard (solid line) with a "fictitious" flow thickness calculated from the pressure measurement at the same location (dashed line). The difference in the traces represents the effect of centrifugal acceleration at the slope transition, and this difference should NOT be interpreted as an actual physical increase in flow thickness. In fact, the actual difference may be more than shown in the plot because the surfboard measurements gave thickness of aerated flow.

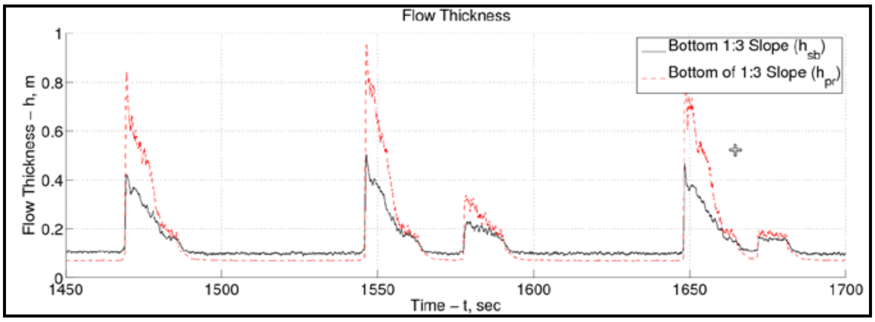

Figure 9. Centrifugal force at transition represented as "effective flow thickness.

Whereas the data confirm the importance of centrifugal forces at slope transitions, it is difficult to parameterize the centrifugal pressure in terms of the unsteady flow variables and levee geometry. One possible approach is to represent this pressure increase as an equivalent (fictitious) flow thickness that is added to the actual flow thickness and applied only over the region of slope transition. This would be equivalent to an imaginary increased water volume at that location working to erode the slope or damage the slope protection, and it could be termed the *"effective flow thickness."* This proposed approach would facilitate application of levee slope erosion analysis techniques such as *erosional equivalence* (Dean, et al. 2010; Hughes 2011) and the similar *hydraulic loading* (Van der Meer, et al. 2010) at vulnerable slope/berm transitions.

SUMMARY

The new Wave Overtopping Test Facility at Colorado State University is a permanent, fixed-in-place installation that can simulate large wave overtopping events and large steady overflow. The main challenge is preparing the soils, grass, or slope protection alternatives in the planter boxes to replicate accurately grass condition or other slope protection alternatives on actual levees.

Resiliency of several levee slope surfaces was examined in the facility at overtopping rates never before tested under controlled conditions. The bare clay slope failed rapidly, but well-maintained and healthy Bermuda grass did not fail under extraordinary levels of wave overtopping. The superior resiliency of the Bermuda grass was attributed to dense roots, ample thatching of the grass plants, and few imperfections. Healthy Bermuda grass with wheel ruts also survived at high average wave overtopping rates, but dormant Bermuda grass did sustain significant damage at reduced overtopping loads. A typical articulated concrete block system proved effective at preventing erosion of the underlying bare clay.

Hydraulic measurements acquired on the simulated levee slope were used to estimate bulk air entrainment by comparing flow thickness time series based on a surfboard that tracked the water surface and a pressure transducer that measured pressure due to water weight. The increase in flow thickness for aerated overtopping flows is substantial for larger waves. At the transition between the 1-on-3 levee slope and the berm, surfboard flow thickness measurements were compared to co-incident pressure measurements from a bottom-mounted pressure transducer to quantify the centrifugal force acting at the levee slope transition. The effect of centrifugal acceleration might be well represented as an effective flow thickness applied in the immediate vicinity of the slope transition.

Additional research that would help advance the state of engineering analysis of grass and slope armoring wave overtopping resiliency includes the following: (a) testing resiliency of less-than-perfect grasses and soils, (b) testing increased resiliency of turf reinforcement mats, (c) testing resiliency of grass on different slopes, (d) quantifying "effective discharge" at levee slope transitions, and (e) linking slope protection resiliency results from steady overflow tests to resiliency tests conducted for wave overtopping.

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Wave overtopping simulator
Levees
Levee resiliency
Wave overtopping
Air entrainment
Full-scale experiments