Technical Report II

Validations of EBSB Wave Induced Erosion and Breaching Analyses

Report to

Katrina Canal Breaches Consolidated Litigation

[Civil Action Number: 05-4182 “K” (2)]

United States District Court

Eastern District of Louisiana

Pertains to MR-GO, Robinson

[No. 06-2268]

By

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I. INTRODUCTION

The purpose of this study was to perform wave induced erosion and breaching analyses so that they could be compared with existing case histories to validate the lateral erosion method developed to estimate wave-induced erosion and resulting breaching of the MR-GO Earthen Berm – Spoil Banks (EBSBs) during Hurricane Katrina in 2005. The wave-induced erosion method was developed to provide a basis by which to estimate the rate and magnitude of erosion to flood protection elements as a result of wave impacts. The wave-induced erosion method consists of three steps:

1. velocity profiles were generated using LS-DYNA (assuming actual geometric configuration) at discrete time intervals;
2. resistance to wave-induced erosion as a result of grass cover (turf) on the flood face of the EBSB was estimated and no wave-induced erosion was applied until the grass cover protection failed, and
3. laboratory based testing soil erodibility characteristics were used, in combination with the estimated wave-induced flood face velocities, to estimate the magnitude of lateral erosion.

Wave-induced cumulative erosion of EBSB materials (E) was calculated using an integrated time-step function (Eq 1) based on the erodibility of the EBSB material at the time step being evaluated (where the erodibility of the time step is determined by the time-average shear velocities calculated at the defined storm surge elevations). The erodibility at the time step ($\dot{e}(v)$) is then multiplied by the value of the time step and summed to calculate the lateral extent of erosion: $\mathrm{E} = \sum \dot{e}(v(t))\Delta t$.

A plot is then generated that displays the estimated lateral erosion as a function of time and EBSB characteristics (geometry, grass cover, erodibility, and hydrodynamics).

The validation aspects included a comparison of lateral erosion as predicted by the wave-induced erosion method, a comparison of velocity profiles predicted with LS-DYNA vs. velocity profiles based on laboratory testing, and a comparison of the predicted lateral erosion via the wave-induced erosion method and closed form analytic solutions (Kriebel & Dean, 1993; Stanczak, 2008 and Allsop et al 2007). These analytical algorithms have been validated with field observations and laboratory experimental data.

II. SCOPE

The scope for this work consisted of developing three simulation validation case studies and conducting analytical calculations of estimated lateral erosion based on Kriebel & Dean (1993) and Stanczak (2008). The three validation case studies are lateral erosion at MR-GO Station 497+00 during Hurricane Gustav, velocity comparison based on laboratory experimental results provided by Hughes (2008), and lateral erosion magnitude and duration validation based on laboratory experimental results provided by Geisenhainer & Kortenhaus (2006).

For the validation numerical modeling analysis to simulate wave attack on the MR-GO levees during the Hurricane Gustav storm surge of 2008, the analysis will be completed using the LS-DYNA software package from Livermore Software Technology Corporation. Hydrodynamic inputs (storm surge, wave periods, and significant wave heights) and MR-GO grass cover

characteristics were provided by Bea (2008c) and van Heerden (2008) as input into these numerical analyses.

Velocity profiles were generated based on results from the laboratory study reported by Hughes (2008), using the LS-DYNA software program. The topography and hydrodynamics used in the experiments reported by Hughes (2008) were used as inputs to the numeric analyses. No lateral erosion measurements were made in the experimental work reported by Hughes (2008). Thus, the validation case study will be limited to overtopping velocity profile comparisons.

The third validation case study will be developed to confirm the wave-induced erosion rate (distance and time to breaching) calculated by the LS-DYNA flood-side wave-induced erosion method. Test results from laboratory experiments performed by Geisenheiner & Kortenhaus (2006), as resported by D'Eliso (2008) are used to validate the LS-DYNA wave side erosion analyses.

Analytic solutions using the algorithms developed by Kriebel & Dean (1993) and Stanczak (2008) and Allsop et al (2007) were derived (in Microsoft Excel) for the erosion analyses for Scenario 1 hydrodynamics (Katrina as was conditions), Scenario 2C hydrodynamics (Katrina Neutral MR-GO conditions), the Hurricane Gustav case study, and the D'Eliso case study. These wave-induced erosion analytic solutions do not address all the parameters accounted for in the LS-DYNA erosion evaluation, but because these analytical solutions have been validated with field observations and laboratory experimental data they will be useful to validate the general magnitudes (and times) of estimated breaching.

III. SUMMARY

The LS-DYNA based analyses of the MR-GO EBSB study location erosion development during Hurricane Gustav showed that there would be no significant erosion (grass cover or soils). The observations performed by van Heerden et al (2008) following Hurricane Gustav showed that there was no significant erosion at this location. Thus, the LS-DYNA analyses are in agreement with the observations.

The LS-DYNA based analyses of the laboratory experimental data reported by Hughes show good agreement between predicted and measured water velocities at crown and backside of model levee.

The LS-DYNA based analyses of the laboratory experimental data reported by Gesenhainer and Kortenhaus (2006) match closely the measured breaching time (and distance) of the model sand dike given that the soil comprising the experimental dike was simulated with a low compaction poorly sorted sand.

Analyses of the EBSB study location predicted breaching times during Hurricane Katrina conditions (Scenario 1) based on the LS-DYNA analyses (1.5 hours) were in good agreement with those based on the analytical models provided by Kriebel and Dean (2.4 hours) and Starczak and Allsop et al (2.0 hours).

Analyses of the EBSB study location predicted breaching times during Hurricane Katrina MR-GO Neutral conditions (Scenario 2C) based on the LS-DYNA analyses (no breaching or significant erosion) were in good agreement with those based on the analytical models provided by Starczak and Allsop (no breaching or significant erosion). Given that consideration is given to the turf / grass cover lift-off time, the analytical model provided by Kriebel and Dean would also predict no significant erosion.

Analyses of the EBSB study location erosion during Hurricane Gustav conditions based on the analytical models provided by Starczak (2008) and Allsop et al (2007) were in excellent agreement with those based on the LS-DYNA analyses (no significant erosion or turf – grass lift off) and with the observations of the EBSB study location following Hurricane Gustav (van Heerden 2008).

Analyses of the laboratory experimental dike wave breaching experiments performed by Geisenhainer and Kortenhaus (2006) based on the analytical models provided by Starczak and Allsop et al (2007) were in excellent agreement with those based on the LS-DYNA analyses (0.4 and 0.5 hours, respectively compared with an experimental result of 0.5 hours).

The primary conclusion reached as a result of the analyses documented in this report is that the LS-DYNA analyses are able to reliably replicate results from laboratory experiments, field observations, and results from other analytical models which have been validated with laboratory and field experimental data.

IV. HURRICANE GUSTAV ANALYSES

The validation numerical modeling analysis to simulate wave attack on the MR-GO levees during the Hurricane Gustav storm surge of 2008 was conducted using the wave-induced erosion method. Site topography at the time of the hurricane were provided by Morris (2008), hydrodynamic inputs (storm surge, wave periods, and significant wave heights) were provided by Risk Assessment and Management Services (RAMS, 2008), and EBSB post-hurricane condition, grass cover characterization and EBSB material characterization was based on van Heerden (2008). A discussion of the model inputs, configuration, and results are presented in the following sections.

Site Topography

A topographic survey of the EBSB study location was performed by Morris in October 2008 (Morris, 2008). The survey included the MR-GO crest elevation from Bayou Bienvenue to MR-GO Station 497+00 and a cross-section survey at MR-GO Station 497+00. The horizontal datum for the survey information was Louisiana State Plane, zone 1702 South, NAD83, the vertical datum was NAVD88 and all units were in feet. Figure 1 shows the surveyed cross section at MR-GO Station 497+00. The USACE design section (USACE, 2006) and maximum Hurricane Gustav storm surge elevations are also shown in Figure 1.

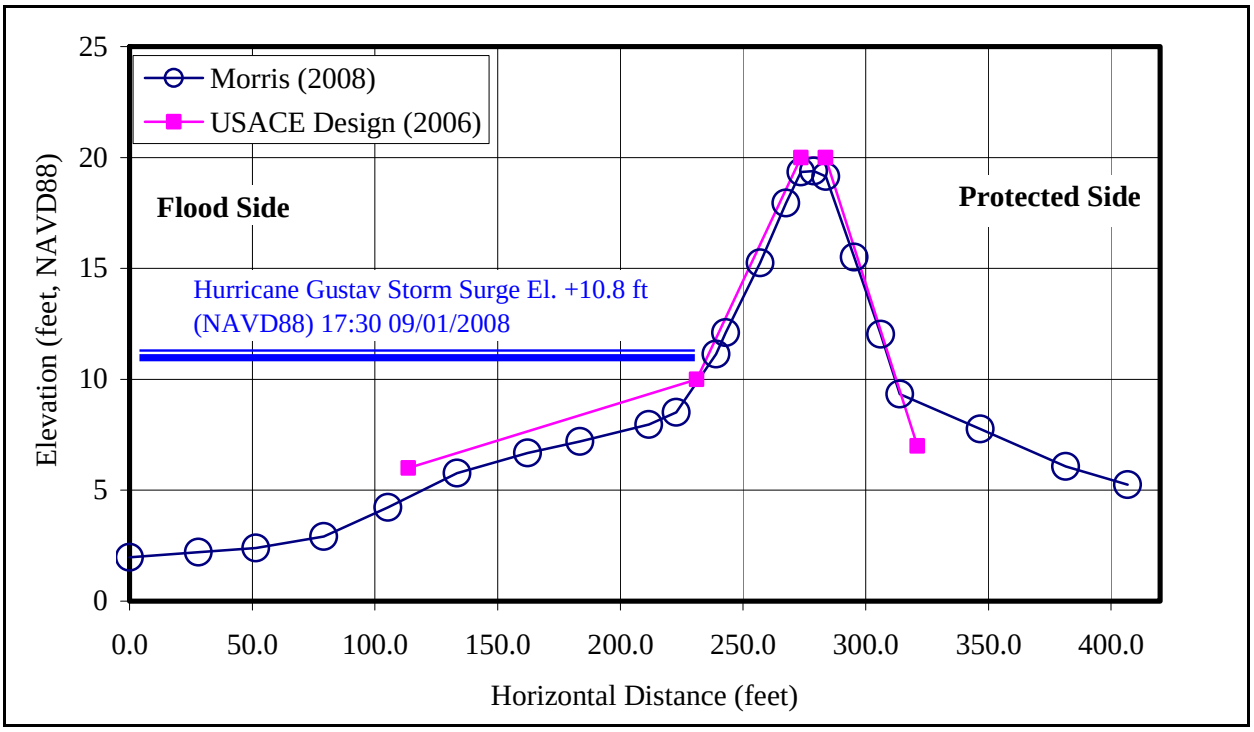


Figure 1: Cross section survey and design section at MR-GO Station 497+00.

The survey by Morris (2008) shows that there has been some settlement of the reconstructed MR-GO levee (approximately 0.8 feet) and the flood side grades are lower than the design condition. These lower site grades allow for larger waves to form for hurricane storm surges due to the increase in depth near the toe of the MR-GO levee.

EBSB Erodibility Characterization

A site reconnaissance was performed by Dr. Ivor van Heerden Dr. Paul Kemp and others in September 2008, following Hurricane Gustav (see Technical Report III for details). The MR-GO flood face was described as experiencing minor erosion damage (most of the erosion was a result of rain-induced rilling). The face materials were described as a 2-inch veneer of black clay overlying 6-8 inches of yellow clay (van Heerden, 2008a). Beneath the clay was sand (van Heerden, 2008a).

There was no information on in-situ density of these materials, but it is assumed that the surficial soils have a low degree of compaction (~ 85 % relative compaction per ASTM D1557) and correspond to a low plasticity clay (CL). Figures 2 through 4 show the observed erosion on the flood face of the reconstructed MR-GO levees and Figure 5 shows the observed sand beneath the flood face clay veneer.



Figure 2: Flood-side erosion of MR-GO face. Active rilling due to rainfall (van Heerden, 2008b).



Figure 3: Erosion of the MR-GO flood face is limited to the active wave rushup/rushdown zone. Grass cover has been eroded and a trash line denotes the high water mark (van Heerden, 2008c).



Figure 4: As shown in Figure 3, the grass cover has been removed in the zone of active wave rushup/rushdown with some erosion of the levee materials visible (van Heerden, 2008a).



Figure 5: The materials underlying the flood face levee veneer was a poorly-graded fine sand (van Heerden, 2008a).

An exponential function was developed to correlate erodibility with shear velocity imposed on the EBSB face as a result of wave-induced uprush and downrush (Figure 6). The maximum erodibility rate was 'capped' at a value of twice the maximum EFA test result value. The ceiling erodibilty rate was imposed to limit the amount of potential erosion as water has a maximum sediment carrying capacity.

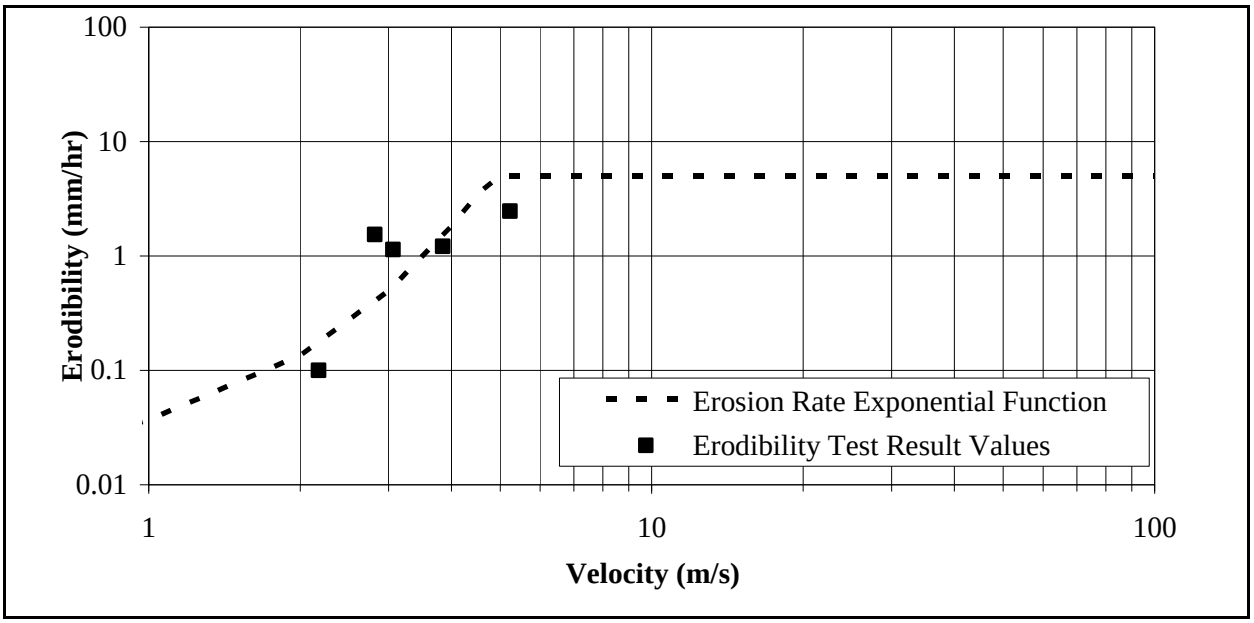


Figure 6: Exponential function used to characterize the erodibility of the MR-GO flood face during Hurricane Gustav.

Storm Hydrodynamics

Hydrodynamic loading considered for these analyses were based on van Heerden and Kemp (Technical Report III) and Bea (2008c). Table 1 presents a summary of the hydrodynamic values used. Due to the limited height of the storm surge in relation to the reconstructed MR-GO levee crest, only the maximum storm surge impacted the levee face. As a result, only one simulation was run at the maximum storm surge of 10.8 feet (NAVD88). This storm surge level was used to characterize the hydrodynamic loading on the levee between 1700 and 1800 CDT.

Table 1: Summary of Hydrodynamic Values at Station 497+00 (Hurricane Gustav)

Time (CDT)	**Storm Surge (ft)**	**Significant Wave Height (ft)**	**Wave Period (s)**	**Overtopping ($ft^3/s/ft$)**
1730	*10.8*	*1.5*	*5.7*	*0.0*

The significant wave height during the occurrence of the peak storm surge was estimated to be 1.5 feet and the significant wave period was estimated to be 5.7seconds (Bea, 2008c). This wave height was based on the maximum water depth (2 feet) over the berm that fronts the EBSB study location and breaking wave conditions based on the USACE STWAVE relationship (Smith 2007) and that provided by Bretschneider (1954) based on field measurements performed in Lake Okeechobee. There was no overtopping of the MR-GO levee during Hurricane Gustav. The storm surge, as recorded by the NOAA/CO-OPS station at Shell Beach is shown in Figure 7.

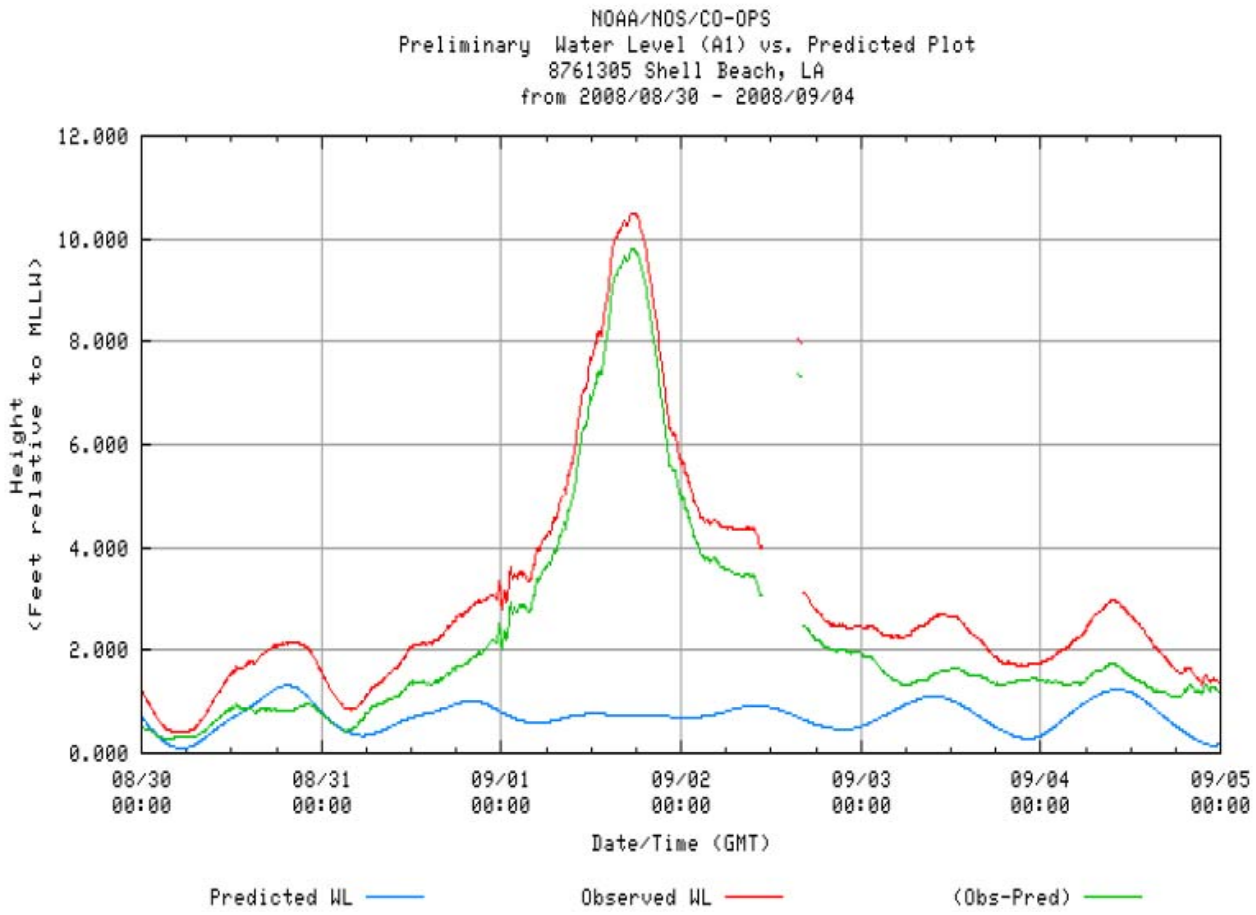


Figure 7: Observed storm surge at the NOAA/CO-Ops Shell Beach station during Hurricane Gustav (van Heerden, 2008c).

Model Configuration

Model geometry was based on the Morris (2008) survey and was composed of four components: the EBSB, water, void space, and the wave generation/water inflow mechanism (for overtopping conditions). Figure 8 presents an overview of the model components and Figure 9 presents an overview of the model geometry (exaggerated, not to scale).

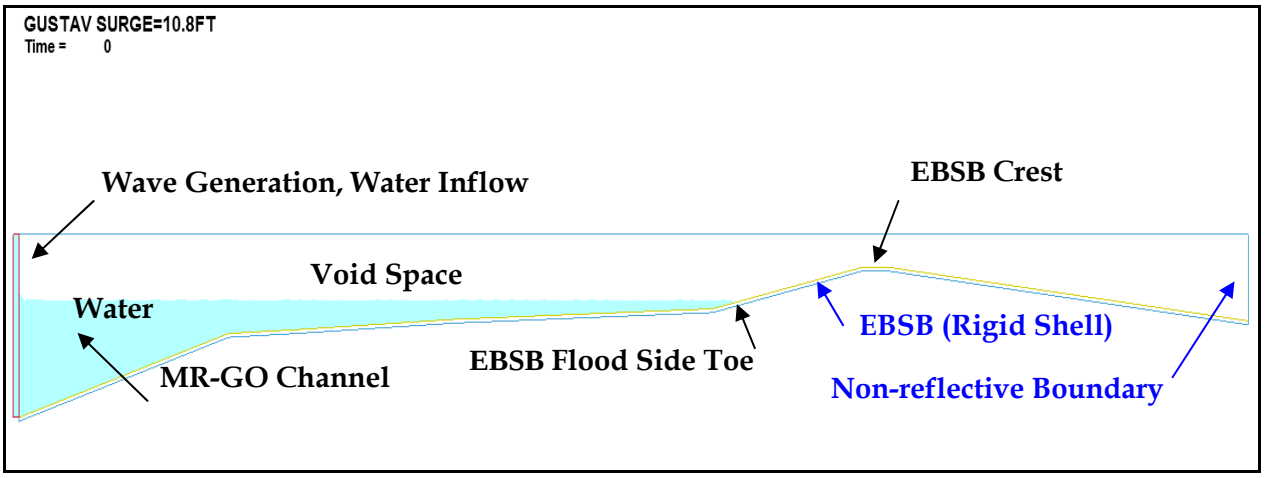


Figure 8**:** An overview of the LS-DYNA model components.

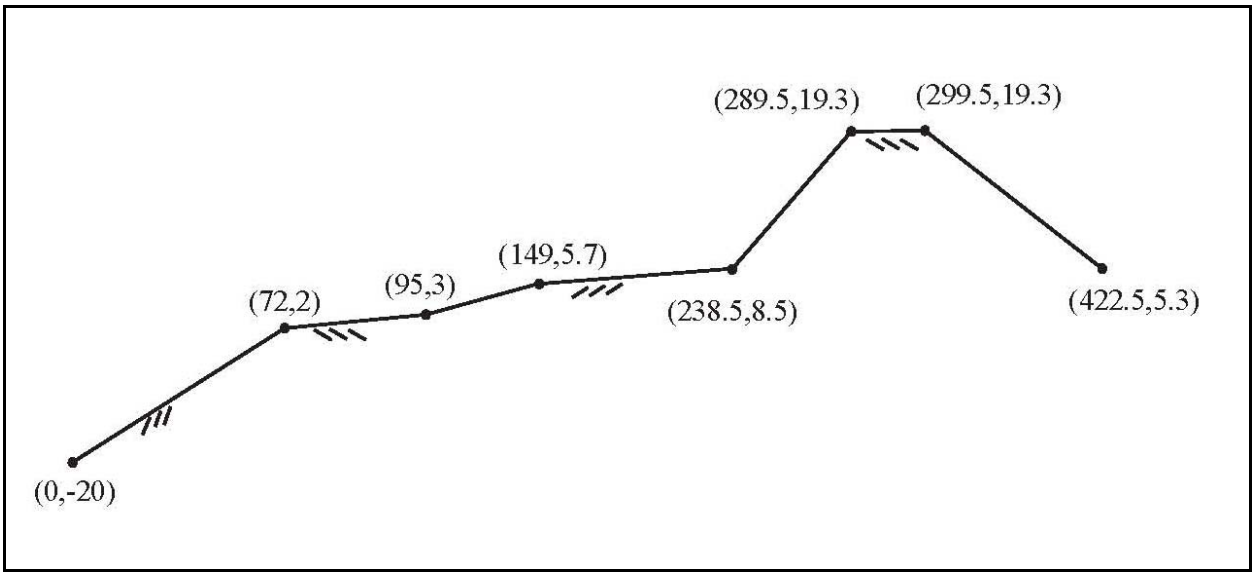


Figure 9: Geometric configuration of the LS-DYNA Gustav simulation (all units in feet, not to scale).

A detailed description of the model components is presented in the following paragraphs:

EBSB – The EBSB was modeled as a non-porous, rigid shell element (*MAT_020), Lagrangian surface, allowing for coupling forces between the fluid and EBSB to be

calculated. No material properties (Young's modulus, Poisson ratio, etc.) were required for this material type.

Fluid/Water – The fluid was modeled as 'generic' material (*MAT_009) allowing equations of state to be considered without computing deviatoric stresses. The water was assigned a mass density of 1.99 slugs/ft^3 (Munson et al, 1998), a pressure cutoff of -1.0E+11 psf (i.e. no pressure cutoff), and a dynamic viscosity coefficient of 2.5E-5 (Munson et al, 1998). Equations of state were used (*EOS_GRUNEISEN) as a constitutive equation to provide a mathematical relationship between state functions of the fluid (such as pressure, volume, and internal energy) along with hourglass controls (*HOURGLASS) to maintain mesh stability.

Void Space – Void space was included in the numerical model to extend the model space above the still water elevation so that the storm surge waves would remain within the model boundary. The void space was modeled as 'vacuum' material (*MAT_140), which is a 'dummy' material representing a vacuum in a multi material Euler/ALE model. Void space was used instead of 'air' in order to simplify the numerical computations and this approximation has very little impact on the calculated values as the interaction between air and the water has minimal damping effects on the incident wave shape and form.

Wave Generator/Water Source – Waves were generated from water elements with a time-dependent velocity profile. The fluid was modeled as 'generic' material (*MAT_009)

allowing equations of state to be considered without computing deviatoric stresses. The water was assigned a mass density of 1.99 slugs/ft^3 (Munson et al, 1998), a pressure cutoff of -1.0E+11 psf i.e. no pressure cutoff), and a dynamic viscosity coefficient of 2.5E-5 (Munson et al, 1998). Equations of state were used (*EOS_GRUNEISEN) as a constitutive equation to provide a mathematical relationship between state functions of the fluid (such as pressure, volume, and internal energy). The boundary is a prescribed-velocity boundary.

The velocity profile was described within LS-DYNA using the parameters v and ω (Table 2), where v is the velocity parameter (used to generate the correct wave height) and ω is the circular rate frequency (where the wave Period (T)=2pi/ω), used to develop the period of the wave.

Table 2: Wave Generation Parameters for Hurricane Gustav Simulation

Time (CDT)	**Storm Surge Elevation (ft)**	**Wave Height Parameter (v)**	**Wave Period Parameter (ω)**	**Overtopping_ Velocity**
1730	10.8	0.600	1.102	0.0

Velocities were determined by tracking the velocity profiles at selected nodes (Table 3) using the *DATABASE_HISTORY_NODE option (nodout). This option generates an ASCII database output with a time-history summary of velocity components and resultants for the selected nodes. The location of the velocity corresponds to the location of the node.

Table 3: Locations of Velocity Tracking Nodes

Node ID	X-Coordinate (ft)	Elevation (ft)
13747	238.5	8.5
13862	243.5	9.6
13931	246.5	10.2
13977	248.5	10.6
14000	249.5	10.8
14069	252.5	11.5
14115	254.5	11.9
14161	256.5	12.3

Wave Impact Analyses

The Hurricane Gustav simulation at 1730 CDT (Figure 10) consisted of an EBSB crest Elevation of +19.3 feet (NAVD88) and hydrodynamics consisting of a storm surge Elevation of +10.8 feet (NAVD88), a wave period of 5.7 seconds and a significant wave height of 1.5 feet. There was no overtopping.

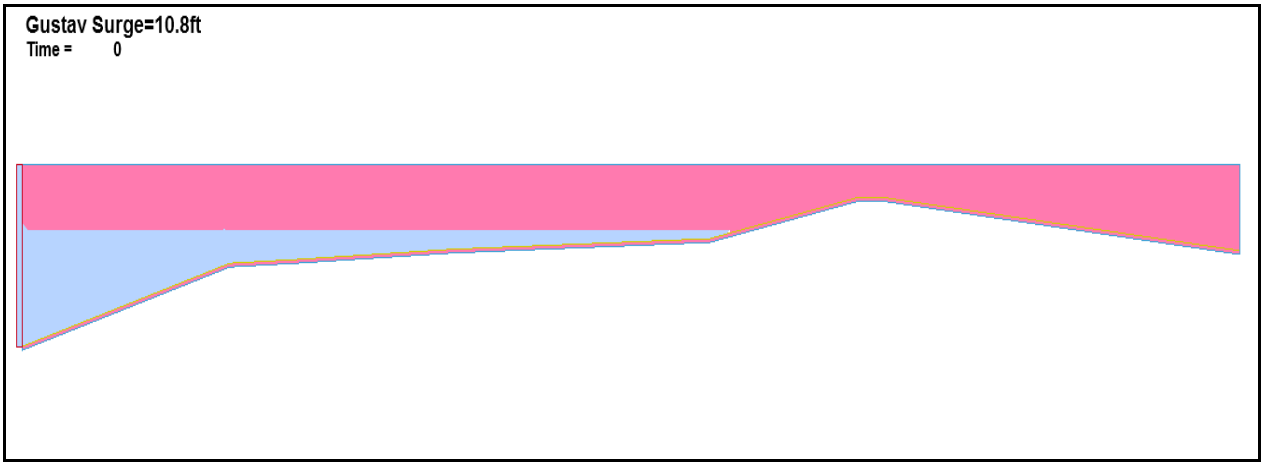


Figure 10: Initial conditions for Hurricane Gustav.

At Elevation +10.8 feet (NAVD88), the storm surge reached the flood side toe of the EBSB. A plot of the shear velocities is presented in Figure 11. The peak shear velocity at the storm surge elevation was determined to be about 11 ft/s. Some irregularities (spikes) were noted in the

output and these are artifacts of the mesh configuration and should not be considered 'realistic' values.

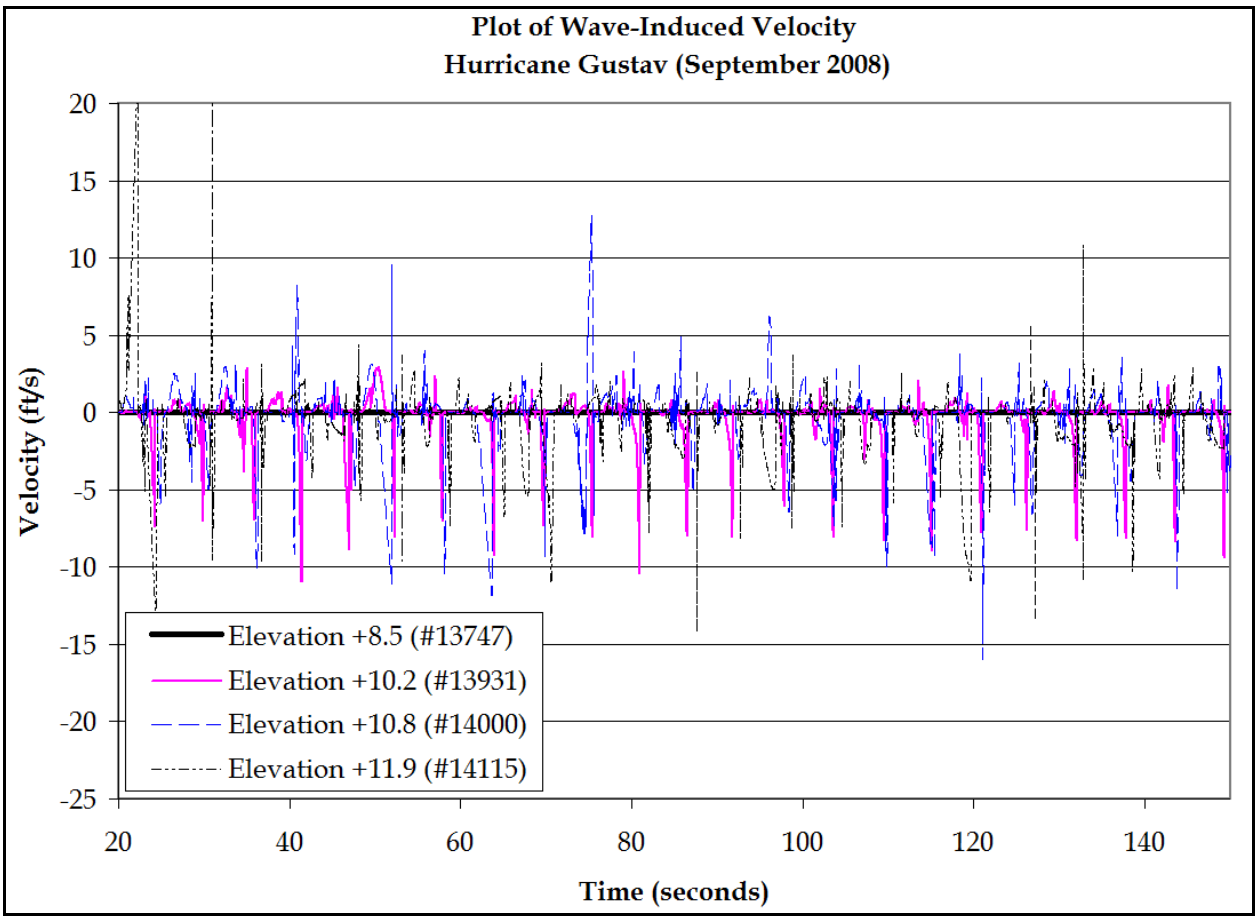


Figure 11**:** A plot of the velocity time history on the flood side face of the EBSB with the storm surge at 1730 CDT.

Figure 12 (below) provides a graphical representation of water movement over time. With the hurricane storm surge at El. +10.8 feet (NAVD88), the EBSB induces a tendency for the waves to exhibit a primarily 'runup' and 'rundown' behavior.

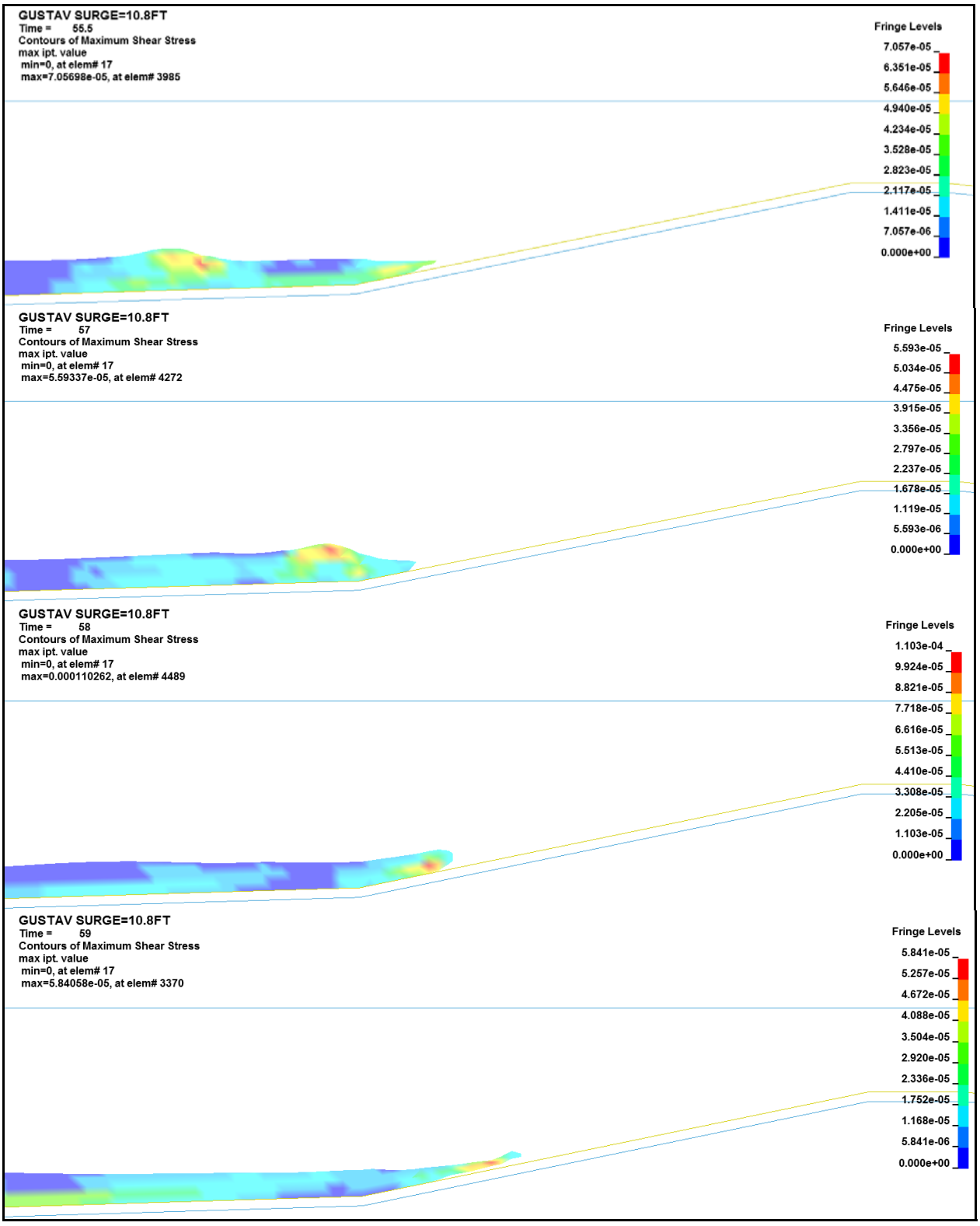


Figure 12: With the hurricane storm surge at El. +10.8 feet (NAVD88), the EBSB induces a tendency for the waves to exhibit a primarily 'runup' and 'rundown' behavior (fringe level units in psf).

Erosion Analyses

Bea (2008a) developed a correlation between incident significant wave height and duration until breaching of the grass cover and initiation of active erosion of the EBSB soil based on full scale experimental results provided by Seijffert and Verheij (1999). Figure 13 presents the correlation between grass turf protection duration and incident significant wave height (Bea, 2008a).

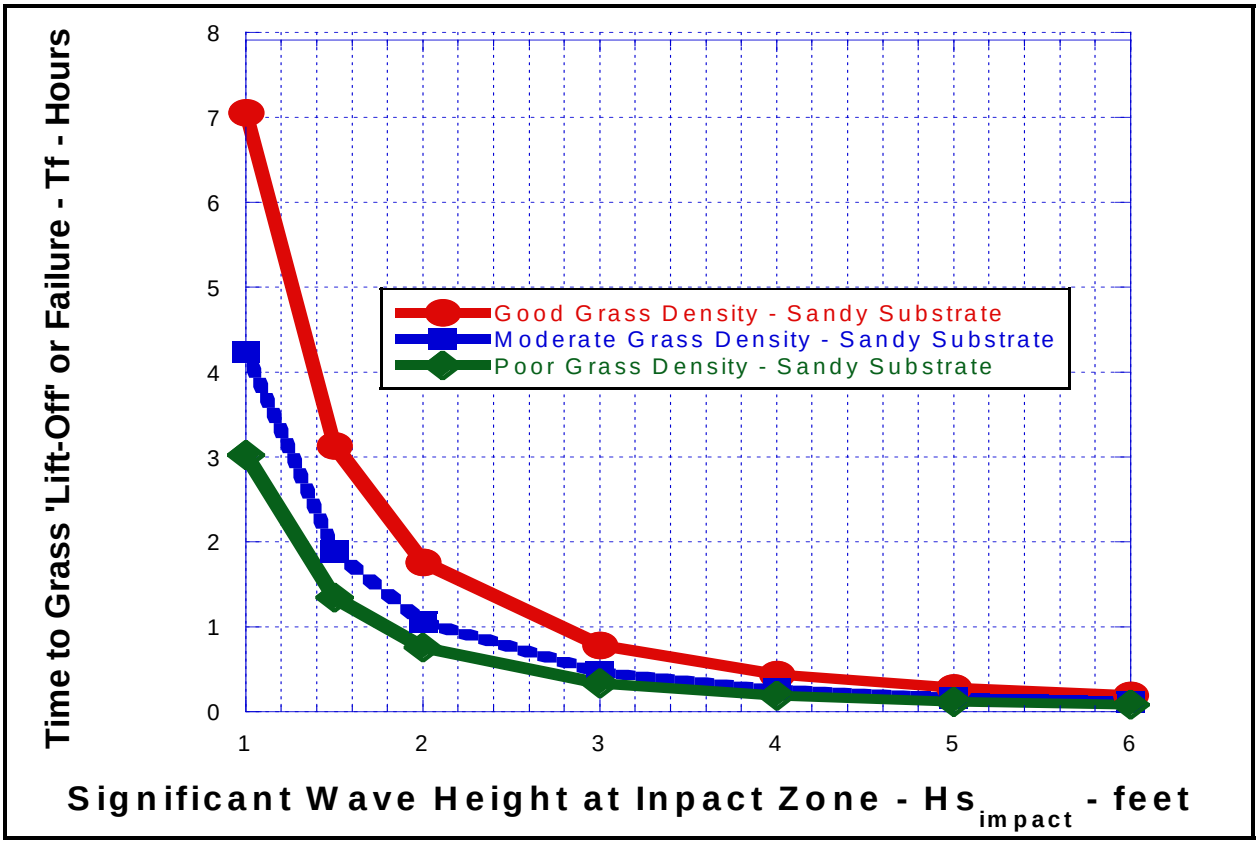


Figure 13: A correlation chart between grass cover protection duration and incident significant wave height onto the EBSB flood side face (Bea, 2008a).

A linear "Miner's fatigue damage accumulation" model (Lematire and Desmorat 2005) was used to determine the duration (hours) of wave-induced uprush/downrush loading until compromise of the grass cover and exposure of the EBSB soils. In this model the damage at which 'failure' (grass lift-off) develops is when the total damage (D) reaches unity (D = 1.0). The total damage is computed as the summation of the time the grass is exposed to each of 'n' time intervals (t_{gi} -

time grass exposed to given 'ith' time interval) divided by the time to grass lift-off in that time interval (Tf_{gi}):

$$D = \sum_{i=1}^{n} \frac{t_{gi}}{Tf_{gi}} \leq 1.0 \text{ (when D = 1 failure occurs)} \qquad \text{Eq [2]}$$

For the Hurricane Gustav hydrodynamics, it was determined that the poor grass density would have been able to sustain 1.5 to 2 hours of wave attack (significant wave height of about 1.5 feet) before being compromised. As such, limited scour would be anticipated and no direct erosion of the flood side of the reconstructed MR-GO levee. The grass turf compromise and resulting lateral erosion calculations is presented in Table 4.

Table 4: Calculation of 'good' grass cover (sandy substrate) for Hurricane Gustav.

Time (CDT)	**Hs (ft)**	**Maximum Turf Erosion Duration (hrs)**	**Turf Exposure Period (hrs)**	**Interval Turf Damage (%)**	**Cumulative Turf Damage (%)**
1730	1.5	1.75	1.00	57%	57%

Wave-induced cumulative erosion of EBSB materials (E) was calculated using an integrated time-step function (Eq 3) based on the erodibility of the EBSB material at the time step being evaluated (where the erodibility of the time step is determined by the time-average shear velocities calculated at the defined storm surge elevations). The erodibility at the time step ($\dot{e}(v)$) is then multiplied by the value of the time step to calculate the lateral extent of erosion.

$$E = \sum \dot{e}(v(t))\Delta t \qquad \text{[Eq 3]}$$

Since the numerical simulation only has an effective time duration of 130 seconds (eliminating the first 20 numerical simulation time required to 'initiate' the model), the cumulative erosion for the 130 second period was extrapolated to the remainder of the time interval (i.e. multiplied by 3600s/130s or 27.74). Table 5 presents a summary of the estimated lateral wave-induced erosion. We evaluated two conditions, one with the grass cover and another assuming no armoring from the grass and only erosion as a function of the soil erodibility was calculated (grass cover is none). We found that for both the 'with grass cover (good grass cover)' and 'no grass cover,' no erosion was anticipated.

Table 5: Determination of Erosion on EBSB Flood Face for Hurricane Gustav

Time (CDT)	Grass Cover	Storm Surge Elev. (ft)	Lateral Erosion (ft)	Cumulative Erosion (ft)
1730	Good	10.8	0	0
1730	None	10.8	0	0

These results are in agreement with the observed conditions at MR-GO Station 497+00 following Hurricane Gustav. No appreciable erosion was found and the LS-DYNA wave-induced erosion method predicted no appreciable erosion should occur.

V. HUGHES LABORATORY EXPERIMENTAL RESULTS ANALYSES

The validation numerical modeling analyses to simulate velocities as a result of levee overtopping and incident waves was performed based the laboratory experimental data reported by Hughes (2008). Model geometry and hydrodynamics (storm surge, wave periods, and significant wave heights) for the simulation were based on the experimental data provided by Hughes (2008). The study documented by Hughes contained measured data on the time histories

of water velocities at the crown – crest and backside of a model levee armored with concrete mattresses. The experiments did not address wave-induced erosion of the model levee, so the wave-induced lateral erosion method was not evaluated as part of this case study. A discussion of the model inputs, configuration, and results are presented in the following sections.

Hydrodynamics

Hydrodynamic loading considered for these analyses were based on Hughes (2008). Three conditions were evaluated, based on a surge elevation of +21 feet. The three conditions varied the significant wave height (3 feet, 6 feet, and 9 feet) and also varied the wave period (6 seconds, 10 seconds, and 14 seconds). Table 6 presents a summary of the hydrodynamic values used.

Table 6: Summary of Hydrodynamic Values from Hughes (2008)

Run ID	Surge (feet)	Significant Wave Height (feet)	Wave Period (seconds)	Overtopping ($ft^3/s/ft$)
s1_h3	21	3	6	~2.75
s1_h6	21	6	10	~2.75
s1_h9	21	9	14	~2.75

Model Configuration

Model geometry was based on Hughes (2008) and was composed of four components: the EBSB, water, void space, and the wave generation/water inflow mechanism (for overtopping conditions). Figure 14 presents an overview of the model components and Figure 15 presents an overview of the model geometry (exaggerated, not to scale).

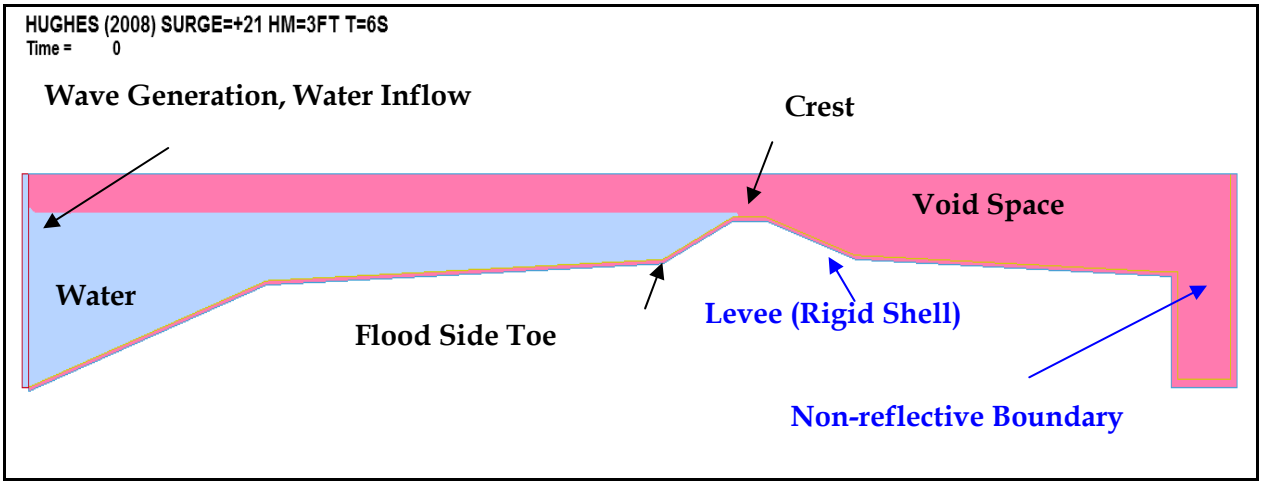


Figure 14**:** An overview of the LS-DYNA model components.

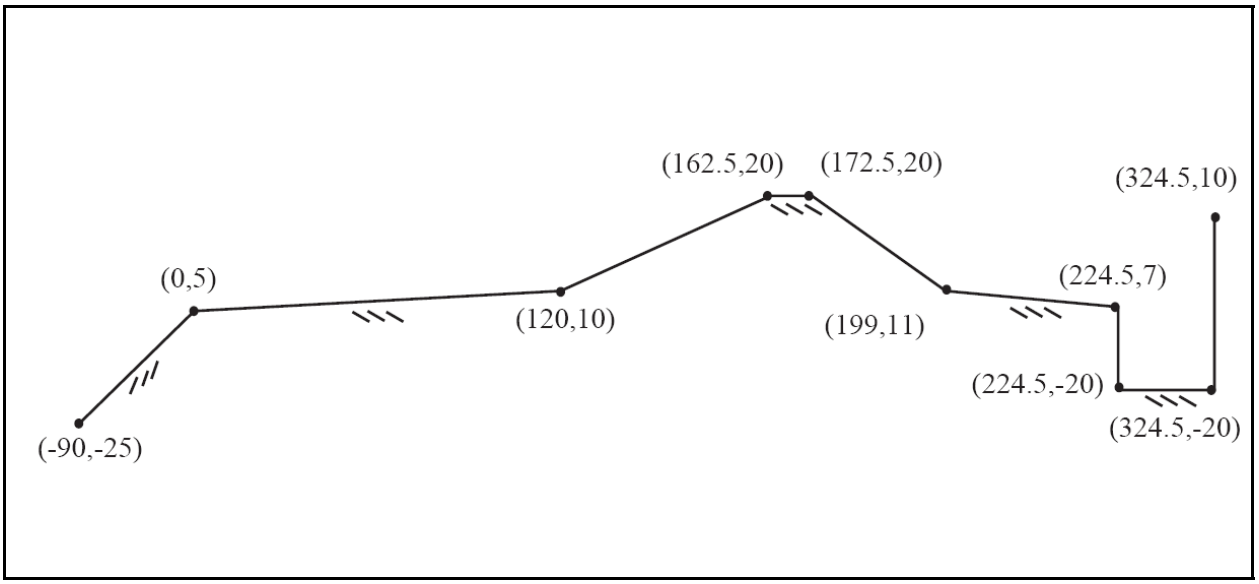


Figure 15: Geometric configuration of the LS-DYNA Gustav simulation (all units in feet).

A detailed description of the model components is presented below:

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Fluid/Water – The fluid was modeled as 'generic' material (*MAT_009) allowing equations of state to be considered without computing deviatoric stresses. The water was assigned a mass density of 1.99 slugs/ft^3 (Munson et al, 1998), a pressure cutoff of -1.0E+11 psf (i.e. no pressure cutoff), and a dynamic viscosity coefficient of 2.5E-5 (Munson et al, 1998). Equations of state were used (*EOS_GRUNEISEN) as a constitutive equation to provide a mathematical relationship between state functions of the fluid (such as pressure, volume, and internal energy) along with hourglass controls (*HOURGLASS) to maintain mesh stability.

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Table 7: Wave Generation Parameters for Hurricane Gustav Simulation

Run ID	Storm Surge Elevation (ft)	Wave Height Parameter (v)	Wave Period Parameter (ω)	Overtopping_ Velocity
s1_h3	21	1.620	1.047	2.75
s1_h6	21	1.801	0.628	2.75
s1_h9	21	2.080	0.449	2.95

Velocities were determined by tracking the velocity profiles at nodes matching locations of sensors installed in the Hughes (2008) study (Table 8) using the *DATABASE_HISTORY_NODE option (nodout). This option generates an ASCII database output with a time-history summary of velocity components and resultants for the selected nodes. The location of the velocity corresponds to the location of the node.

Table 8: Locations of Velocity Tracking Nodes

Node ID	X-Coordinate (ft)	Elevation (ft)
15382	162.5	20.0
15487	165.0	20.0
15697	170.0	20.0
15886	174.5	19.3
16096	179.5	17.7
16306	184.5	16.0
16516	189.5	14.3
16726	194.5	12.7

Velocity Analyses

Velocity profiles were developed for three hydrodynamic conditions (as described above). Typical wave progression profiles for the simulated conditions are shown in Figure 16 (S=+21 feet, Hm=3 feet, and T=6 seconds), Figure 17 (S=+21 feet, Hm=6 feet, and T=10 seconds), and Figure 18 (S=+21 feet, Hm=9 feet, and T=14 seconds). This velocity profile matches the graphical wave progression profiles, shown in Figures 16-18.

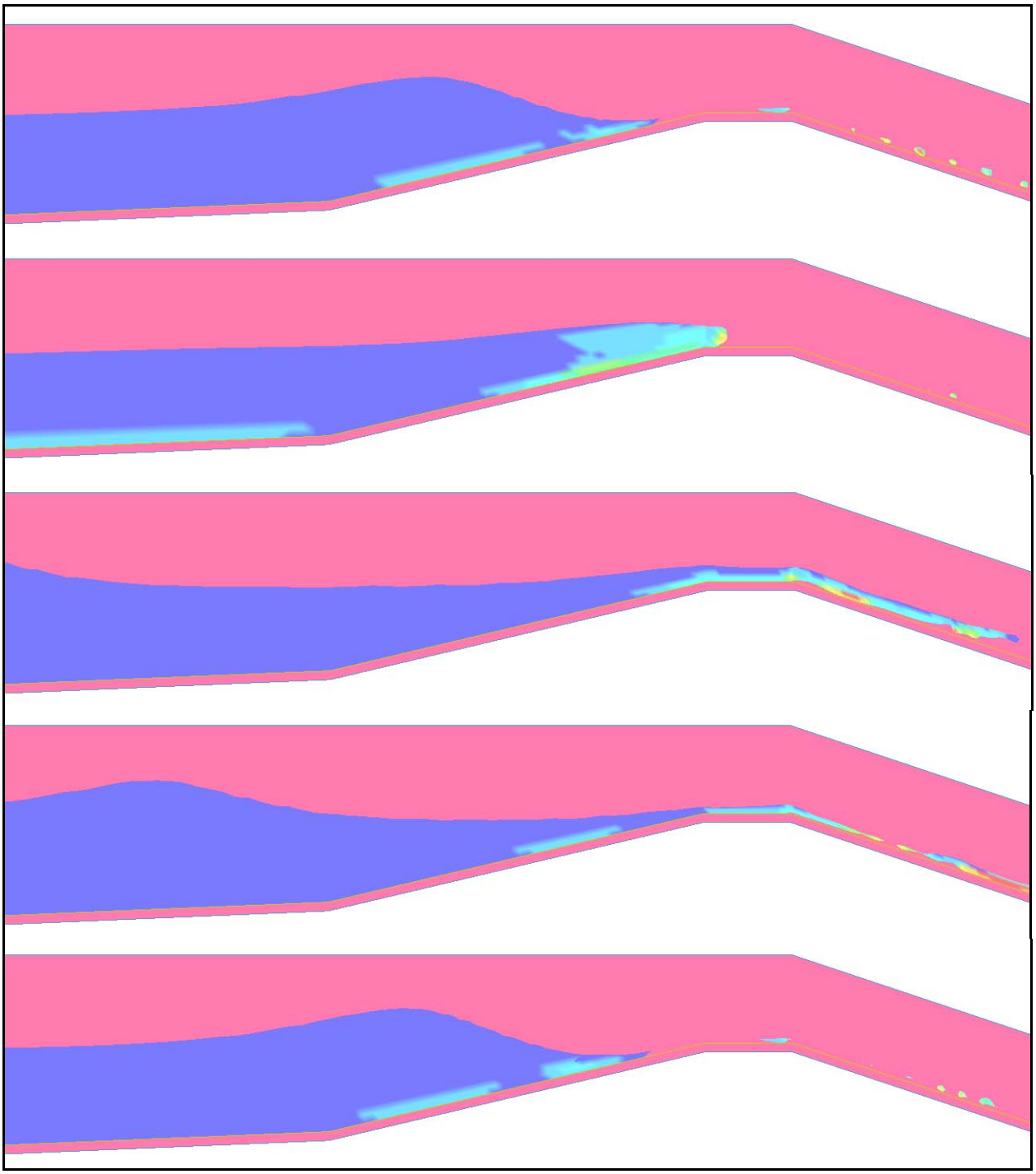


Figure 16: Wave impact on the levee with a surge elevation of +21 feet, a significant wave height of 3 feet, and a period of 6 seconds.

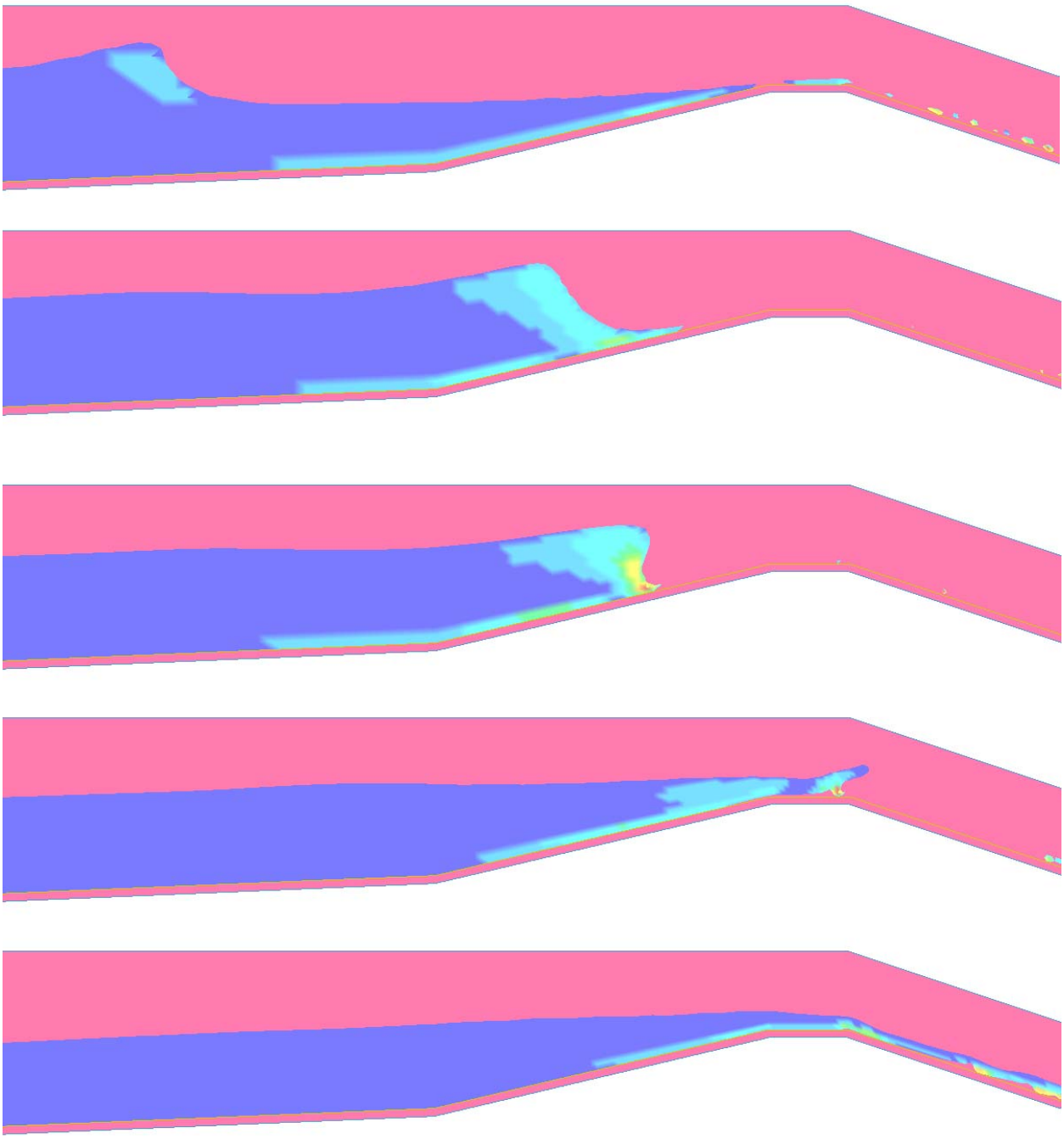


Figure 17: Wave impact on the levee with a surge elevation of +21 feet, a significant wave height of 6 feet, and a period of 10 seconds.

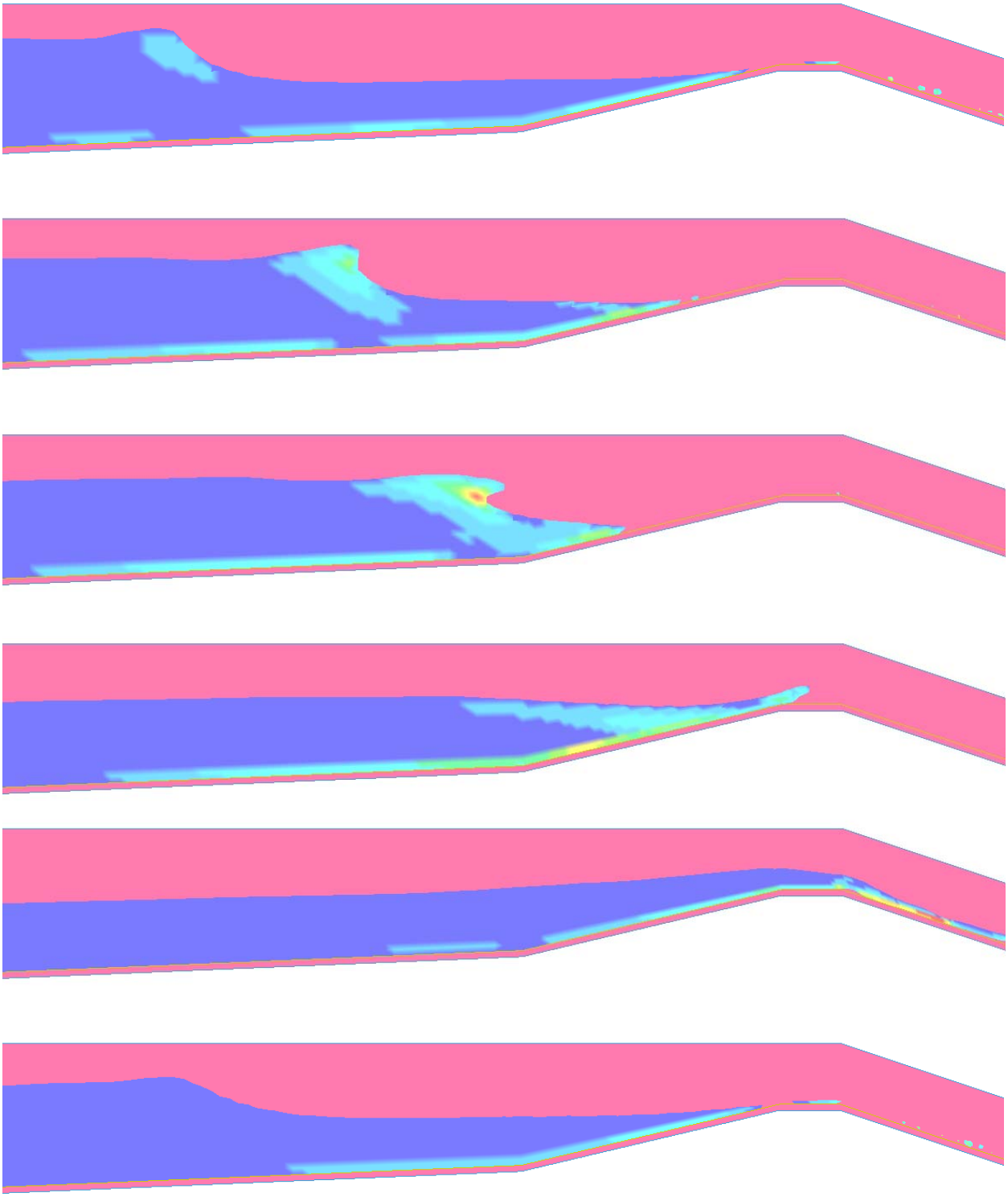


Figure 18: Wave impact on the levee with a surge elevation of +21 feet, a significant wave height of 9 feet, and a period of 14 seconds.

The simulation results developed using LS-DYNA showed the velocity profiles peak at a maximum velocity as the wave rushes over the levee crest and decreases to zero feet per second (i.e. no water running over the levee) during down-rush wave cycles. This overtopping and down-rush cycle is also depicted in Hughes (2008) (Figure 19), which has a significant wave height of 6.2 feet and a period of 10.5 seconds. For this wave loading condition (with no water spilling over the top of the levee crest), it would be expected that the velocity magnitude would drop to zero as the depth overtopping water goes to zero. However, the Hughes (2008) velocity profiles show a minimum velocity of about 2.5 feet per second. The reasons for this anomaly are not apparent.

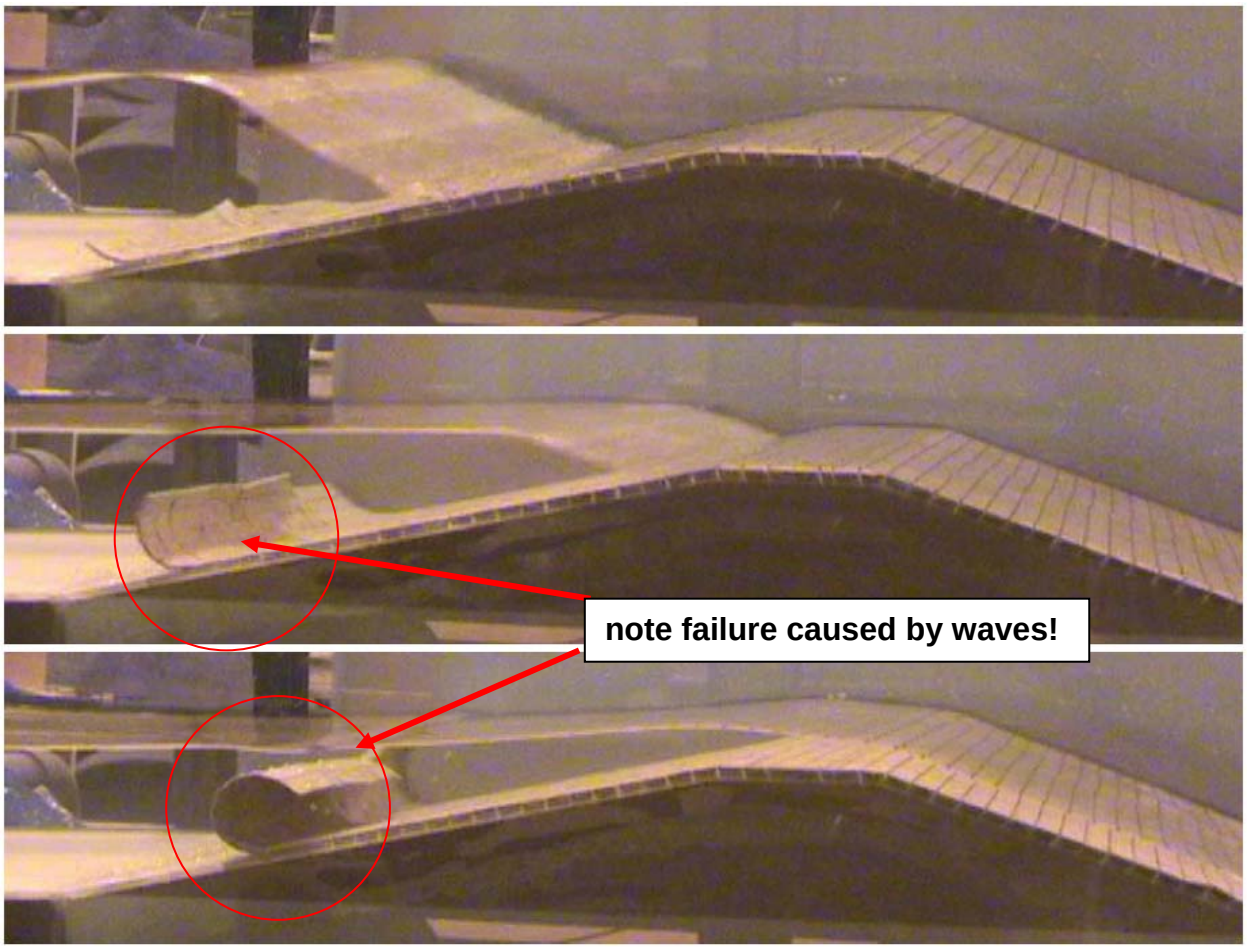


Figure 19: During wave down-rush cycles, there is no active overtopping over the levee crest (after Hughes, 2008). Note failure – uplift and rolling - of the concrete mattress by waves.

The LS-DYNA generated maximum velocities are approximately 20-30% above the reported values from Hughes (2008). A comparison between the reported Hughes (2008) and LS-DYNA velocity profiles for a surge of +21 feet are presented. Figures 20 and 21 show the velocity profiles for a significant wave height of 3 feet & period of 6 seconds (Hughes (2008) and LS-DYNA, respectively). Figures 22 and 23 show the velocity profiles for a significant wave height of 6 feet and a period of 10 seconds (Hughes (2008) and LS-DYNA, respectively). Figures 24 and 25 show the velocity profiles for a significant wave height of 9 ft & period of 14 s (Hughes (2008) and LS-DYNA, respectively).

It is interesting to note that the magnitude of overtopping velocities is very similar (within the same order of magnitude) for all hydrodynamic conditions, but the number of cycles increases with decreasing periods. This, as a result, implies that short period waves can be more erosive than long period waves for coastal protection devices that are susceptible to wave-induced erosion.

The duration of the simulated wave action for the LS-DYNA case was much less (150 seconds compared with 1500 seconds) than Hughes (2008), however, the general magnitude ranges of the velocity profiles are in good agreement.

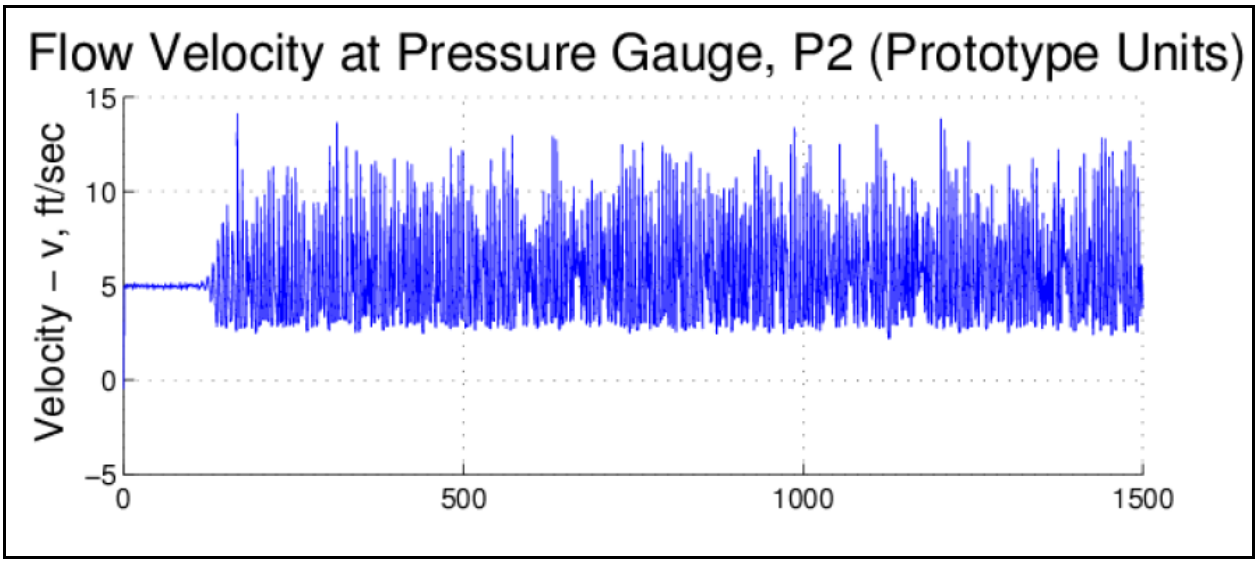


Figure 20: Velocity profile at P2 for a storm surge at +21 feet, a significant wave height of 3 feet and a period of 6 seconds (Hughes, 2008).

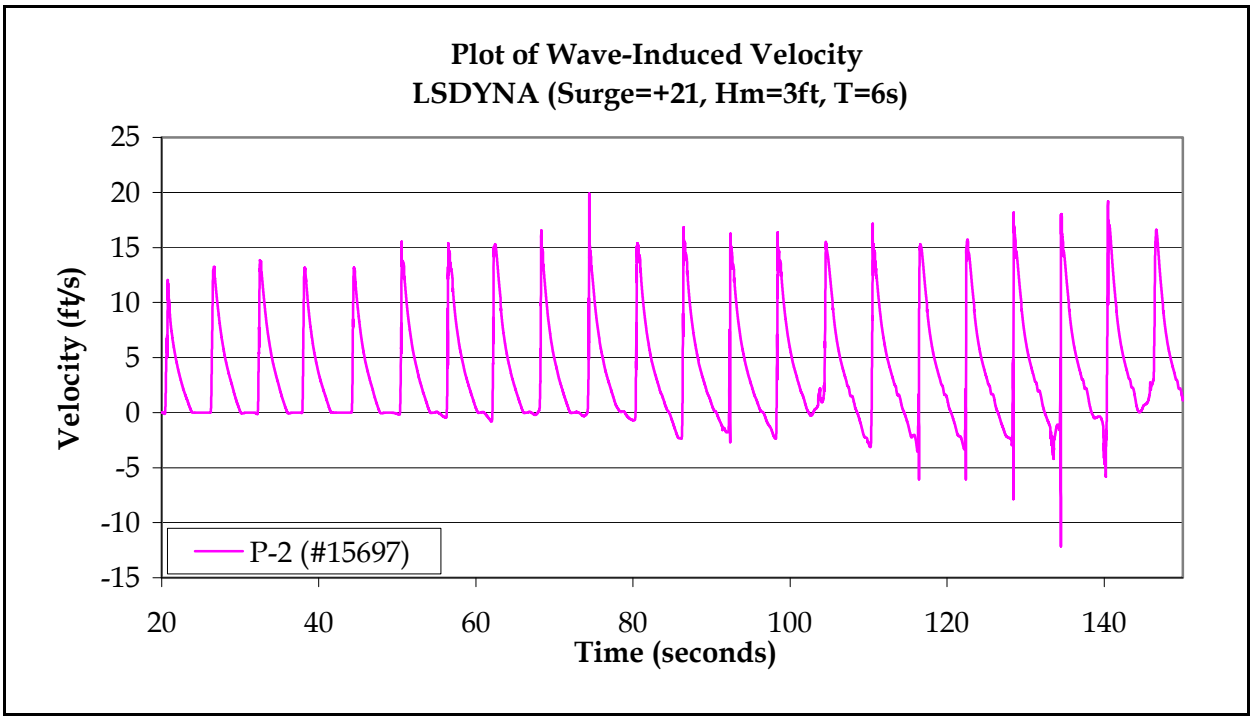


Figure 21: Velocity profile as determined by LS-DYNA. The peak velocities are very similar to those determined during the experiments reported by Hughes (2008).

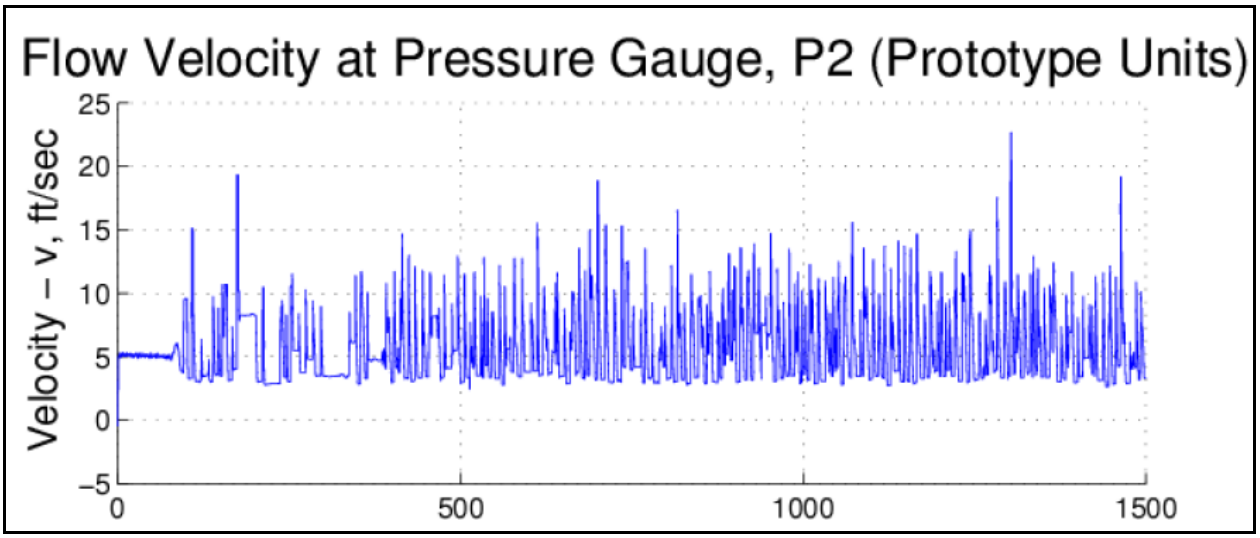


Figure 22: Velocity profile at P2 for a storm surge at +21 feet, a significant wave height of 6 feet and a period of 10 seconds (Hughes, 2008).

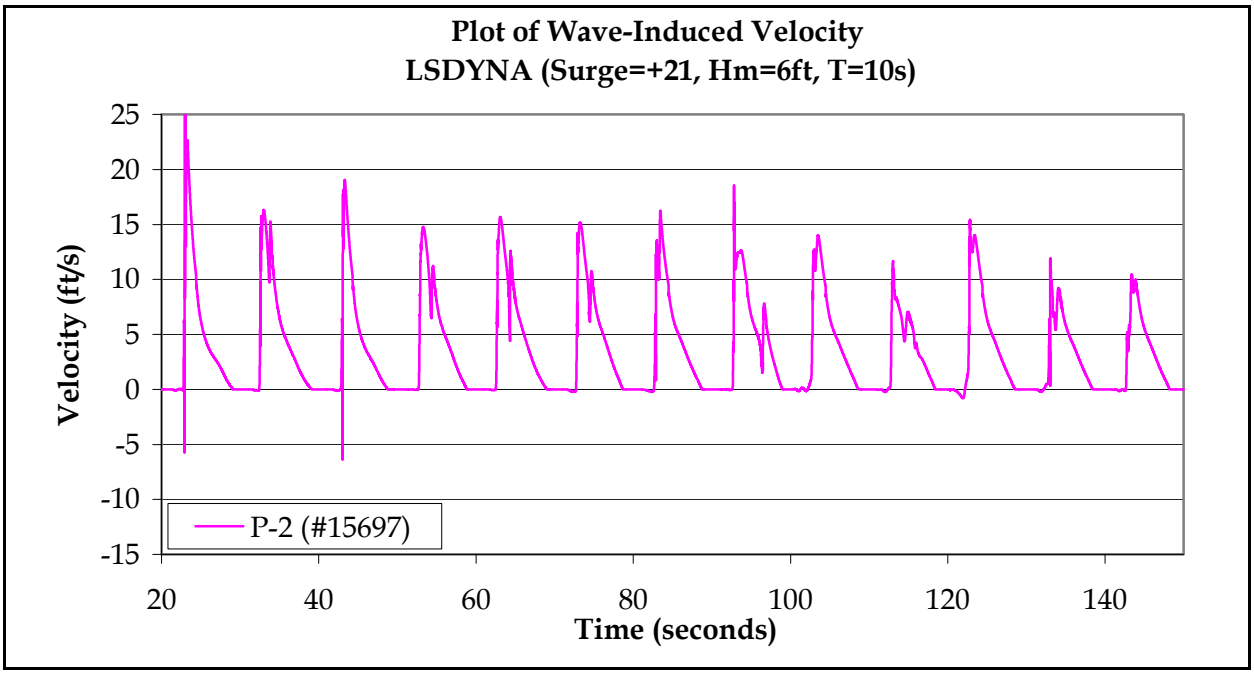


Figure 23: Velocity profile as determined by LS-DYNA. The velocity range for the LS-DYNA simulation is in the same range (10-15 feet per second) as the Hughes (2008) velocity magnitudes.

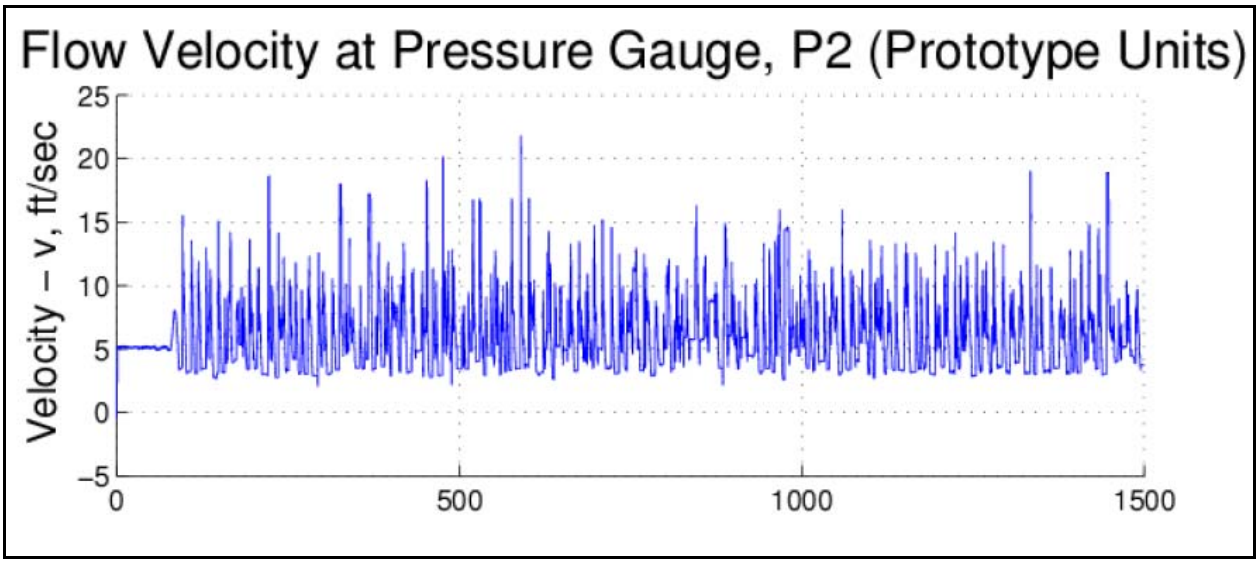


Figure 24: Velocity profile at P2 for a storm surge at +21 feet, a significant wave height of 9 feet and a period of 14 seconds (Hughes, 2008).

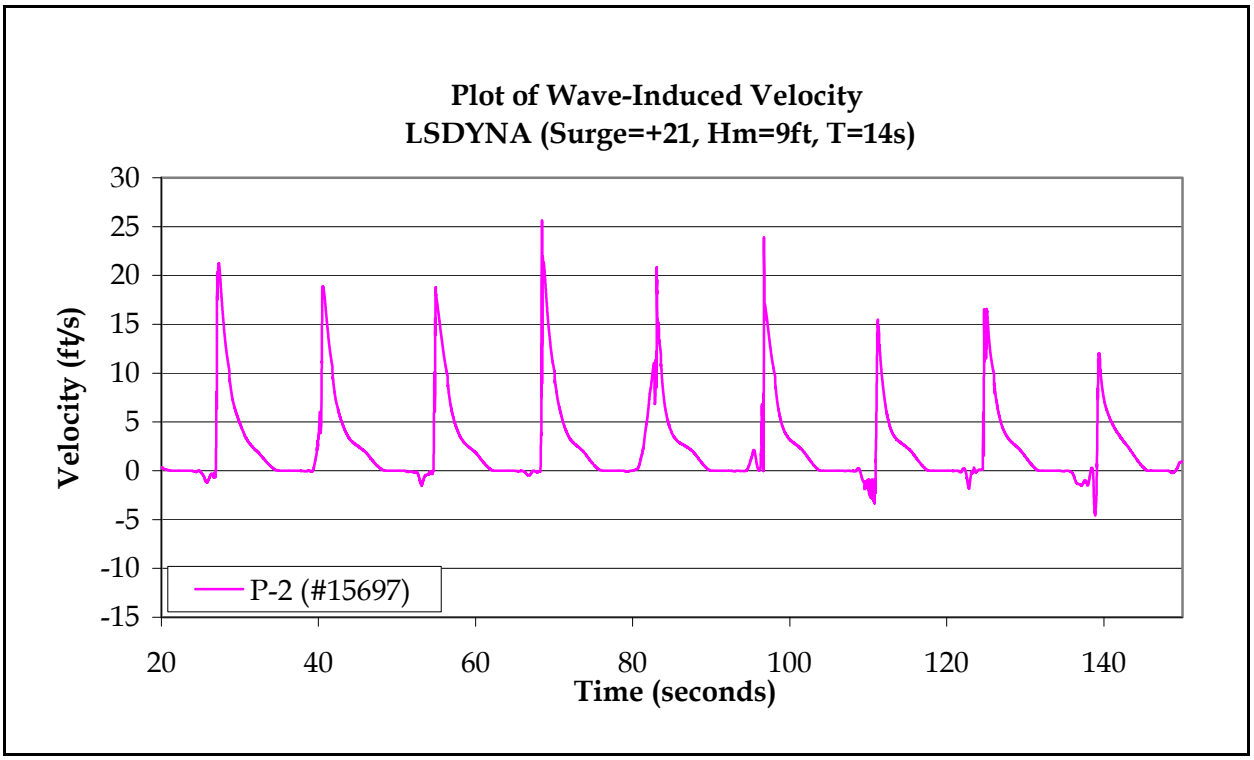


Figure 25: Velocity profile as determined by LS-DYNA. The velocity range for the LS-DYNA simulation is in the same range as the Hughes (2008) velocity magnitudes.

VI. GEISENHAINER AND KORTENHAUS LABORATORY EXPERIMENTAL RESULTS ANALYSES

Model tests were conducted by the Rijkswaterstaat in 1961 to evaluate the differences in performance characteristics between sand dikes with and without clay covers. An overview of the 1961 study was reported by D'Eliso (2007), and those reported values were used in this study to compare the breach time as predicted by the wave-induced erosion method compared with the reported time from D'Eliso (2007).

Hydrodynamics

Hydrodynamic loading considered for these analyses were based on values reported by D'Eliso (2007). Table 9 presents a summary of the hydrodynamic values used.

Table 9: Summary of Hydrodynamic Values at Station 497+00 (Hurricane Gustav)

Storm Surge (ft)	**Significant Wave Height (ft)**	**Wave Period (s)**	**Overtopping ($ft^3/s/ft$)**
1.54	*0.5*	*2.25*	*0.0*

The significant wave height during the occurrence of the peak storm surge was estimated to be 0.5 feet and the significant wave period was estimated to be 2.25 seconds (D'Eliso, 2007). There was no overtopping.

Erodibility

There was no explicit information available on the erodibility of the dike materials used by the 1961 Rijkswaterstaat (D'Eliso, 2007) study. However, the material was described as a clean sand with a D_{50} of 0.2 mm. The density of the sand was not detailed, and this has a major impact on the erodibility characteristics of the sand. For this validation study, it was first assumed that moderate compactive effort was used to construct the sand dike test embankment and a generic erodibility curve from ILIT (2005) was used to approximate the erodibility of the sand. An exponential function was developed to correlate erodibility with shear velocity imposed on the sand dike face as a result of wave-induced uprush and downrush. The maximum erodibility rate was 'capped' at a value of twice the maximum test result value to simulate 'saturation' of the water with suspended sediment. The ceiling erodibilty rate was imposed to limit the amount of potential erosion as water has a maximum sediment carrying capacity.

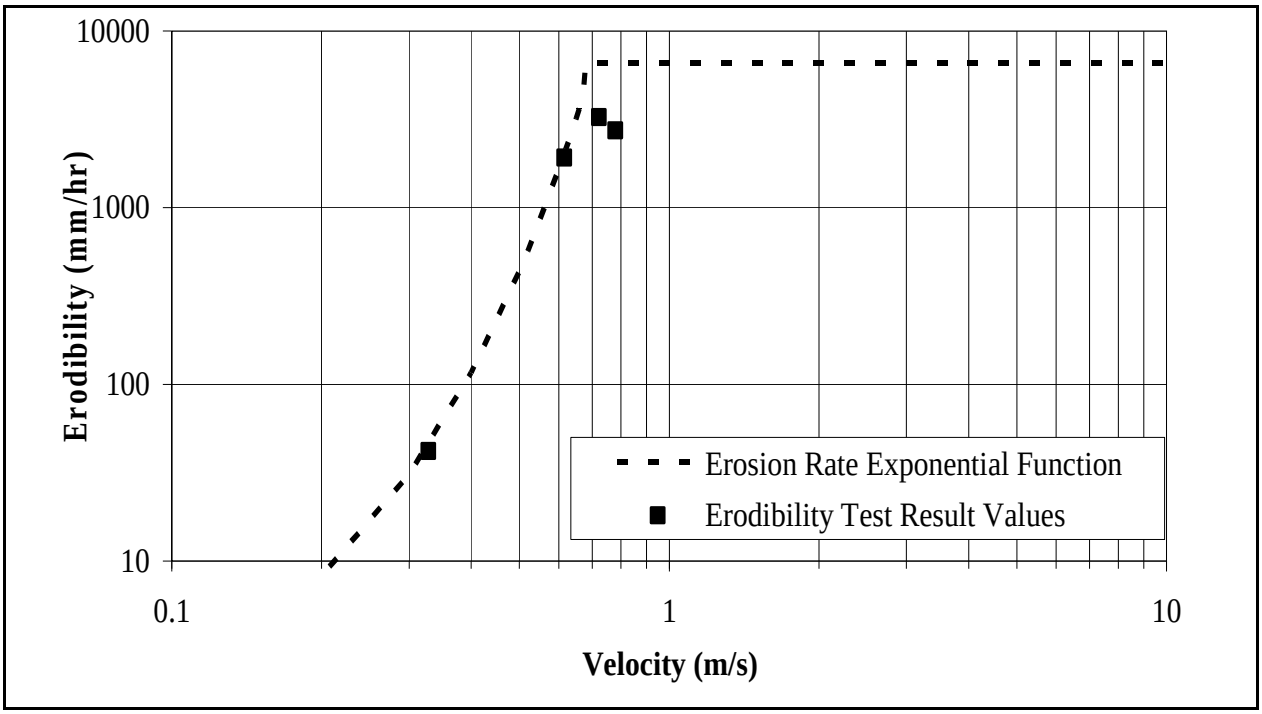


Figure 26: Exponential function used to characterize the erodibility of the levee as presented in D'Eliso (2007).

Model Configuration

Model geometry was based on the reported values in D'Eliso (2007) and was composed of four components: the dike, water, void space, and the wave generation. Figure 27 presents an overview of the model components and Figure 28 presents an overview of the model geometry (exaggerated, not to scale).

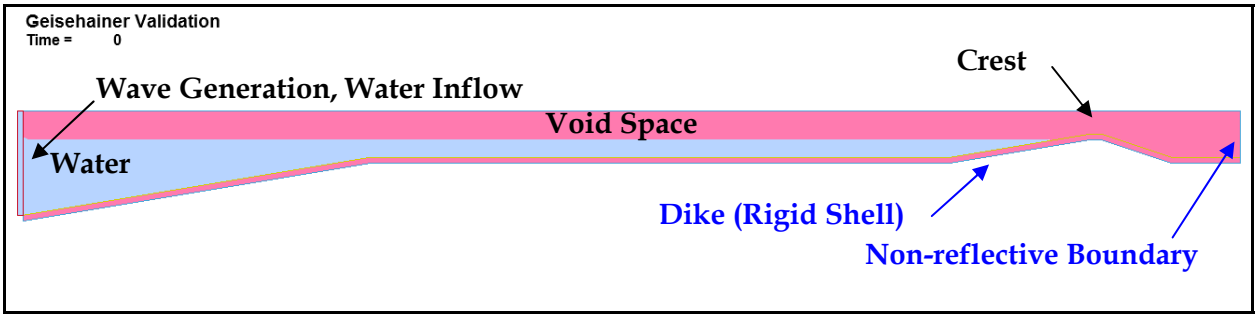


Figure 27: An overview of the LS-DYNA model components.

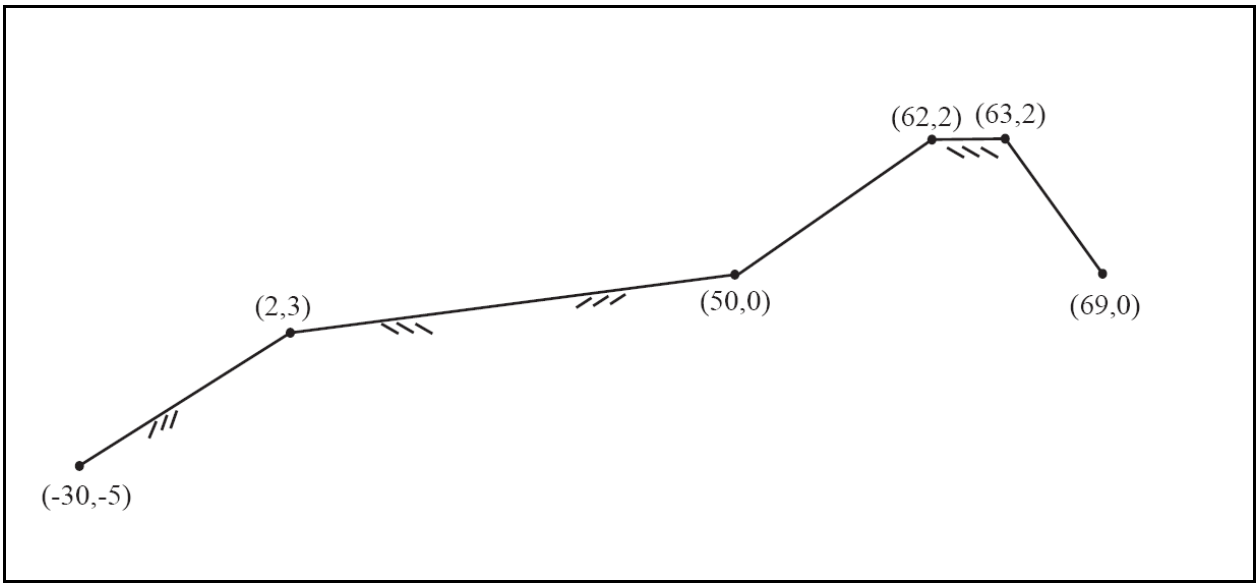


Figure 28: Geometric configuration of the LS-DYNA D'Eliso (2007) simulation (all units in feet, not to scale).

A detailed description of the model components is presented below:

Dike – The dike was modeled as a non-porous, rigid shell element (*MAT_020), Lagrangian surface, allowing for coupling forces between the fluid and dike to be calculated. No material properties (Young's modulus, Poisson ratio, etc.) were required for this material type.

Fluid/Water – The fluid was modeled as 'generic' material (*MAT_009) allowing equations of state to be considered without computing deviatoric stresses. The water was assigned a mass density of 1.99 slugs/ft^3 (Munson et al, 1998), a pressure cutoff of -1.0E+11 psf (i.e. no pressure cutoff), and a dynamic viscosity coefficient of 2.5E-5 (Munson et al, 1998). Equations of state were used (*EOS_GRUNEISEN) as a constitutive equation to provide a mathematical relationship between state functions of the fluid (such as pressure, volume, and internal energy) along with hourglass controls (*HOURGLASS) to maintain mesh stability.

Void Space – Void space was included in the numerical model to extend the model space above the still water elevation so that the storm surge waves would remain within the model boundary. The void space was modeled as 'vacuum' material (*MAT_140), which is a 'dummy' material representing a vacuum in a multi material Euler/ALE model. Void space was used instead of 'air' in order to simplify the numerical computations and this approximation has very little impact on the calculated values as the

interaction between air and the water has minimal damping effects on the incident wave shape and form.

Wave Generator/Water Source – Waves were generated from water elements with a time-dependent velocity profile. The fluid was modeled as 'generic' material (*MAT_009) allowing equations of state to be considered without computing deviatoric stresses. The water was assigned a mass density of 1.99 slugs/ft^3 (Munson et al, 1998), a pressure cutoff of -1.0E+11 psf i.e. no pressure cutoff), and a dynamic viscosity coefficient of 2.5E-5 (Munson et al, 1998). Equations of state were used (*EOS_GRUNEISEN) as a constitutive equation to provide a mathematical relationship between state functions of the fluid (such as pressure, volume, and internal energy). The boundary is a prescribed-velocity boundary.

The velocity profile was described within LS-DYNA using the parameters v and ω (Table 10), where v is the velocity parameter (used to generate the correct wave height) and ω is the circular rate frequency (where the wave Period (T)=2pi/ω), used to develop the period of the wave.

Table 10: Wave Generation Parameters for Simulation

Surge Elevation (ft)	**Wave Height Parameter (v)**	**Wave Period Parameter (ω)**	**Overtopping Velocity**
1.54	0.625	2.793	0.0

Velocities were determined by tracking the velocity profiles at selected nodes (Table 11) using the *DATABASE_HISTORY_NODE option (nodout). This option generates an ASCII

database output with a time-history summary of velocity components and resultants for the selected nodes. The location of the velocity corresponds to the location of the node.

Table 11: Locations of Velocity Tracking Nodes

Node ID	X-Coordinate (ft)	Elevation (ft)
13928	56.25	1.04
13991	57.00	1.17
14054	57.75	1.29
14117	58.50	1.42
14180	59.25	1.54
14243	60.00	1.67
14348	61.25	1.88
14411	62.00	2.00

Wave Impact Analyses

The D'Eliso (2007) simulation (Figure 29) consisted of a Dike crest Elevation of +2 feet and hydrodynamics consisting of a storm surge Elevation of +1.54 feet, a wave period of 2.25 seconds and a significant wave height of 0.5 feet. There was no overtopping.

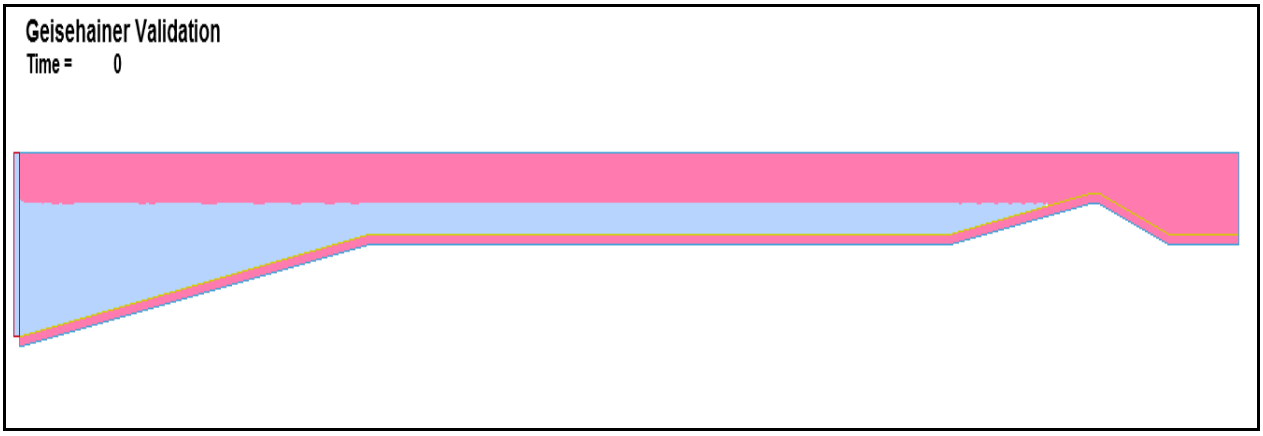


Figure 29: Initial conditions for the D'Eliso (2007) simulation.

At Elevation +1.54feet, the surge reached the flood side toe of the Dike. A plot of the shear velocities is presented in Figure 30. The peak shear velocity at the storm surge elevation was determined to be about 0.1 ft/s. Some irregularities (spikes) were noted in the output and these are artifacts of the mesh configuration and should not be considered 'realistic' values.

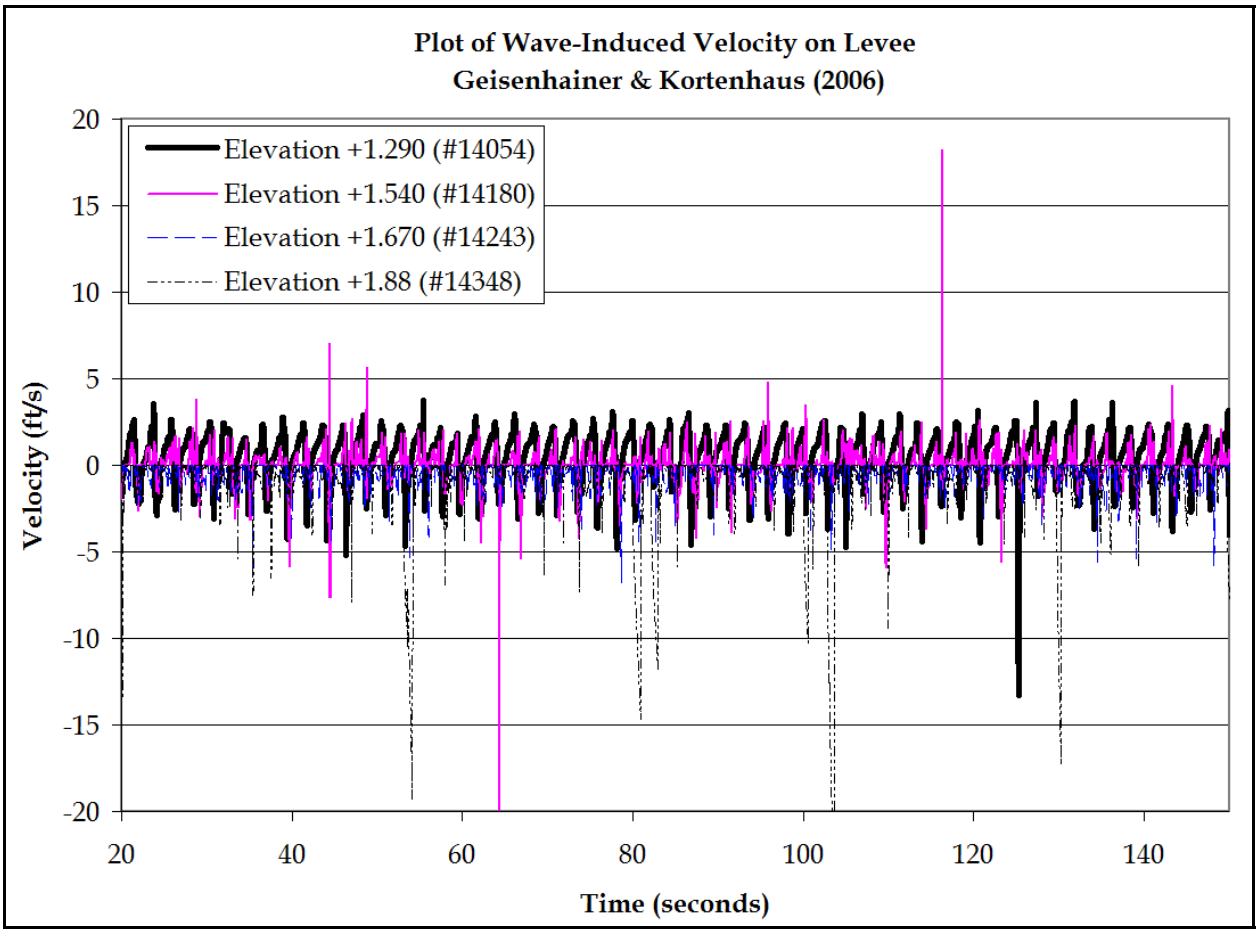


Figure 30**:** A plot of the velocity time history on the flood side face.

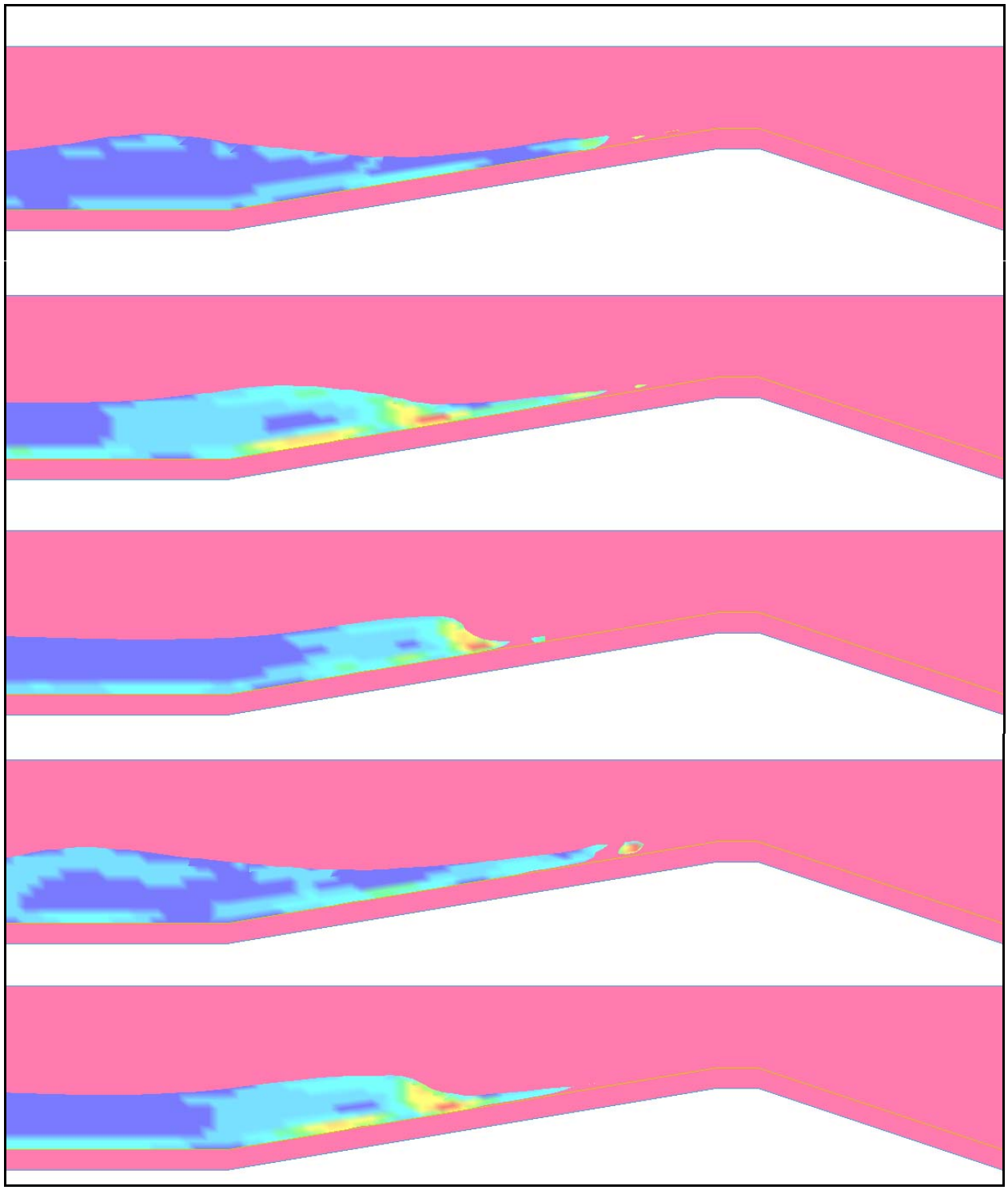


Figure 31 (below) provides a graphical representation of water movement over time. With the hurricane storm surge at El. +1.54 feet , the Dike induces a tendency for the waves to exhibit a primarily ‘runup’ and ‘rundown’ behavior.

Erosion Analyses

Wave-induced cumulative erosion of EBSB materials (E) was calculated using an integrated time-step function (Eq 3) based on the erodibility of the Dike material at the time step being evaluated (where the erodibility of the time step is determined by the time-average shear velocities calculated at the defined storm surge elevations).

Since the numerical simulation only has an effective time duration of 130 seconds (eliminating the first 20 numerical simulation time required to 'initiate' the model), the cumulative erosion for the 130 second period was extrapolated to the remainder of the time interval (i.e. multiplied by 3600s/130s or 27.74). Table 12 presents a summary of the estimated lateral wave-induced erosion. Because the dike tested did not have a grass cover, this aspect was neglected in this modeling as well. The breach time was determined to be 1.5 hours, with a total lateral erosion of 3.8 feet.

Table 12: Determination of Erosion on sand Dike

Grass Cover	Breach Time (hrs)	Surge Elev. (ft)	Lateral Erosion (ft)	Cumulative Erosion (ft)
None	1.5	1.54	3.8	3.8

D'Eliso (2007) reported that the dike breached within 31 minutes, significantly faster than predicted by the wave-induced erosion method. However, this would be largely influenced by the assumed erodibility characteristic curve defined in this study compared with the actual erodibility characteristics of the original test model (as reported in D'Eliso, 2007). In order to evaluate the effects of a poorly compacted and poorly graded sand a Modified Erodibility

function was developed based on results from laboratory tests on these types of materials (ILIT 2006). A comparison plot of the two erodibility curves is presented in Figure 32.

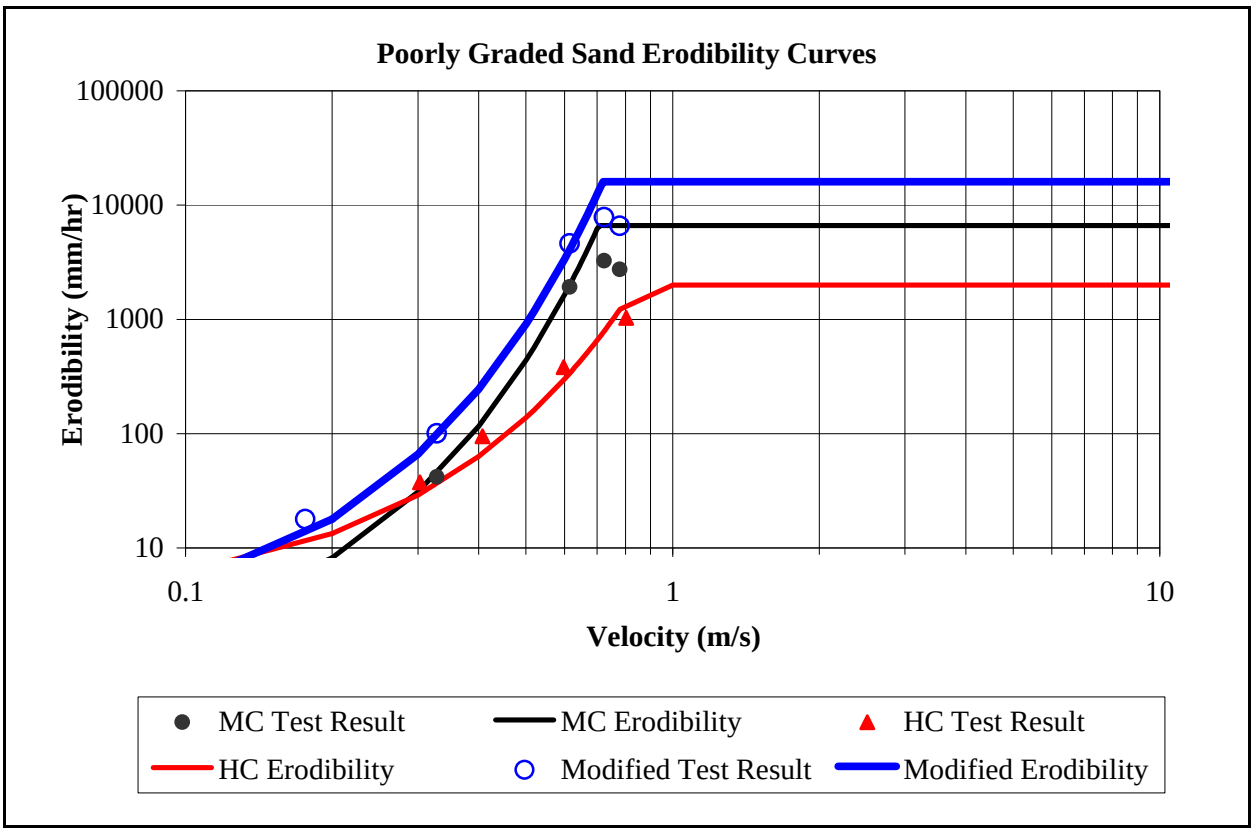


Figure 32: A comparison between a high-compaction sand (HC), a moderate compaction (MC) sand, and a low compaction (modified) sand.

The High Compaction (HC) test results and erodibility plots represent a material that has a high degree of compaction (ILIT, 2006). The Moderate Compaction (MC) test results and erodibility plots were the basis for the analyses that determined the breach time would occur in 1.5 hours. This corresponds to a moderately compacted poorly graded sand (ILIT, 2006). The Modified Erodibility corresponds to a low compaction poorly graded sand. Using the Modified Erodibility, LS-DYNA analyses show that the breach time matches closely the reported value of 0.5 hrs (Table 13).

Table 13: Determination of Erosion on sand Dike with a Modified Erodibility Curve

Grass Cover	Breach Time (hrs)	Surge Elev. (ft)	Lateral Erosion (ft)	Cumulative Erosion (ft)
None	0.5	1.54	7.2	7.2

VII. COMPARISONS WITH VALIDATED ANALYTICAL MODELS

The results developed via the wave-induced erosion method were compared with existing empirical formulations of wave-induced erosion to validate the method and the magnitude of results generated. Two approaches were used, Kriebel and Dean (1993) and Stanczak (2008) & Allsop et al (2007). Kriebel and Dean (1993) only evaluate cases for sand-core dunes, whereas Stanczak (2008) and Allsop et al (2007) allow for the evaluation of erosion of a turf cover over sandy substrate. Kriebel and Dean (1993) analyses were performed for the Hurricane Katrina (Scenario 1 – Katrina As Was Conditions, and 2C – Katrina Neutral MRGO Conditions), excluding the protective effects of the turf cover, and the Geisenhainer & Kortenhaus case study. Stanczak (2008) and Allsop et al (2007) analytical algorithms were used to evaluate all cases. For the Hurricane Katrina scenarios, poor grass density on sandy substrate was assumed in these analyses.

The Stanczak (2008), D'Eliso (2008), Carlson and Sayre (1961), and Allsop et al (2007) studies have particular importance to this validation study. These studies specifically address wave side initiated breaching of dikes with grass and clay covers and sand cores (Figure 33). These studies are part of a long-term (2002 – 2008) study of failure mechanisms for flood defense structures sponsored by the European Community and the Consortium for Integrated Flood Risk Analysis and Management Methodologies.

Development of the analytical models were based on field observations of wave induced breaching of dikes with grass and clay covers and sand cores (Figure 34) and on previous studies performed to evaluate erosion of sand dunes due to wave impacts (Larson et al 2004). The analytical models were validated with case history studies of dikes that had eroded and breached due to wave attack during storms (Figures 34 and 35) and with results from small scale wave flume tests (Figure 36).

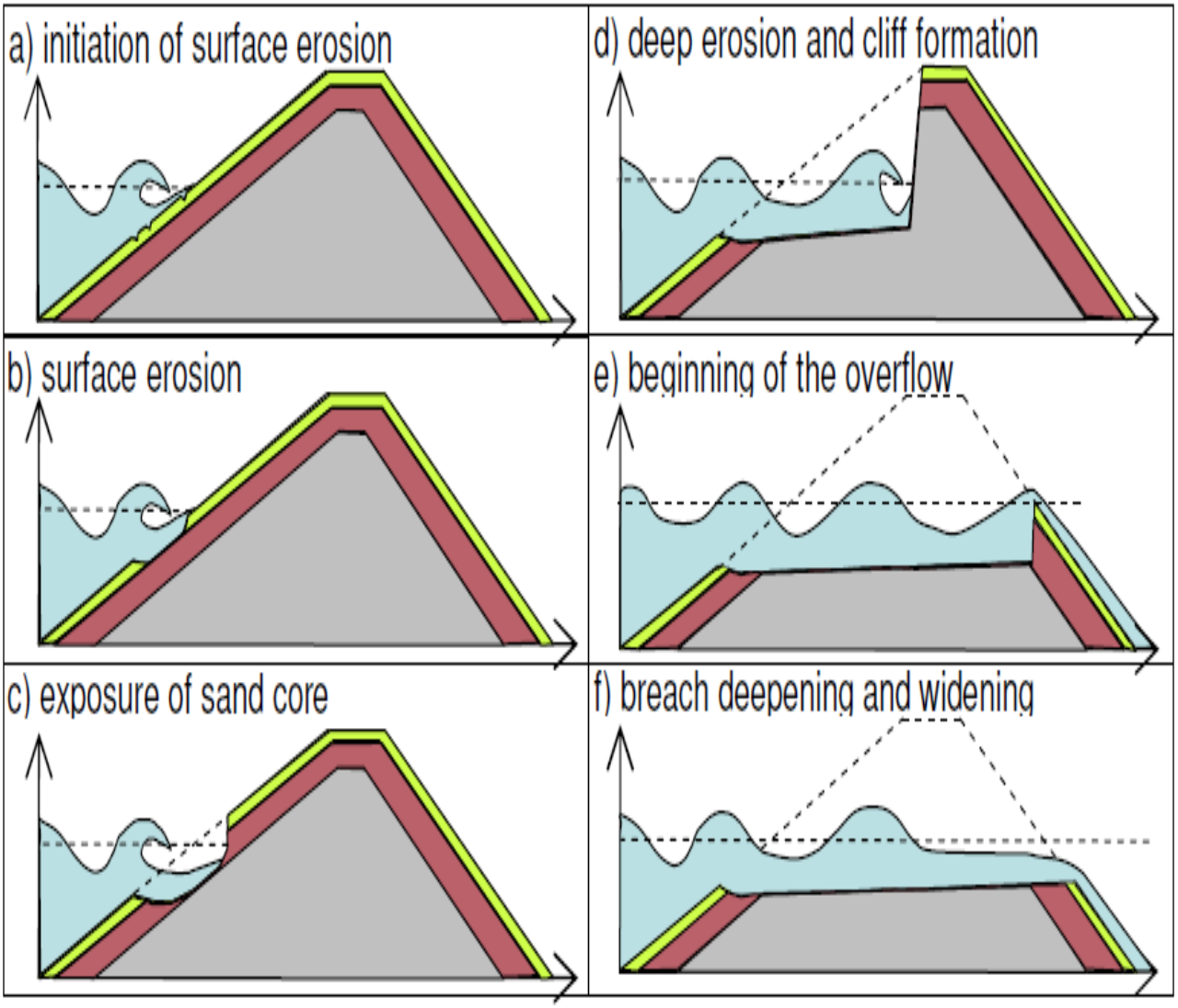


Figure 33: Analytical models used to characterize wave side initiated breaching of grass and clay covered sand core dikes (Stanczak 2008).



Figure 34: Photographs of wave side attack initiated breaching of clay and grass covered dikes (Stanczak 2008).

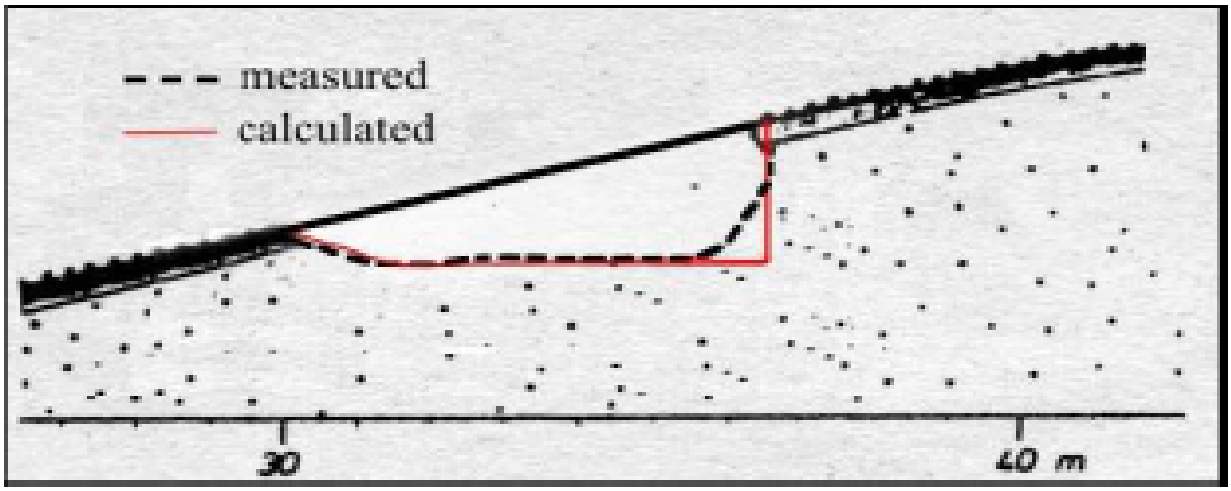


Figure 35b: Example of validation of analytical models developed by Stanczak (2008) and Allsop et al (2007) with field data from sand core dikes subjected to wave attack (Stanczak 2008).

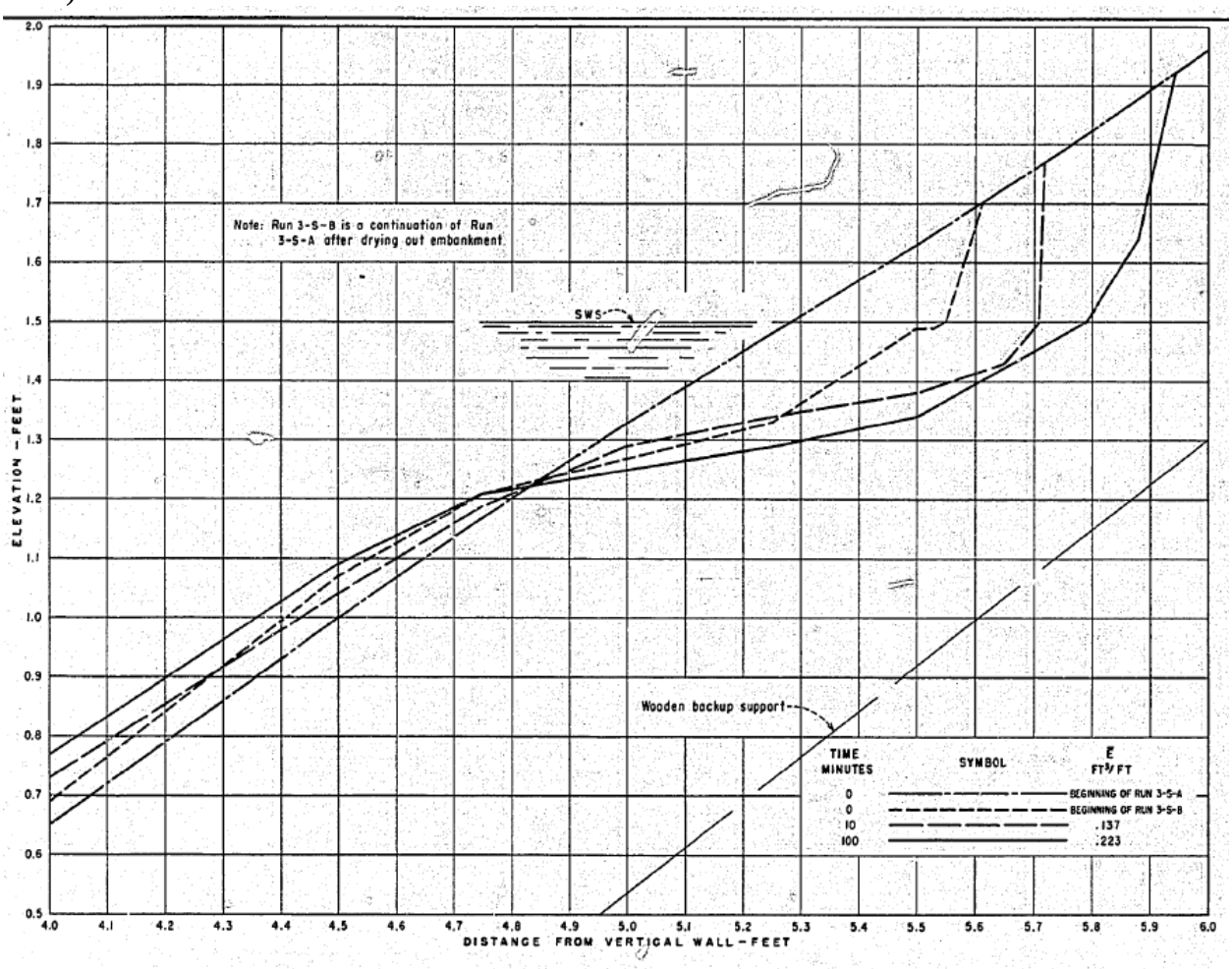


Figure 35b: Erosion cross sections developed during labratory wave flume tests of a compacted earth embankment (Carlson and Sayre 1961).

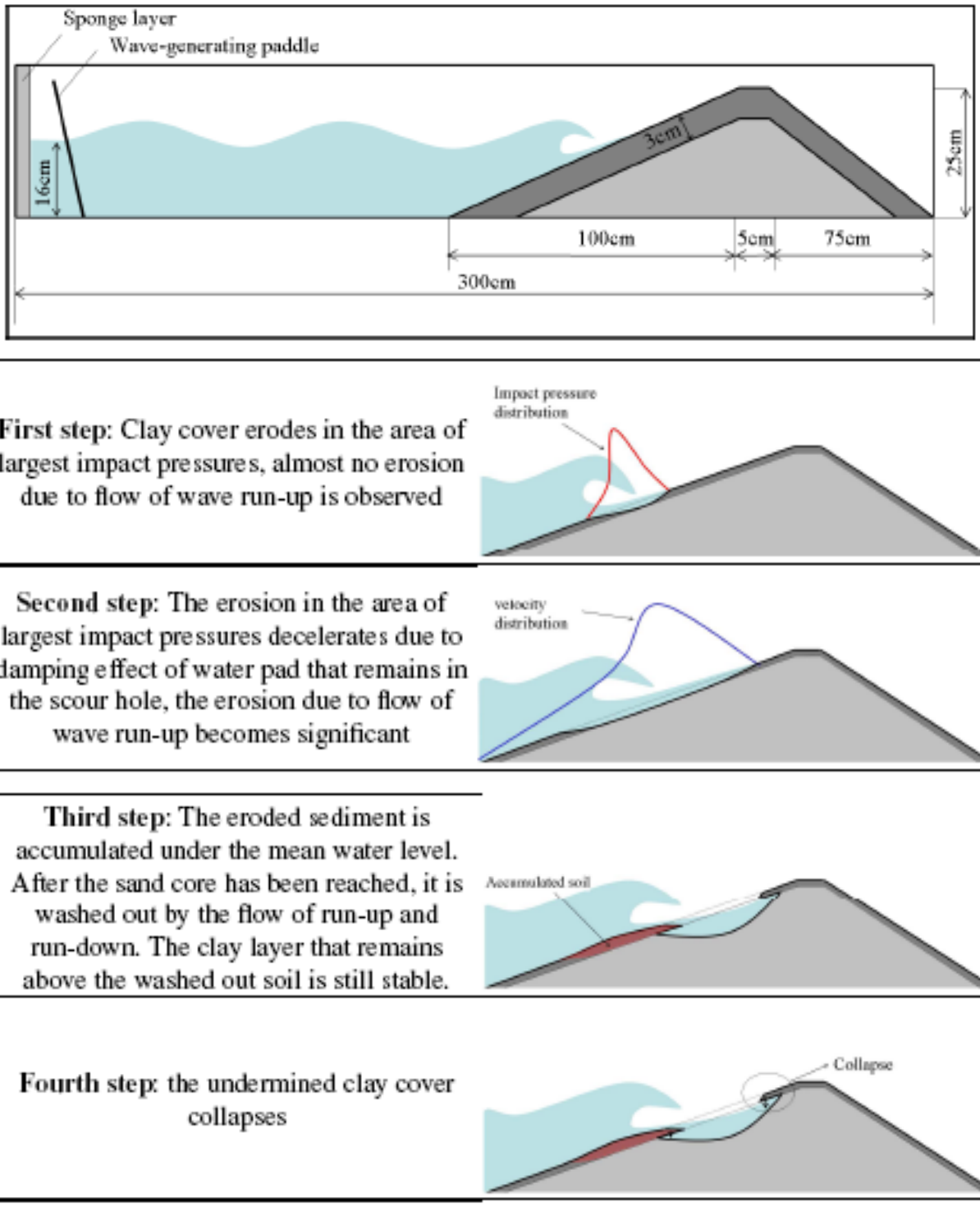


Figure 36(a): Small scale wave flume test observations used to validate wave breaching analytical model components (Stanczak 2008)

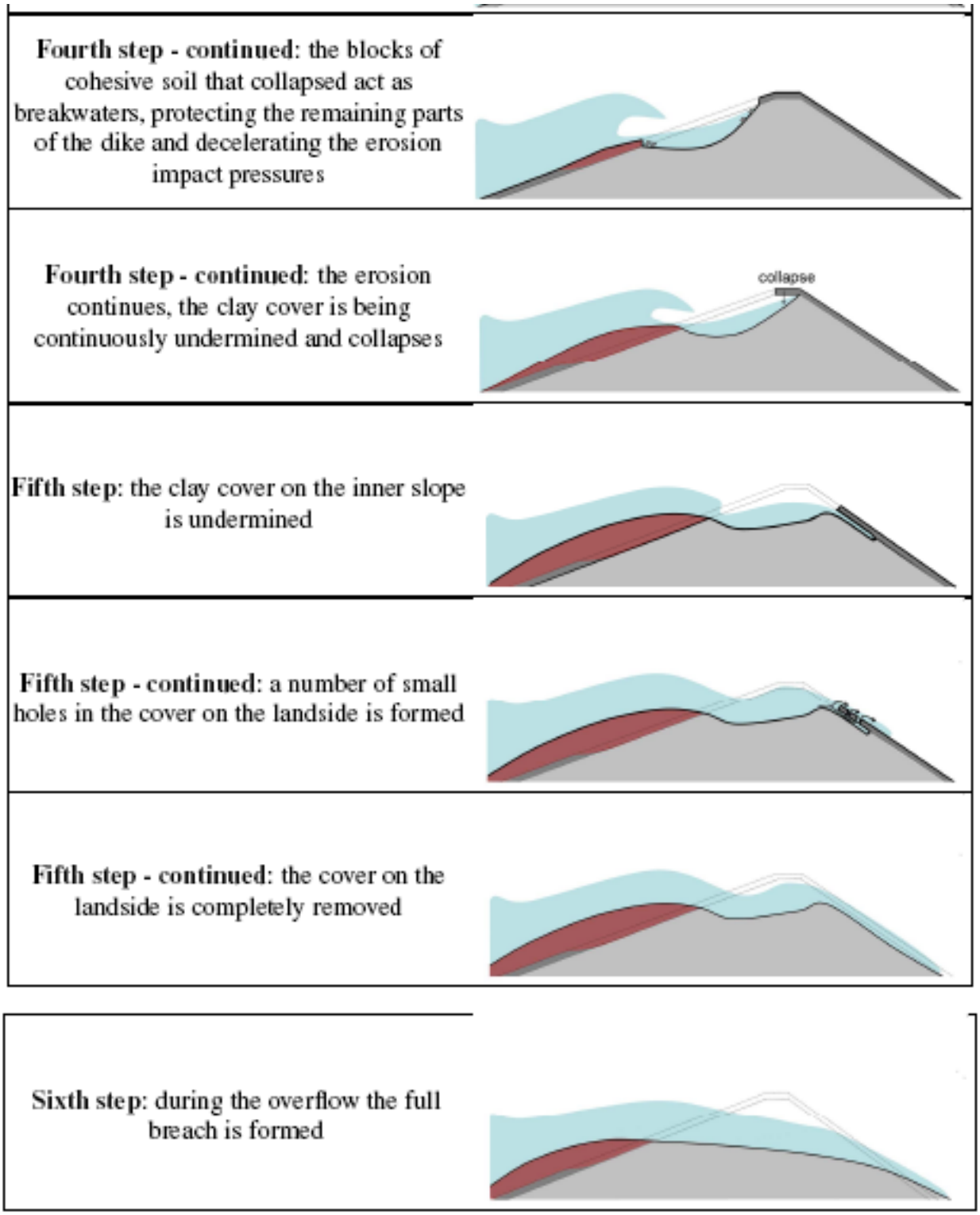


Figure 36 (b): Small scale wave flume test observations used to validate wave breaching analytical model components (Stanczak 2008)

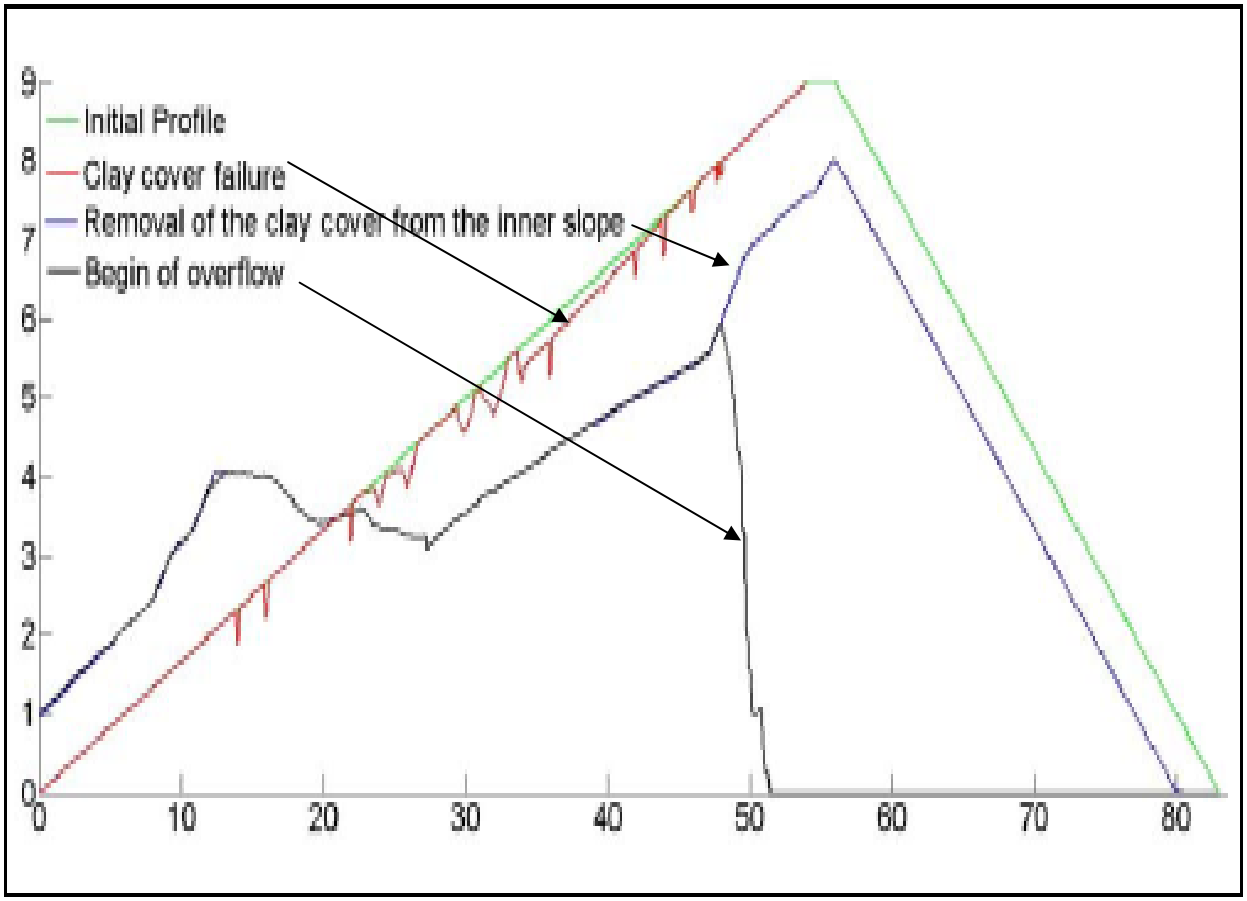


Figure 36 (c): Small scale wave flume test observations used to validate wave breaching analytical model components (Stanczak 2008). Note how the erosion feature face reverses after overtopping flow.

Kriebel and Dean (1993)

The Convolution Method for time-dependent beach-profile response (Kriebel and Dean, 1993) was used as a closed-form analytic solution by which to compare with results generated based on the wave-induced erosion method. Kriebel and Dean (1993) requires information on the hydrodynamic conditions, as well as the topographic conditions. The formula to calculate the maximum potential advance (R_∞)is shown in Equation 1 and the equation for the characteristic erosion time scale (T_s) is shown in Equation 2 and the equation parameters are listed in Table 14.

$$R_\infty = \frac{S(x_b - \frac{h_b}{m})}{B + D + h_b - \frac{S}{2}} \qquad \text{EQ [1]}$$

$$T_s = C_1 \left(\frac{H_b^{3/2}}{g^{1/2} A^3} \right) \left(1 + \frac{h_b}{B} + \frac{m x_b}{h_b} \right)^{-1} \qquad \text{EQ [2]}$$

Table 14: Kriebel and Dean (1993) Parameters

Parameter	Parameter Symbol	Units
Beach "Freeboard"	B	ft
Dune Height	D	ft
Wave Level Rise	S	ft
Gravity	g	ft/s^2
Linear Beach-Face Slope	m	- -
Wave Breaking Depth	h_b	ft
Surf Zone Width	x_b	ft
Sediment Fall Velocity	ω	ft/s
Wave Breaking Height	H_b	ft
Profile Steepness Coefficient	A	ft
Dimensionless Coefficient	C_1	- -

Stanczak (2008) & Allsop et al (2007)

The closed form solutions for grass-cover erosion by wave attack and erosion of sand core levees, as reported by Stanczak (2008) and Allsop et al (2007) were also used to compare results generated based on the wave-induced erosion method. The Stanczak (2008) and Allsop et al (2007) methods require information on the hydrodynamic conditions, topographic conditions, and grass-cover quality. The formulas to evaluate erosion of the grass cover are shown in Equations 3 and 4, and the formula to evaluate erosion of a dike core is shown in Equations 6 - 15. The equation parameters are defined in Table 15.

$$E_{grass} = t_{RG} - t_s$$ EQ [3]

$$t_{RG} = \frac{d_G}{\gamma_G c_E H_s^{\,2}}$$ EQ [4]

$$E_{core} = t_e - t_s$$ EQ [5]

$$t_e = N_w \cdot T_p$$ EQ [6]

$$l_c = \sum_{i=1}^{N_w} X_i = (h_k - y_{imp})(m+n) + B_k$$ EQ [7]

$$y_{imp} = h_w - (0.8 + 0.6 \cdot \tanh(\xi - 2.1)) H_S$$ EQ [8]

$$\xi = \frac{\tan\alpha}{\sqrt{H_s / L_0}}$$ EQ [9]

$$L_0 = \frac{g \cdot T_p^{\,2}}{2 \cdot \pi}$$ EQ [10]

$$X_i = \frac{2 \cdot Q_i}{y_i + y_{i-1}}$$ EQ [11]

$$Q_i = const = C_s \cdot \frac{u_0^4}{g^2 \cdot T_P}$$ EQ [12]

$$C_s = A \cdot e^{-b\frac{H_s}{D_{50}}}$$ EQ [13]

$$u_0 = k^* \cdot \sqrt{2 \cdot g \cdot A_{98}}$$ EQ [14]

$$A_{98} = 3 \cdot h_S \cdot \tanh(0.65 \cdot \xi)$$ EQ [15]

Table 15: Stanczak (2008) and Allsop et al (2007) Parameters

Parameter	Parameter Symbol	Units
Remaining of grass cover erosion time	E_{grass}	hr
Maximum duration of grass cover erosion	t_{RG}	hr
Duration of storm	t_S	hr
Thickness of grass cover	d_G	ft
Velocity coefficient	γ_G	- -
Coefficient for erosion resistance of grass cover	c_E	$(ft*s)^{-1}$
Significant wave height	H_S	ft
Remaining sand core erosion time	E_{core}	s
Time for erosion of sand core over the erosion length	t_e	s
Duration of storm	t_s	s
Number of waves until erosion of core is completed	N_w	- -
Peak wave period	T_p	s
Horizontal length of core for initial erosion event	l_c	ft
Horizontal length of single erosion segment	X_i	ft
Height of crest	h_k	ft
Y-coordinate of impact point on outboard slope relative to toe	y_{imp}	ft
Outer slope	m	- -
Inner slope	n	- -
Width of crest	B_k	ft
Still water level at toe of dike	h_w	ft
Wave breaker parameter	ξ	- -
Slope angle	α	degrees
Wavelength	L_0	ft
Gravitational constant	g	ft/s^2
Volume of single erosion segment	Q_i	ft^3/ft
Empirical coefficient according to Larson et al. (2004)	C_s	- -
Wave run-up velocity at still water level	u_0	ft/s
Empirical factor according to Larson et al. (2004)	A	- -
Empirical factor according to Larson et al. (2004)	b	- -
Diameter of sand particles	D_{50}	ft
Empirical factor	k*	- -
Wave run-up height	A_{98}	ft

Hurricane Katrina Scenario 1

The hydrodynamic conditions for Hurricane Katrina (Scenario 1) are shown in Table 14 (from Bea 2008a). For an EBSB with poor grass density and sandy (highly erodible) substrate, the estimated time to failure via the wave-induced erosion method was determined to be about one

hour for erosion of the turf cover and then another 30 minutes for breach of the sand core (Bea, 2008a). It should be noted that the hydrodynamic conditions during these time periods were not constant, as indicated in Table 16. Failure of the EBSB was estimated to be around 0600 CDT (Bea, 2008a)

Table 16: Summary of Scenario 1 Hydrodynamic Values at Station 497+00 (Actual MR-GO)

Time (CDT)	**Storm Surge (ft) NAVD88**	**Significant Wave Height (ft)**	**Wave Period (s)**	**Overtopping ($ft^3/s/ft$)**
0400	*9.2*	*1.9*	*3.8*	*0.0*
0430	10.1	2.0	4.0	0.0
0500	*11.0*	*2.1*	*4.2*	*0.0*
0530	12.0	2.7	4.5	0.0
0600	*13.0*	*3.3*	*4.7*	*0.0*
0630	14.2	4.1	4.9	0.0
0700	*15.4*	*4.9*	*5.1*	*0.0*
0730	16.6	5.5	5.4	0.2
0800	*17.8*	*6.0*	*5.6*	- - -
0830	16.1	4.8	5.2	0.2
0900	*14.3*	*3.6*	*4.7*	- - -

The Kriebel and Dean (1993) formulation found that the time to breach would be on the order of 2.4 hours. It should be noted that Kriebel and Dean (1993) do not directly account for density differences in EBSB composition, which impacts the rate of erosion. The Stanczak (2008) and Allsop et al (2007) found about 0.4 hrs were required to remove the grass cover and 1.6 hrs were

required for breaching. Table 17 presents all the analytic results for Hurricane Katrina, Scenario 1.

Table 17: Comparison of results for Hurricane Katrina Scenario 1

Analysis Method	Calculated Time to Breach
Wave-Induced Erosion Method	1.5 hrs
Kriebel and Dean (1993)	2.4 hrs
Stanczak (2008) and Allsop et al (2007)	2.0 hrs

Hurricane Katrina Scenario 2C

The hydrodynamic conditions for Hurricane Katrina (Scenario 2C) are shown in Table 16 (from Bea 2008b). These analyses assumed an EBSB with poor grass density and sandy (highly erodible) substrate. The wave-induced erosion method predicted that no breach of the crest would occur. The estimated time for turf failure was determined to be about 2 hours (Bea, 2008b). It should be noted that the hydrodynamic conditions during these time periods were not constant, as indicated in Table 18. Failure of the EBSB was estimated to be around 0600 CDT (Bea, 2008a).

Table 18: Summary of Scenario 2C Hydrodynamic Values at Station 497+00 (Neutral MR-GO)

Time (CDT)	**Storm Surge (ft) NAVD88**	**Significant Wave Height (ft)**	**Wave Period (s)**	**Overtopping ($ft^3/s/ft$)**
0400	*9.0*	*0.5*	*2.4*	*0.0*
0430	9.9	0.6	2.7	0.0
0500	*10.7*	*0.8*	*2.9*	*0.0*
0530	11.8	1.0	3.1	0.0
0600	*12.8*	*1.3*	*3.2*	*0.0*
0630	14.0	1.5	3.4	0.0
0700	*15.2*	*1.8*	*3.5*	*0.0*
0730	16.2	2.0	3.5	0.2
0800	*17.1*	*2.2*	*3.5*	- - -
0830	16.0	1.7	3.5	0.2
0900	*14.9*	*1.2*	*3.4*	- - -

The Kriebel and Dean (1993) formulation found that no breach would occur (the erosion distance was much less than the distance required to breach the crest). The Stanczak (2008) and Allsop et al (2007) found about 3.3 hrs were required to remove the grass cover and 1 hr was required for breaching, however, the storm surge did not last this long, so no breaching was possible. Table 19 presents all the analytic results for Hurricane Katrina, Scenario 2C.

Table 19: Comparison of results for Hurricane Katrina Scenario 2C

Analysis Method	Calculated Time to Breach
Wave-Induced Erosion Method	No Breach
Kriebel and Dean (1993)	No Breach
Stanczak (2008) and Allsop et al (2007)	No Breach

Hurricane Gustav

The hydrodynamic conditions for Hurricane Katrina (Scenario 2C) are shown in Table 20. The estimated time for turf failure was determined to be about 1.5 to 2 hours via the wave-induced erosion method, with no breaching. The Stanczak (2008) and Allsop et al (2007) found about 3.3 hrs were required to remove the grass cover and 2.1 hrs were required for breaching, however, the storm surge did not last this long, so no breaching was possible. Both methods predicted that a duration longer than the maximum storm surge was required to remove the grass covering, however, some damage (in accordance with the Miner's fatigue damage accumulation model). Some damage to the grass covering was observed in the field following the Hurricane.

Table 20: Summary of Hydrodynamic Values at Station 497+00 (Hurricane Gustav)

Time (CDT)	Storm Surge (ft)	Significant Wave Height (ft)	Wave Period (s)	Overtopping ($ft^3/s/ft$)
1730	*10.8*	*1.5*	*5.7*	*0.0*

Results of the analyses are presented in Table 21 for the Hurricane Gustav simulation. The Kriebel and Dean (1993) formulation was not employed because it does not address the damage of turf covers, which was the only damage experienced during Hurricane Gustav.

Table 21: Comparison of results for Hurricane Gustav

Analysis Method	Grass Cover Eroded
Wave-Induced Erosion Method	Grass Cover Not Compromised
Kriebel and Dean (1993)	Not Applicable
Stanczak (2008) and Allsop et al (2007)	Grass Cover Not Compromised

Geisenhainer and Kortenhaus

The hydrodynamic conditions for Geisenhainer and Kortenhaus (as reported in D'Eliso, 2007) are shown in Table 22. These analyses assumed a sandy (highly erodible) levee. Two erodibility profiles were used with the wave-induced erosion model. The in-situ density of the levee tested by Geisenhainer and Kortenhaus was not specified, so an erodibility characterization was assumed for the first run, which predicted a breach time of 1.5 hrs. Since it is very possible that the materials used in the laboratory experiement were of a different density than assumed, it was

found that a slightly more erodible material would result in levee breaching within the observed 0.5 hr failure time.

Table 22: Summary of Hydrodynamic Values at Station 497+00 (Hurricane Gustav)

Storm Surge (ft)	**Significant Wave Height (ft)**	**Wave Period (s)**	**Overtopping ($ft^3/s/ft$)**
1.54	*0.5*	*2.25*	*0.0*

The Kriebel and Dean (1993) formulation found that the time to breach would be on the order of 12.3 hours. The Stanczak (2008) and Allsop et al (2007) found about 0.4 hrs were required for breaching. Table 23 presents all the analytic results for Geisenhainer and Kortenhaus (as reported in D'Eliso, 2007).

Table 23: Comparison of results for Geisenhainer and Kortenhaus (D'Eliso, 2007)

Analysis Method	**Calculated Time to Breach**
Wave-Induced Erosion Method	1.5 hrs/ 0.5 hrs
Kriebel and Dean (1993)	12.3 hrs
Stanczak (2008) and Allsop et al (2007)	0.4 hrs
Reported laboratory test breach time	*0.5 hrs*

VIII. CONCLUSIONS

The LS-DYNA based analyses of the MR-GO EBSB study location erosion development during Hurricane Gustav showed that there would be no significant erosion (grass cover or soils). The observations performed by van Heerden et al (2008) following Hurricane Gustav showed that

there was no significant erosion at this location. Thus, the LS-DYNA analyses are in agreement with the observations.

The LS-DYNA based analyses of the laboratory experimental data reported by Hughes show good agreement between predicted and measured water velocities at crown and backside of model levee.

The LS-DYNA based analyses of the laboratory experimental data reported by Gesenhainer and Kortenhaus (2006) closely match the measured breaching time (and distance) of the model sand dike given that the soil comprising the experimental dike was simulated with a low compaction poorly sorted sand.

Analyses of the EBSB study location predicted breaching times during Hurricane Katrina conditions (Scenario 1) based on the LS-DYNA analyses (1.5 hours) were in good agreement with those based on the analytical models provided by Kriebel and Dean (2.4 hours) and Starczak and Allsop et al (2.0 hours).

Analyses of the EBSB study location predicted breaching times during Hurricane Katrina MR-GO Neutral conditions (Scenario 2C) based on the LS-DYNA analyses (no breaching or significant erosion) were in good agreement with those based on the analytical models provided by Starczak and Allsop (no breaching or significant erosion). Given that consideration is given to the turf / grass cover lift-off time, the analytical model provided by Kriebel and Dean would also predict no significant erosion.

Analyses of the EBSB study location erosion during Hurricane Gustav conditions based on the analytical models provided by Starczak (2008) and Allsop et al (2007) were in excellent agreement with those based on the LS-DYNA analyses (no significant erosion or turf – grass lift off) and with the observations of the EBSB study location following Hurricane Gustav (van Heerden 2008).

Analyses of the laboratory experimental sand dike wave breaching experiments performed by Geisenhainer and Kortenhaus (2006) based on the analytical models provided by Starczak and Allsop et al (2007) were in excellent agreement with those based on the LS-DYNA analyses; 0.4 and 0.5 hours, respectively, compared with an experimental result of 0.5 hours.

The primary conclusion reached as a result of the analyses documented in this report is that the LS-DYNA analyses are able to reliably replicate results from laboratory experiments, field observations, and results from other analytical models which have been validated with laboratory and field experimental data.

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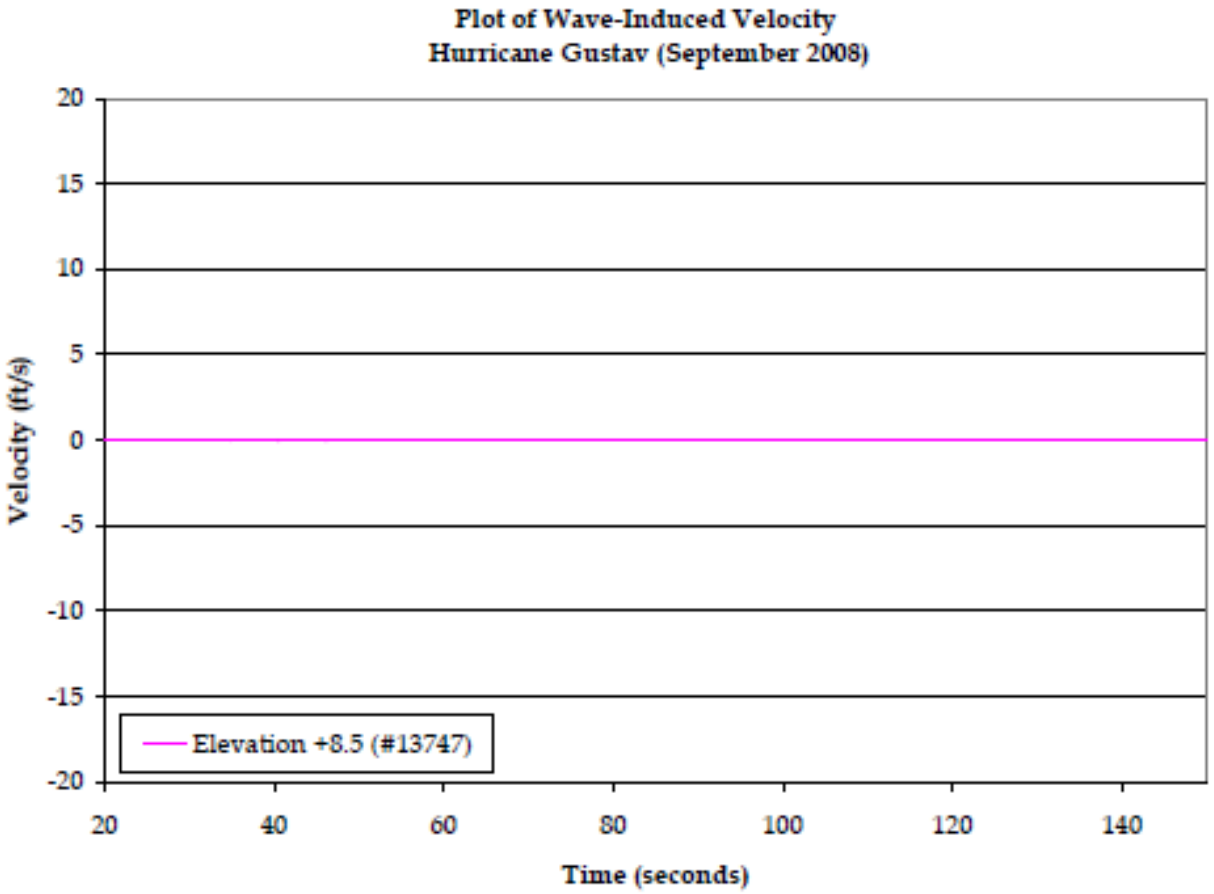
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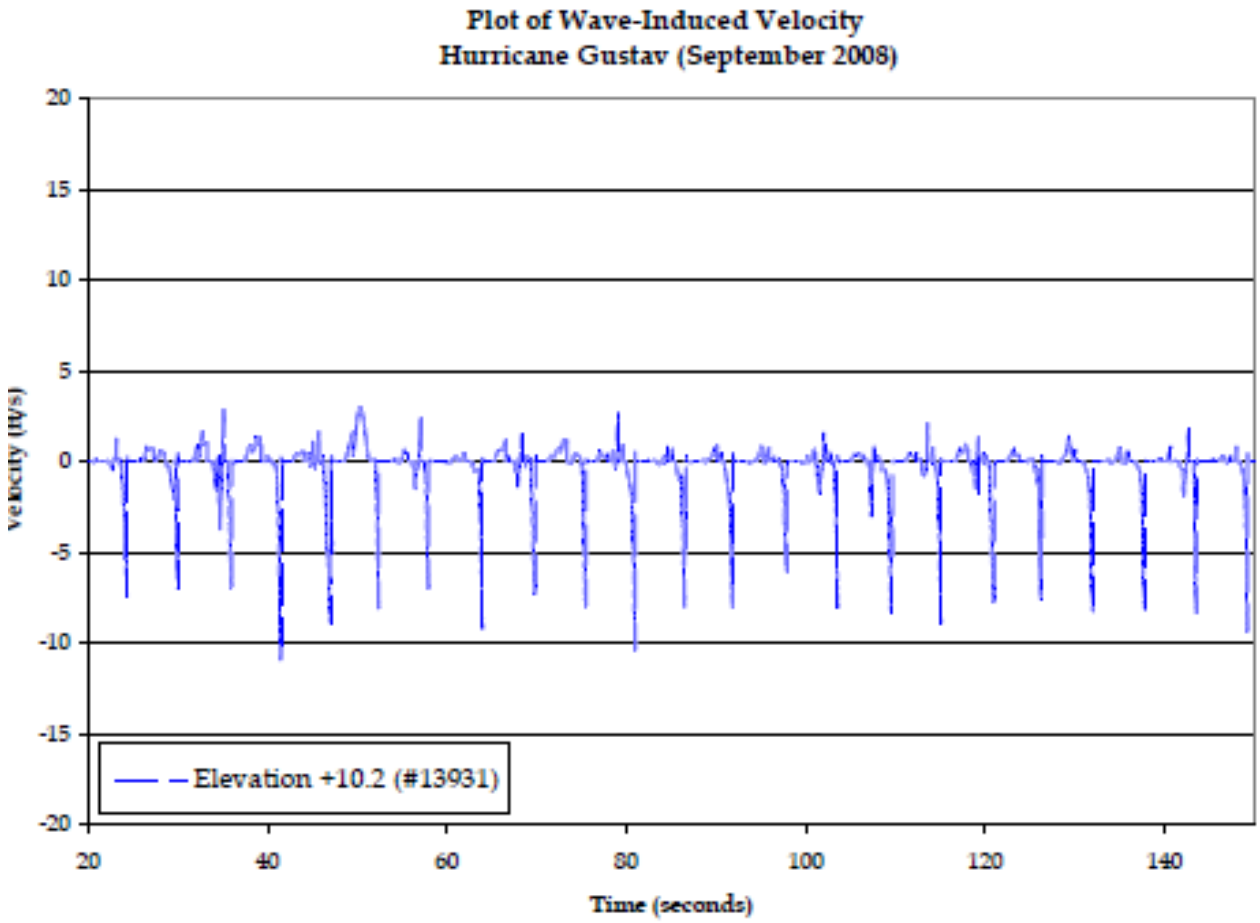
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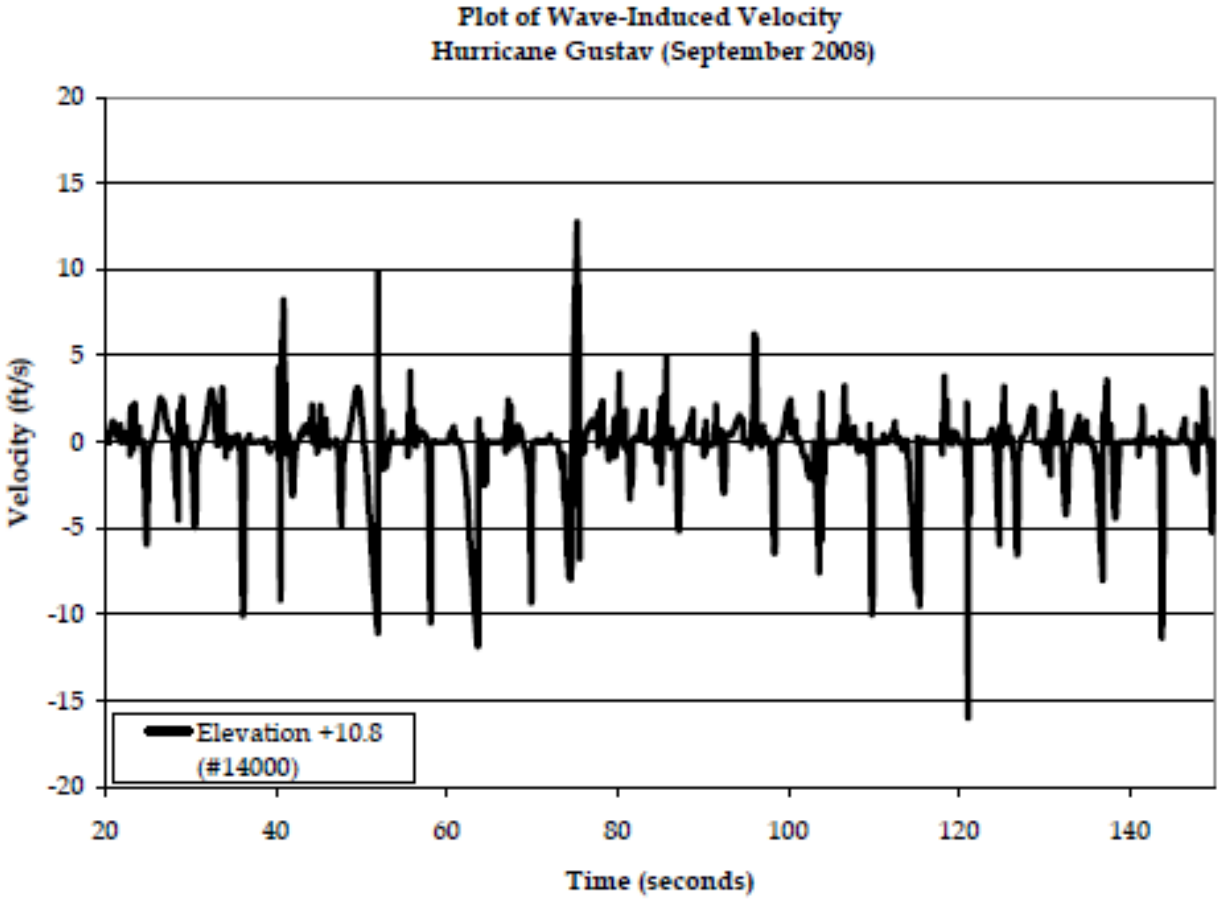
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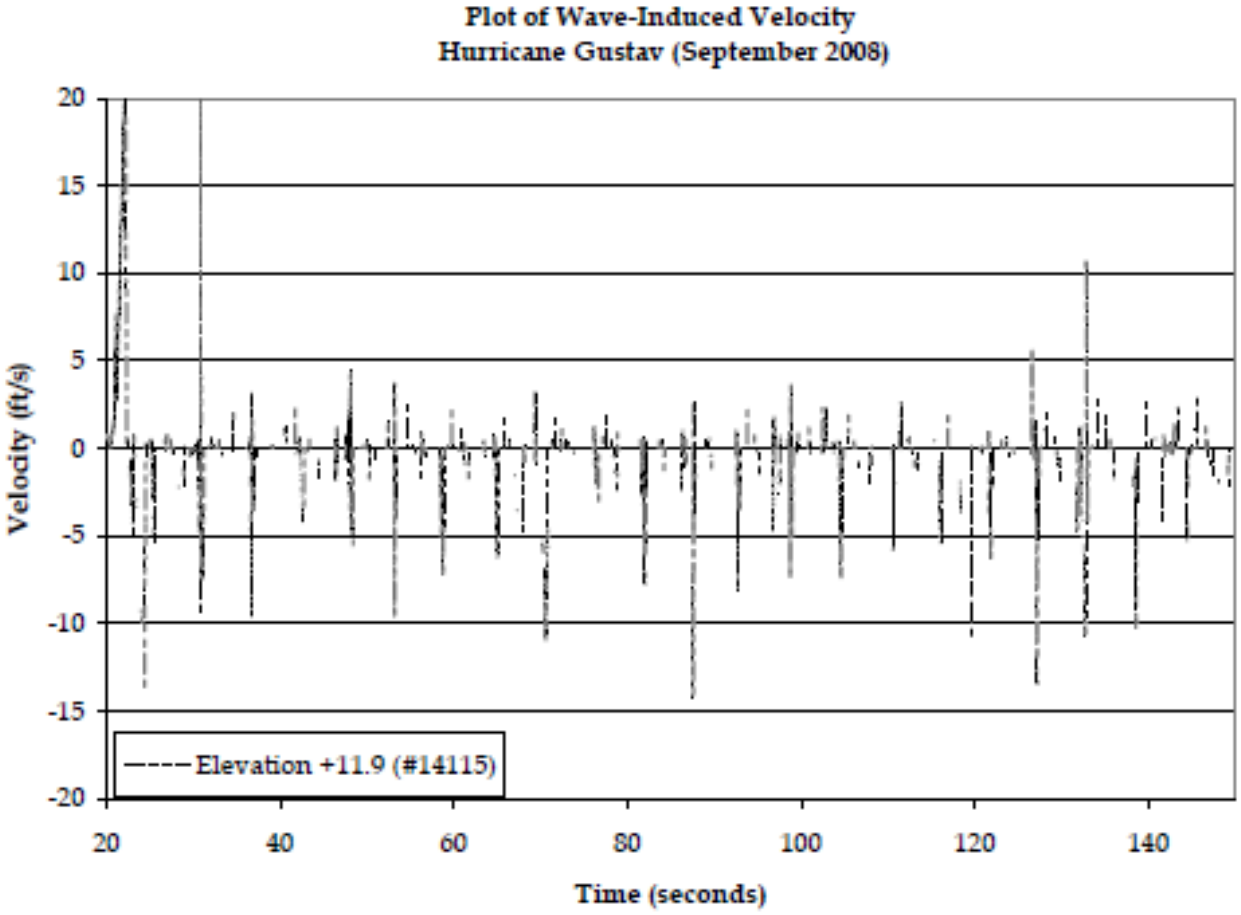
Appendix I

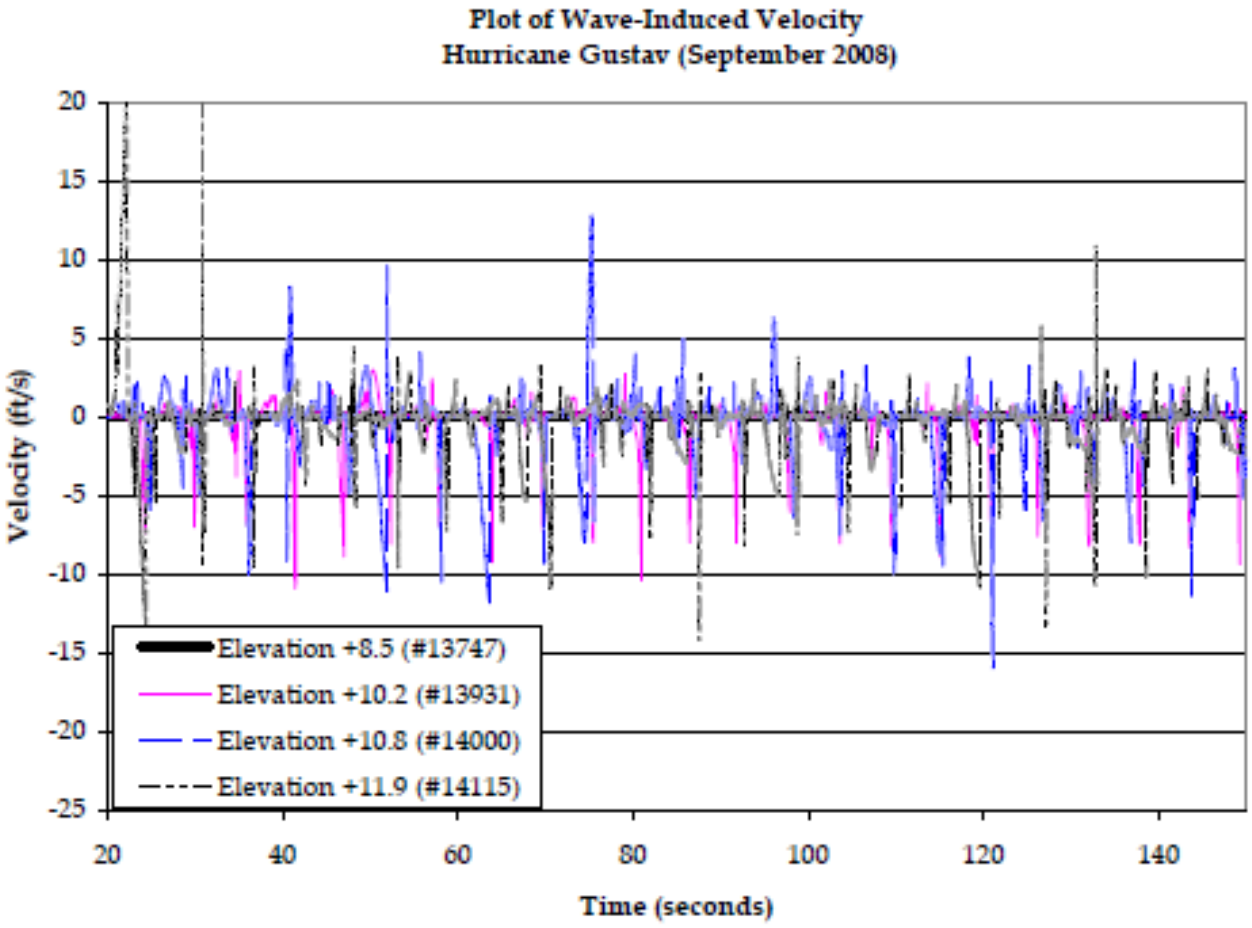
Hurricane Gustav Simulation Velocity and Cumulative Erosion Plots


Plot of Wave-Induced Velocity
Hurricane Gustav (September 2008)
Velocity (ft/s)
20
15
10
5
0
-5
-10
-15
-20
Elevation +8.5 (#13747)
20
40
60
80
100
120
140
Time (seconds)


Plot of Wave-Induced Velocity
Hurricane Gustav (September 2008)
Velocity (ft/s)
20
15
10
5
0
-5
-10
-15
-20
20
40
60
80
100
120
140
Time (seconds)
Elevation +10.2 (#13931)

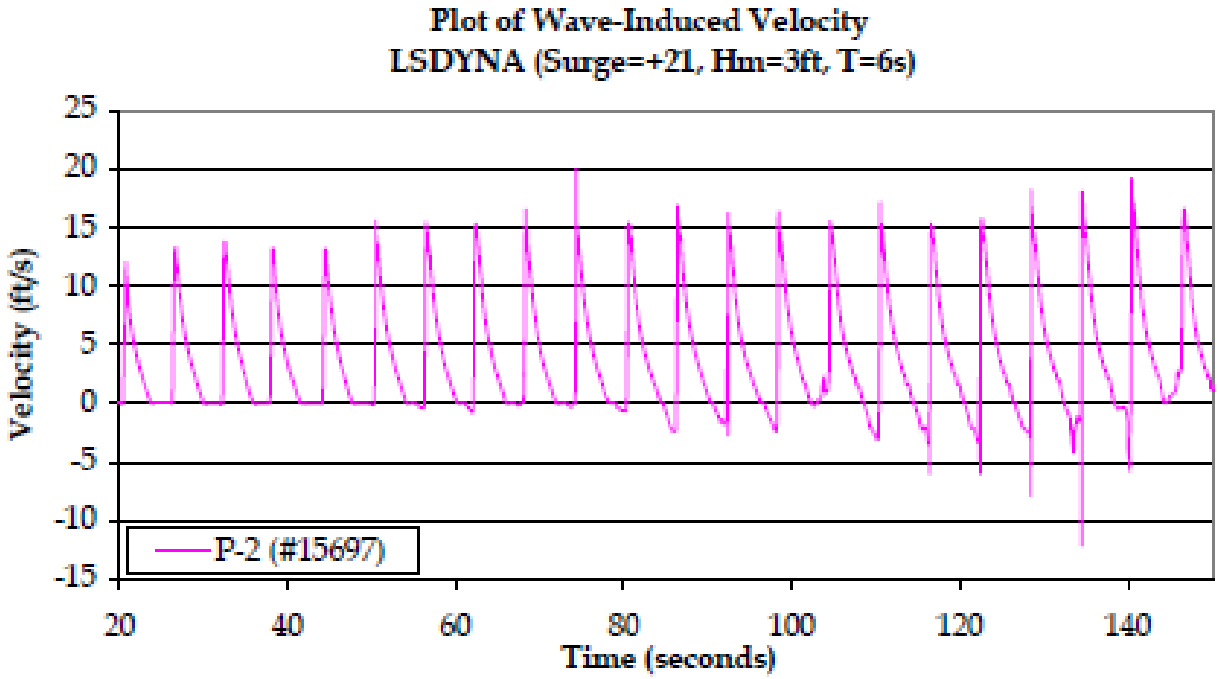

Plot of Wave-Induced Velocity
Hurricane Gustav (September 2008)
Velocity (ft/s)
20
15
10
5
0
-5
-10
-15
-20
20
40
60
80
100
120
140
Time (seconds)
Elevation +10.8
(#14000)

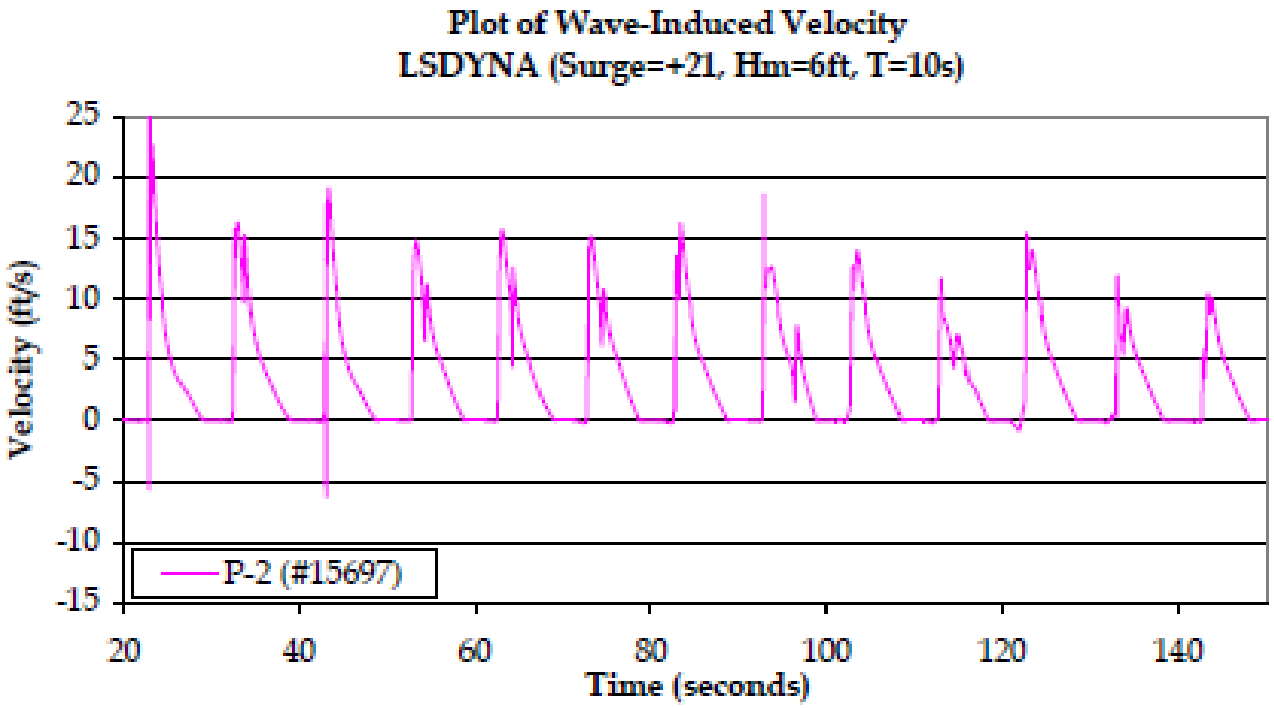

Plot of Wave-Induced Velocity
Hurricane Gustav (September 2008)
Velocity (ft/s)
20
15
10
5
0
-5
-10
-15
-20
20
40
60
80
100
120
140
Time (seconds)
Elevation +11.9 (#14115)

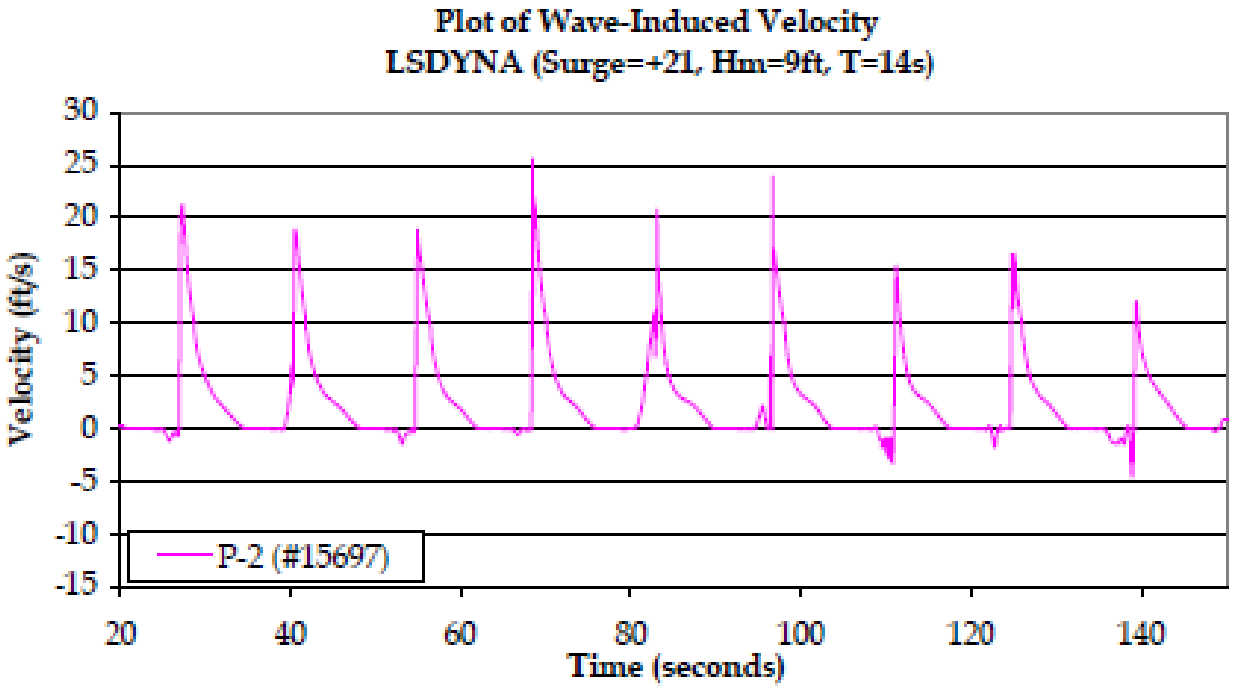

Plot of Wave-Induced Velocity
Hurricane Gustav (September 2008)
Velocity (ft/s)
Time (seconds)
Elevation +8.5 (#13747)
Elevation +10.2 (#13931)
Elevation +10.8 (#14000)
Elevation +11.9 (#14115)
20
15
10
5
0
-5
-10
-15
-20
-25
20
40
60
80
100
120
140

Appendix II

Hughes (2008) Velocity Plots


Plot of Wave-Induced Velocity
LSDYNA (Surge=+21, Hm=3ft, T=6s)
Velocity (ft/s)
25
20
15
10
5
0
-5
-10
-15
P-2 (#15697)
20
40
60
80
100
120
140
Time (seconds)

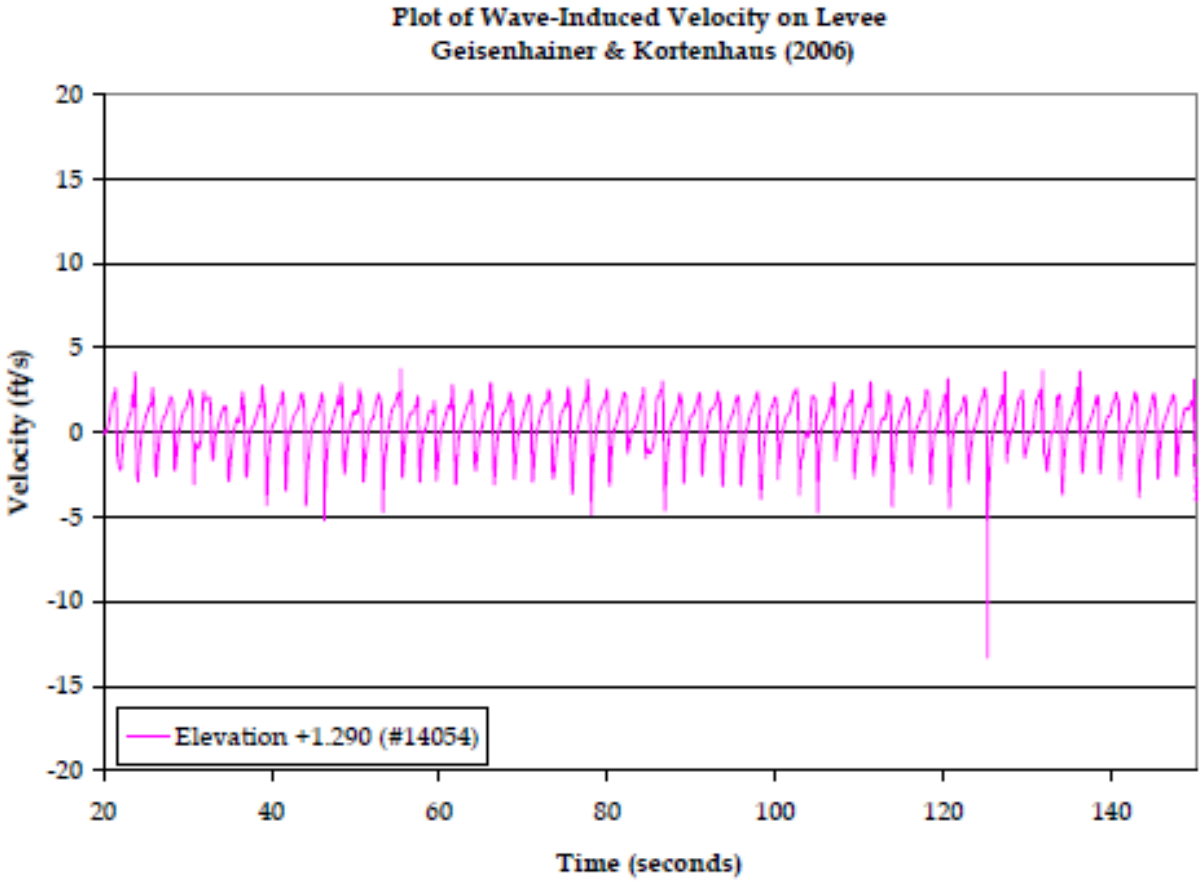

Plot of Wave-Induced Velocity
LSDYNA (Surge=+21, Hm=6ft, T=10s)
Velocity (ft/s)
25
20
15
10
5
0
-5
-10
-15
20
40
60
80
100
120
140
Time (seconds)
P-2 (#15697)

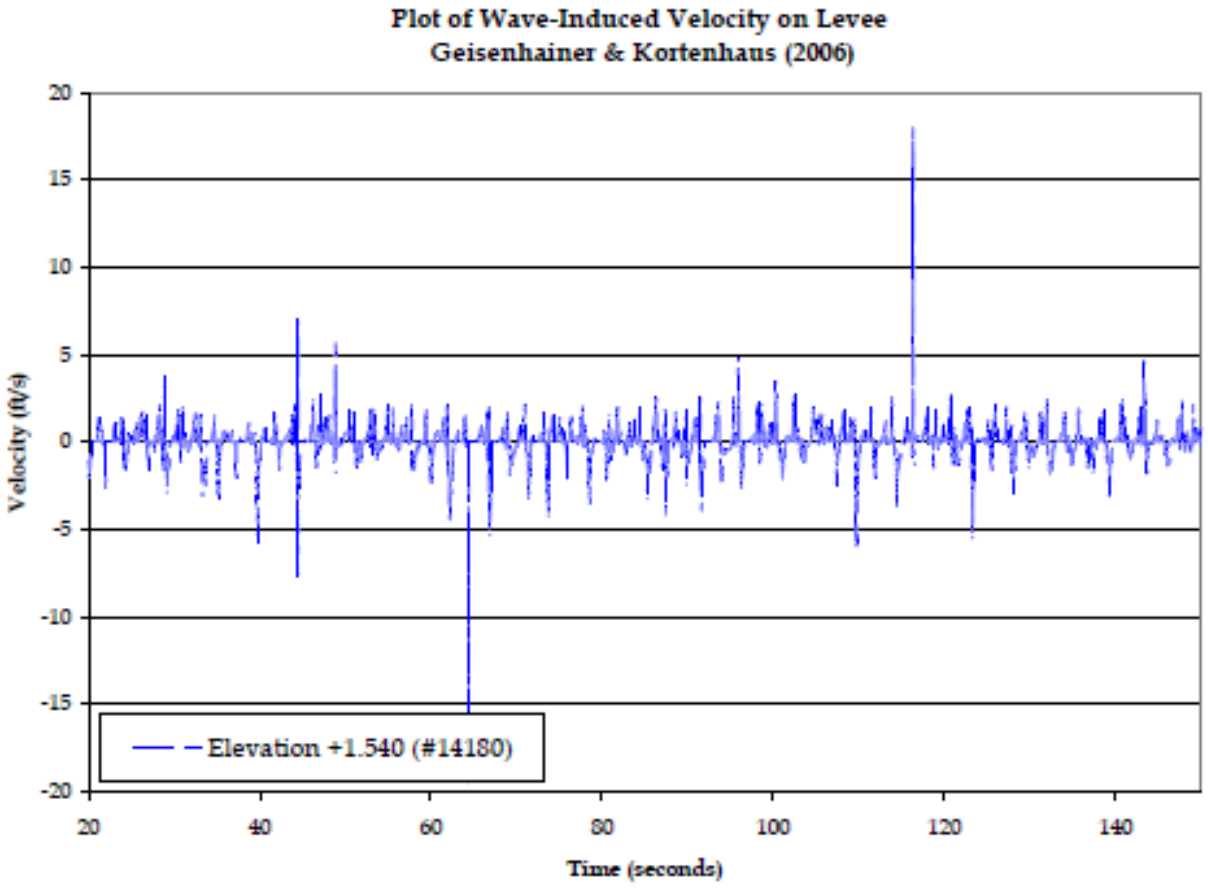

Plot of Wave-Induced Velocity
LSDYNA (Surge=+21, Hm=9ft, T=14s)
Velocity (ft/s)
30
25
20
15
10
5
0
-5
-10
-15
P-2 (#15697)
20
40
60
80
100
120
140
Time (seconds)

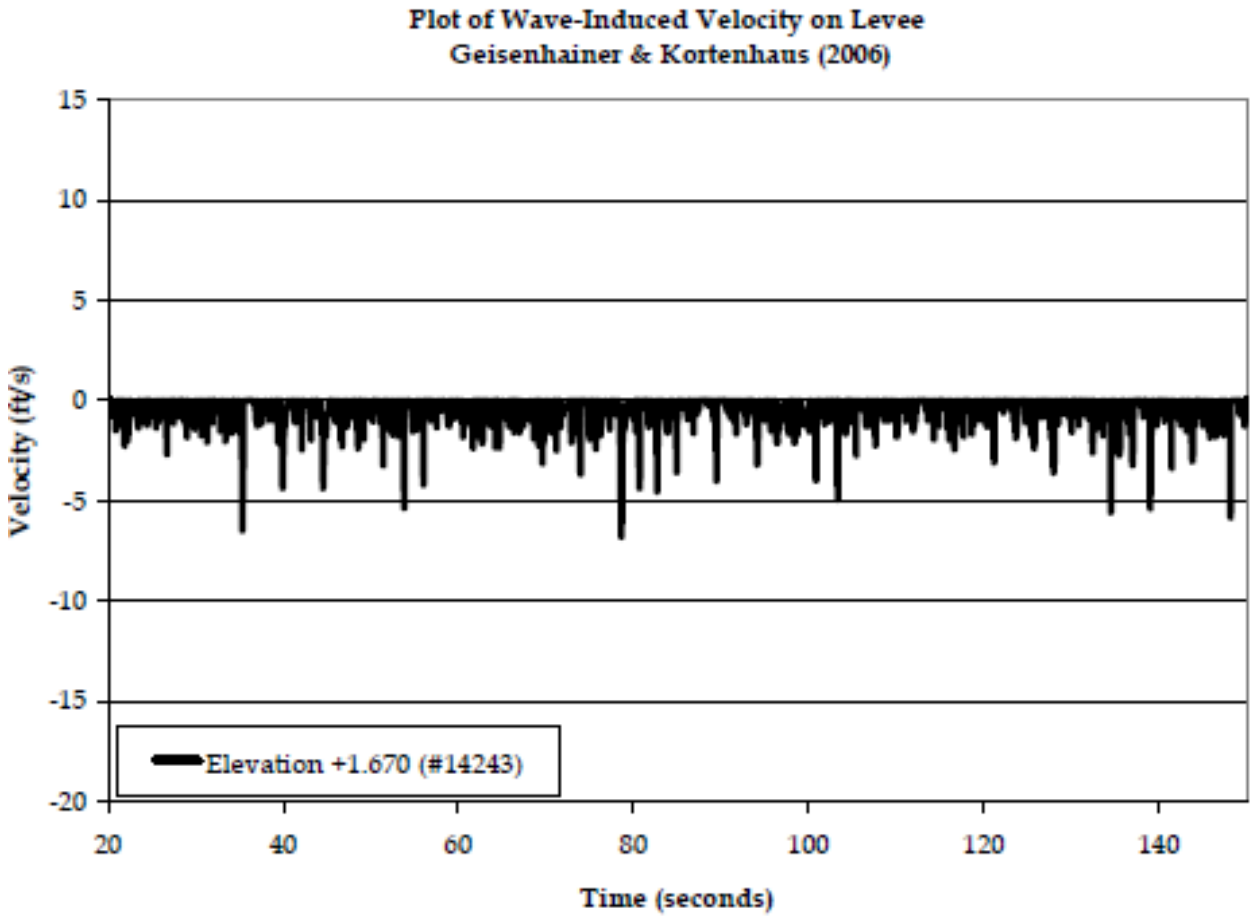
Appendix III

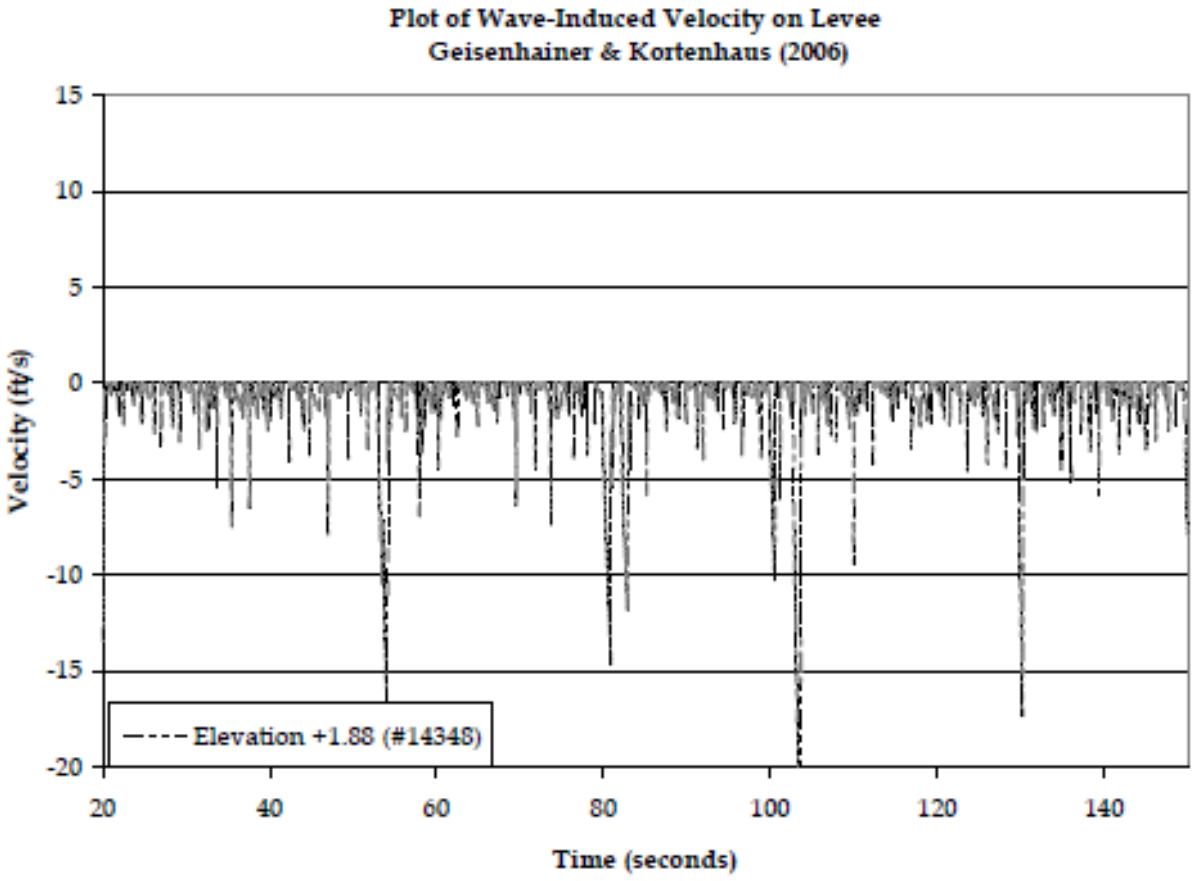
Geisenhainer & Kortenhaus Simulation

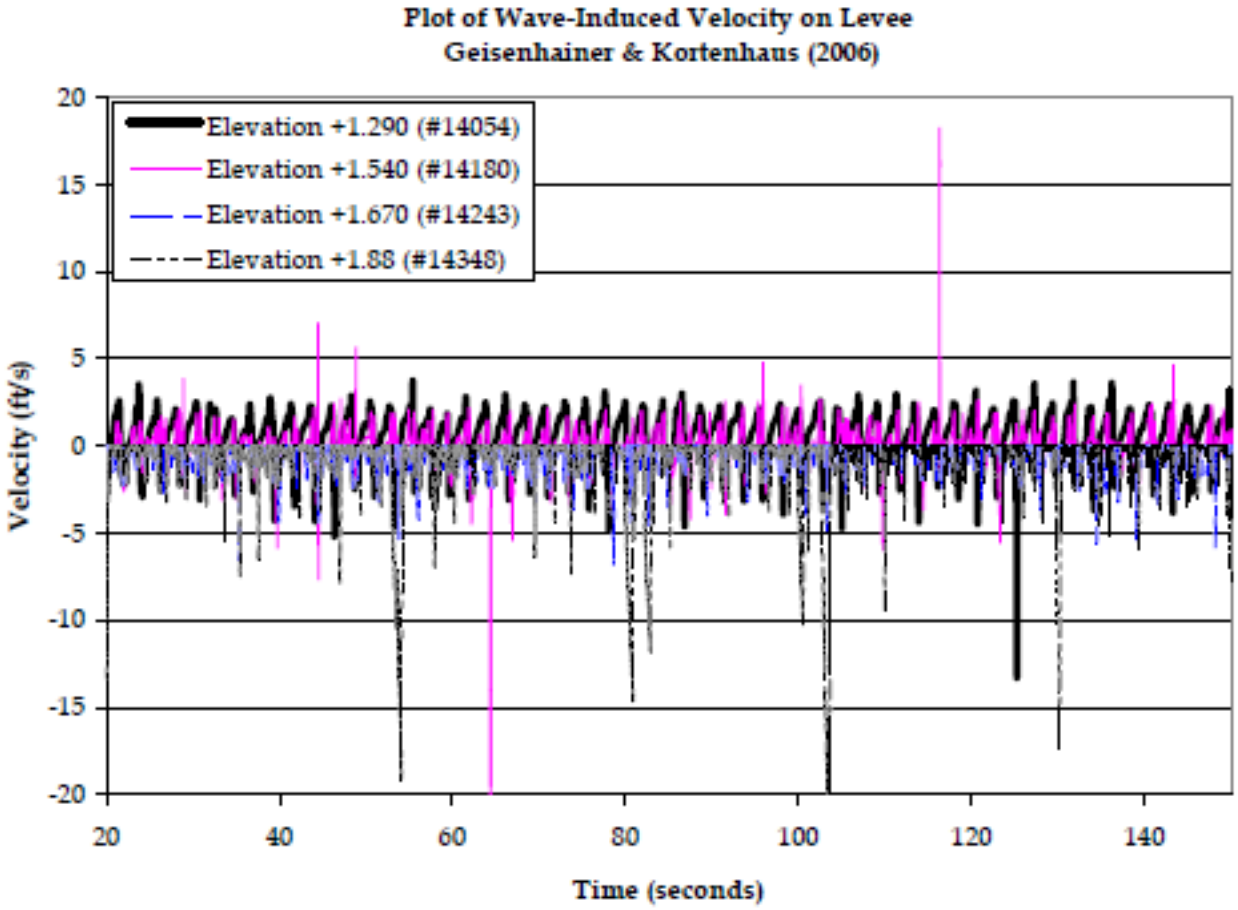
Velocity & Cumulative Erosion Plots


Plot of Wave-Induced Velocity on Levee
Geisenhainer & Kortenhaus (2006)
Velocity (ft/s)
20
15
10
5
0
-5
-10
-15
-20
20
40
60
80
100
120
140
Time (seconds)
Elevation +1.290 (#14054)


Plot of Wave-Induced Velocity on Levee
Geisenhainer & Kortenhaus (2006)
Velocity (ft/s)
20
15
10
5
0
-5
-10
-15
-20
20
40
60
80
100
120
140
Time (seconds)
Elevation +1.540 (#14180)


Plot of Wave-Induced Velocity on Levee
Geisenhainer & Kortenhaus (2006)
15
10
5
0
-5
-10
-15
-20
Velocity (ft/s)
Elevation +1.670 (#14243)
20
40
60
80
100
120
140
Time (seconds)


Plot of Wave-Induced Velocity on Levee
Geisenhainer & Kortenhaus (2006)
15
10
5
0
-5
-10
-15
-20
Velocity (ft/s)
Elevation +1.88 (#14348)
20
40
60
80
100
120
140
Time (seconds)

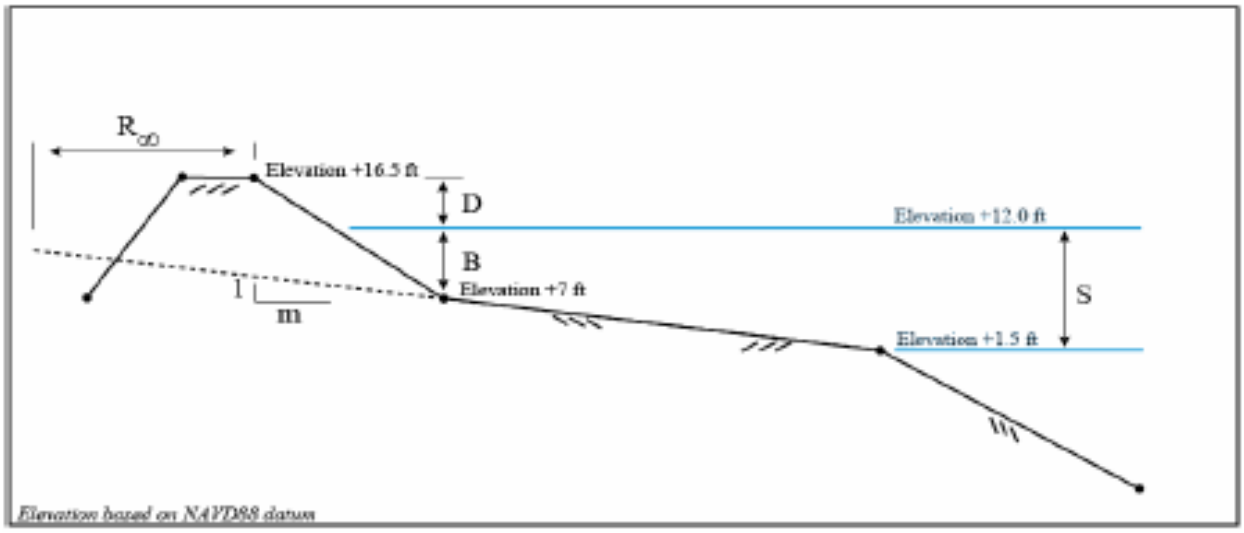

Plot of Wave-Induced Velocity on Levee
Geisenhainer & Kortenhaus (2006)
Elevation +1.290 (#14054)
Elevation +1.540 (#14180)
Elevation +1.670 (#14243)
Elevation +1.88 (#14348)
Velocity (ft/s)
Time (seconds)
20
15
10
5
0
-5
-10
-15
-20
20
40
60
80
100
120
140

Appendix IV

Analytic Calculations

Kriebel and Dean (1993) Analytic Beach-Profile Response Solution
Applied to: MR-GO Scenario 1
As reported in Storesund & Bea (2008)

Model Geometry



Model Parameters

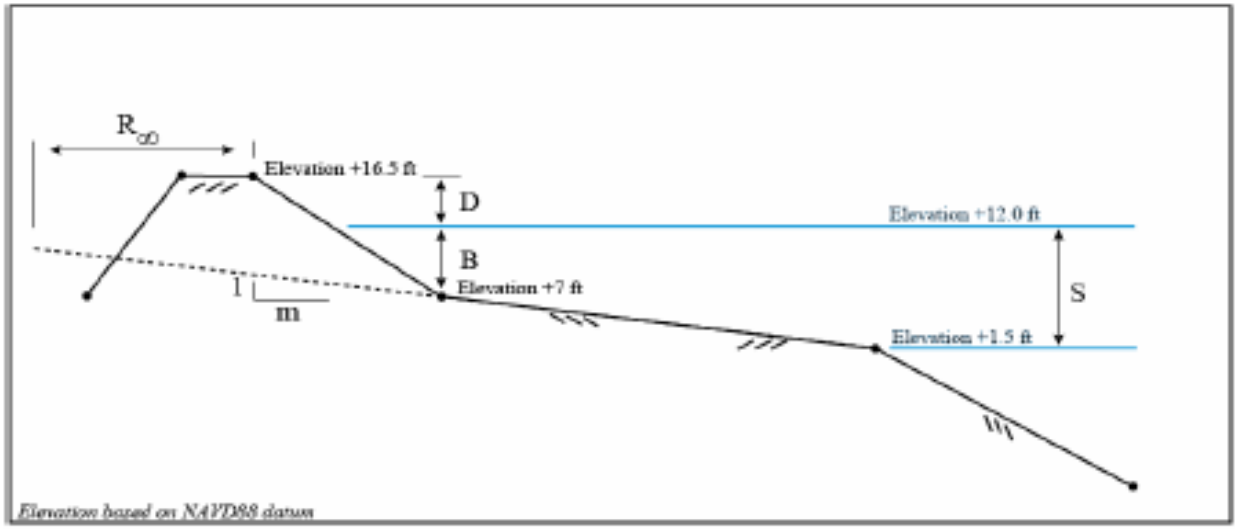
S=	10.5 ft	A=	0.536 ft
D=	4.5 ft	x_b=	28.5 ft
B=	5.0 ft	g=	32.2 ft/s^2
ω=	0.66 ft/s	H_b=	3.9 ft
m=	66 - -		
h_b=	5.0 ft	C_1=	320 - -

$$R_\infty = \frac{S\left(x_b - \frac{h_b}{m}\right)}{B + D + h_b - \frac{S}{2}}$$

R_∞=	32.2 ft
T_s=	2.4 hrs

Kriebel and Dean (1993) Analytic Beach-Profile Response Solution
Applied to: MR-GO Scenario 2C
As reported in Storesund & Bea (2008)

Model Geometry



Model Parameters

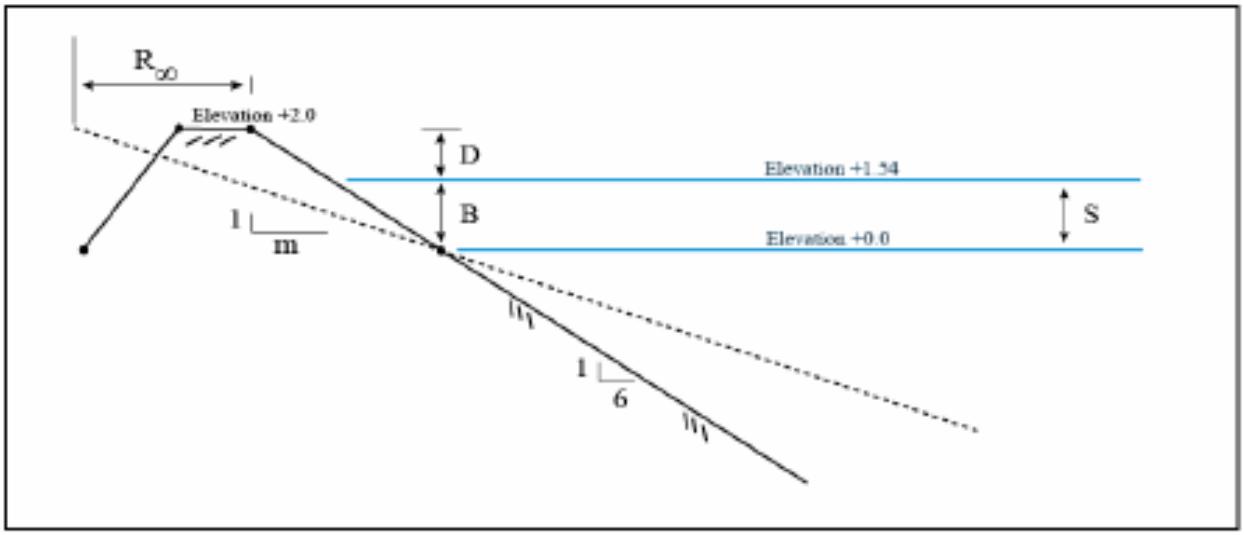
S=	10.5 ft	A=	0.536 ft
D=	4.5 ft	x_b=	2.5 ft
B=	5.0 ft	g=	32.2 ft/s^2
ω=	0.66 ft/s	H_b=	0.8 ft
m=	66 - -		
h_b=	1.0 ft	C_1=	320 - -

$$R_\infty = \frac{S\left(x_b - \frac{h_b}{m}\right)}{B + D + h_b - \frac{S}{2}}$$

R_∞=	5.1 ft
T_s=	1.8 hrs

Kriebel and Dean (1993) Analytic Beach-Profile Response Solution
Applied to: Geisenhainer & Kortenhaus (2006)
As reported in D'Eliso (2007)

Model Geometry



Model Parameters

S=	1.5 ft	A=	0.536 ft
D=	0.5 ft	x_b=	4.9 ft
B=	1.5 ft	g=	32.2 ft/s^2
ω=	0.66 ft/s	H_b=	1.2 ft
m=	10 - -		
h_b=	1.5 ft	C_1=	320 - -

$$R_\infty = \frac{S\left(x_b - \frac{h_b}{m}\right)}{B + D + h_b - \frac{S}{2}}$$

R_∞=	2.6 ft
T_s=	12.3 hrs

Evaluation: Hurricane Katrina Scenario 1

Model Configuration		
Time Period		
Significant Wave Height (H)	2.7	ft
Wave Period (T)	4.5	s
Duration	2	hr
D50	0.0006562	ft
Soil void ratio (e)	0.65	
Floodside Slope (1:x)	3.5	
Surge Elevation	12	ft

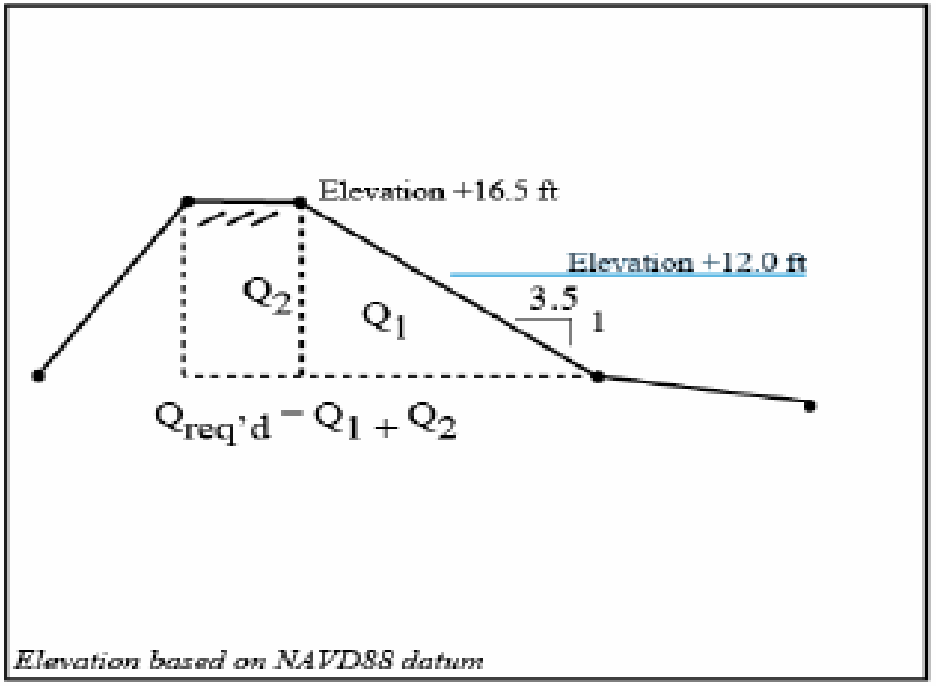
Constants		
Gravity	32.2	ft/s2
Water Density	1.99	slugs/ft3
Gs	2.71	

Model Properties		
Duration Increments		hr
Number of Increments	800	
Wave Velocity (Uo)	19.6	ft/s
Cu	2.1	
Cs	0.00134	ft3/lb
Porosity	0.39	
Soil density (ps)	3.95	slugs/ft3
Breaker Type (x)	1.8	-Plunging
Floodside Slope	15.95	degrees
Deep water wave length (Lo)	104	ft

Grass Cover Erosion		
dgrass	0.5	ft
Egrass	0.0000426	1/ft*s
dg,max	0.0013975	ft
Cover erosion time	0.4	hrs

Qi Erosion Determination		
Qi	0.0426698	ft3/s
Qreq'd	253	ft3
time to breach (Qreq'd/Qi)	1.6	hrs

Stanczak (2008) & Allsop et al (2007) Analytic Profile Response Solution
Applied to: Hurricane Katrina (2005)
As reported in Bea (2008a)



Evaluation: Hurricane Katrina Scenario 2C

Model Configuration		
Time Period		
Significant Wave Height (H)	1	ft
Wave Period (T)	3	s
Duration	2	hr
D50	0.0006562	ft
Soil void ratio (e)	0.65	
Floodside Slope (1:x)	3.5	
Surge Elevation	12	ft

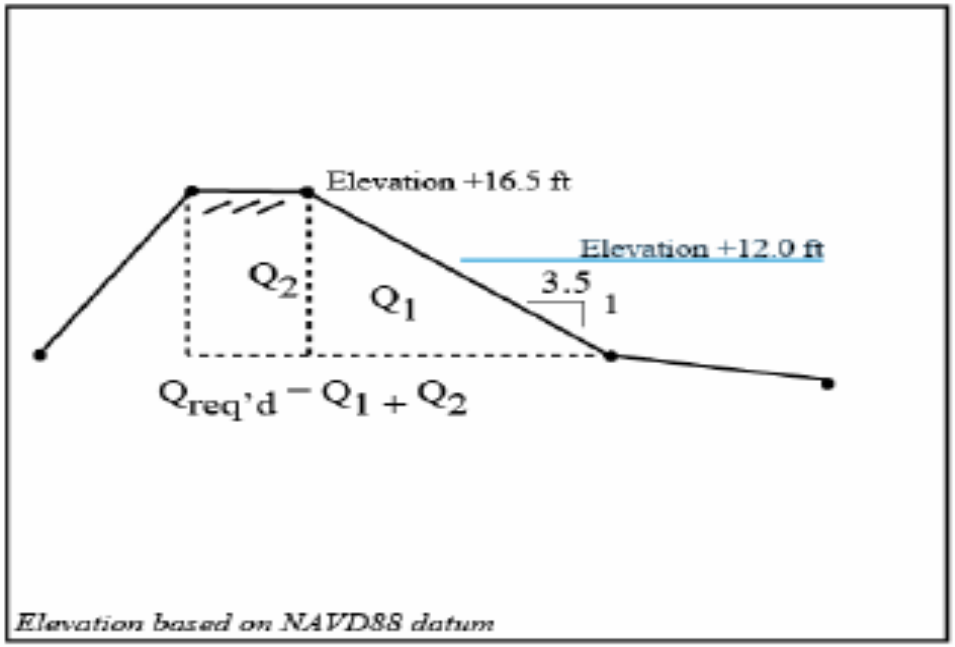
Constants		
Gravity	32.2	ft/s2
Water Density	1.99	slugs/ft3
Gs	2.71	

Model Properties		
Duration Increments		hr
Number of Increments	1200	
Wave Velocity (Uo)	19.6	ft/s
Cu	3.5	
Cs	0.00134	ft3/lb
Porosity	0.39	
Soil density (ps)	3.95	slugs/ft3
Breaker Type (x)	1.9	-Plunging
Floodside Slope	15.95	degrees
Deep water wave length (Lo)	46	ft

Grass Cover Erosion		
dgrass	0.5	ft
Egrass	0.0000426	1/ft*s
dg,max	0.0001278	ft
Cover erosion time	3.3	hrs

Qi Erosion Determination		
Qi	0.0640576	ft3/s
Qreq'd	253	ft3
time to breach (Qreq'd/Qi)	1.1	hrs

Stanczak (2008) & Allsop et al (2007) Analytic Profile Response Solution
Applied to: Hurricane Katrina (No MR-GO)
As reported in Bea (2008b)



Evaluation: Geisenhainer & Kortenhaus

Model Configuration		
Time Period		
Significant Wave Height (H)	0.5	ft
Wave Period (T)	2.25	s
Duration	0.5	hr
D50	0.0006562	ft
Soil void ratio (e)	0.65	
Floodside Slope (1:x)	6	
Surge Elevation	1.54	ft

Constants		
Gravity	32.2	ft/s2
Water Density	1.99	slugs/ft3
Gs	2.71	

Model Properties		
Duration Increments	0	hr
Number of Increments	1600	
Wave Velocity (Uo)	7.0	ft/s
Cu	1.8	
Cs	0.00134	ft3/lb
Porosity	0.39	
Soil density (ps)	3.95	slugs/ft3
Breaker Type (x)	1.2	-Plunging
Floodside Slope	9.46	degrees
Deep water wave length (Lo)	26	ft

Grass Cover Erosion		
dgrass	0.0	ft
Egrass	0.0000000	1/ft*s
dg,max	0.0000000	ft
Cover erosion time	#DIV/0!	hrs

Qi Erosion Determination		
Qi	0.001407	ft3/s
Qreq'd	1.9668	ft3
time to breach (Qreq'd/Qi)	0.4	hrs

Stanczak (2008) & Allsop et al (2007) Analytic Profile Response Solution
Applied to: Geisenhainer & Kortenhaus (2006)
As reported in D'Eliso (2007)

